Manuscript Title: On-chip electro-optic frequency shifters and beam splitters

Reviewer Reports on the Initial Version:

Referee #1 (Remarks to the Author):

Dramatic advances in thin-film lithium niobate photonics have been reported in the last couple of years, with several papers in high profile journals such as Nature. The Harvard group of Prof. Marko Loncar, who is the senior author of this submission, is at the lead of such advances. Lithium niobate has long been considered the go-to material for optical phase and intensity modulation, due to its high electro-optic coefficient, but was not capable of supporting complex integrated systems due to the large size of the waveguides and optical mode. Recent advances allowing fabrication of low loss, high confinement waveguides in thin film lithium niobate material has fundamentally changed the situation. Recent reports include a number of very exciting device demonstrations: phase modulators with record bandwidth, on-chip electro-optic cavity comb generators, record efficiency second harmonic generation, and others. The current work reports a highly efficient, low loss optical frequency shifter that currently operates in the multi-GHz up to few tens of GHz regime. Although efficient acousto-optic devices that provide near complete optical frequency shifting exist in lower frequency bands, to date there have been no satisfactory solutions applicable to tens of GHz frequency shifts – a regime that has important established applications in classical optical communications and RF systems, and potential applications in quantum technologies.

The work reported is high quality and impressive, and the functionality is indeed unique. Therefore, I do believe this report is worth considering for publication in Nature.

That said, my biggest question concerns the relation to the group’s previous work on an “Electronically programmable photonic molecule” published in Nature Photonics (2018). The basic device structure, a pair of coupled electro-optic microresonators with hybridized resonances, is the same. The concept of coupling the hybridized resonances through a lumped electro-optic modulation is also the same. Already in the 2018 paper, the authors report “We demonstrate that the photonic molecule can be used for unitary transformation of light in the frequency domain by controlling the dispersive and dissipative coupling between the two optical modes.” Although they did not demonstrate unidirectional frequency shifting or a frequency beam splitter in the 2018 paper, these operations can be anticipated, as they are among the most commonly invoked unitary transformations (for example, they are named X-gate and Hadamard gate in the quantum community).

In my view the main new result in the current paper is that authors worked out the coupling conditions needed to obtain complete frequency conversion with low loss and successfully demonstrated such operation in a very convincing way. A second new result is a concept to use multiple coupled electro-optic rings to achieve larger net frequency shifts and simulations showing the possibility of reaching 100 GHz or more. These are both significant results, so I see the question of how to decide on the current manuscript given the 2018 publication as a policy call on the part of the Nature editors. At a minimum though, I would call on authors to more clearly acknowledge the relationship to the 2018 Nature Photonics paper and to add discussion that clearly identifies the new features in the current submission, compared to their previous paper.

Otherwise, I have just a few small points.
Please comment on the optical power handling. This will not be an issue for quantum applications, where low power is expected, but may be important for classical applications such as lidar or radar signal processing. Even though the output light from the device can be amplified, the power has to be high enough to achieve amplification without excessive addition of noise — that will a problem if the power is excessively low.

Figure 2f y-axis shows “MW power before the amp” with relatively low powers: -25 dbm to – 50 dbm. This is a very strange way to label the axis, especially since I do not recall seeing the amplification factor specified. It is easy for the reader to get the wrong impression that it works at very low power and voltage. But later an example voltage is listed as ~3V, not unreasonable, but not extraordinarily low either. The dissipated power on chip may be low, but only because most of the power is reflected. Please modify the labeling of the y-axis so that is not likely to leave readers with the wrong impression about the power.

Please give more explanation about the electrode geometry and why the rather complicated looking geometry shown was adopted.


Referee #2 (Remarks to the Author):

This manuscript, entitled “Reconfigurable electro-optic frequency shifter,” describes a new scheme for high-efficiency, electro-optic frequency conversion. The scheme involves engineering resonant structures and their coupling to a continuum of states. By achieving an effective critical coupling condition, the frequency of incident light can be shifted with near unity conversion efficiency. The authors present measurements from devices and theoretical modeling to explain the effects. They also describe applications and extensions, such as using the device as a tunable beamsplitter, swapping frequency channels and extending the device to larger frequency shifts by coupling a cascade of resonances together. The performance of their devices is impressive, and I believe their ideas are creative and impactful. However, I found the manuscript difficult to follow, requiring several repeated readings to understand the meaning and relationships between certain statements. I’ve tried to describe these points of confusion below. After improving the clarity, I believe the manuscript deserved publication in a high-profile journal.

The work described in this manuscript is part of a family of impressive devices pioneered by the authoring research group in thin-film lithium niobate. Their fabrication expertise has allowed the realization of devices demonstrating highly efficient electro-optic conversion. The centerpiece of this manuscript is the near unity conversion efficiency obtained by engineering couplings between a pair of resonances and a continuum. The data (Fig 2b and 2c) show >99% conversion efficiency. However, I found it puzzling that the actual required microwave (MW) driving voltage to achieve this conversion is not mentioned anywhere in the main text or figures, and not until line 458 in the methods section. Also, the authors seek to highlight the “reconfigurability” of their device, particularly in the title of the manuscript, but I would argue the device performance is more impressive and perhaps more novel since four-wave mixing Bragg scattering beamsplitters (Raymer, et al Optics Communications 283, 747 (2010)) and other nonlinear beamsplitters (Pelc, et al, Optics Express 20, 19075 (2012)) have similar reconfigurability capabilities.

My main concern with this manuscript is its clarity. The body of the text describes the operation at a high level (as an analogy to energy levels in an atomic system coupled to a continuum), but I did not understand the mapping until I carefully read the model described in the “numerical
simulation” and “theoretical analysis” sections and the end of the paper. For instance, throughout the discussion on page 3, I was confused by the relationship between Omega (Rabi frequency), the doublet splitting and the MW drive (both MW frequency and MW amplitude). With the suggestive language used (Rabi frequency), I had the image of Autler-Townes splitting, where the doublet splitting depends on the MW drive (which is NOT the case here). It only became clear to me what was going on after I read the theoretical analysis section at the end of the paper. Can you summarize the explicit relationships between Omega, doublet splitting, and microwave drive in the body of the text? Also, the main text does not mention mu, the coupling between the two physical rings. I think you should mention that the two physical rings are strongly coupled to each other and must be thought of as a single device (the two rings are strongly coupled with delta frequency = 2 mu = 11 to 28 GHz, which exceeds gamma, the coupling rate to the waveguide). Then it would make more sense why the continuum waveguide only needs to couple to one ring. Thirdly, in lines 109-110, the authors speak about "the cavity" while there are actually two cavities/resonances. Saying the waveguide couples to only one cavity adds to the confusion. The waveguide couples to both A and AS resonances, and the rate is 30x higher than the intrinsic loss of both resonances (not the loss of just one cavity).

Another area that I believe could be clarified is explaining better how the insertion loss and MW drive voltage depend on device parameters. Some limited hand-waving arguments are presented in the methods section titled "characterization and limitation of insertion loss". Is there a theoretical expression upon which Extended Data Fig 3 is based? Does the insertion loss also depend on mu? In this section, it is also mentioned that the MW voltage should decrease with smaller gamma. Is there a theoretical formula for the MW drive voltage, or some intuition as to how MW drive voltage depends on gamma and other parameters (eg omega_m, FSR, etc)?

I also have several specific questions and areas for improved clarity:

- Page 3. How do you control the direction of the coupling to the continuum? The continuum is kind of like a blackbody that both absorbs and emits radiation. Would it be better to draw double-ended arrows for the coupling? Or at least mention in the text that the direction comes from whether you populate the levels omega_1 or omega_2.

- Paragraph starting line 116 and Figs 2b,c. Conversion efficiency depends on MW drive power (Omega). What MW powers are used to achieve the conversion efficiencies for up- and down-conversion?

- Fig 2d and discussion starting line 129. Why is the y-axis of Fig 2e "MW frequency"? I would have expected the y-axis to be shifted optical power (a.u). It looks like the 8 - 11 GHz is the label of each curve (which should be a legend), not the actual y-axis. Also, when you give an eta value, it is the peak efficiency right?

- What is the meaning of the dashed line in Fig 2e? I don't see any mention of it in the text or caption.

- Fig 3 and discussion starting line 149. There is only one tunable filter in Fig 3a (not a dichroic beam splitter), so the experiment doesn't seem to show SIMULTANEOUS swapping of the two channels (you seem to be checking only one channel at a time). Is this correct? Also, what is the filter and what is its extinction ratio? Do you observe cross-talk (perhaps due to imperfect extinction of the filter)?

- Also, regarding Fig 3 and the discussion, what is the MW drive power? Is it obvious that up- and down-shifting would require identical MW power? Even independent of the filter, why isn't there cross-talk? I could imagine if you accidentally over- or under-drive the system, you could have information on the wrong output channel (which would negate the claim of information exchange without detection).
- How do you increase the modes n in the cascading scheme? By changing size of ring 3 to have larger FSR?

- For the cascaded device (Fig 4), how do you tune the resonances of rings 1, 2 & 3 to be degenerate at the correct frequencies?

- Line 190, is there a reference paper describing dynamic coupling (microwave MZI)?

- In the conclusion, what is the acceptance bandwidth of omega_L (the laser to be shifted), and how does this affect your claim that your device can frequency shift quantum dots or probabilistic quantum emitters (which may have 10s GHz or even nm-wide spectra)?

- In the simulation of cascaded frequency shift, it is reasonable to assume the Q of all three resonators is the same? Generally speaking, Q is proportional to 1/FSR and there are different FSRs.

- Line 417. It says TM light is unshifted, but in extended fig 2, it looks like the TM light does have a Stokes shifted but no anti-Stokes. That doesn't seem like unshifted.

- Line 512-514 (and 500-501). The notation kappa_i and kappa_j seem confusing (especially in close proximity to each other). It seems j=1 or 2 but i=intrinsic (and is NOT an index). Maybe you should call intrinsic kappa something else (kappa_int or kappa_0). Also, why would the intrinsic loss of the two rings be the same? Is that a law, or just an assumption from fabrication?

Referee #3 (Remarks to the Author):

The current manuscripts build on the very new and promising technology of photonic integrated circuits based on LiNbO3 – which the Loncar group and others pioneered in recent years. In the current manuscript Hu and colleagues present work on photonic integrated electro-optic frequency shifters with high efficiency and low-loss. This is achieved using a new architecture of resonant modulation using a pair of coupled resonators and electro optic modulation on the novel lithium niobate on insulator platform.

Frequency shifting is important in a number of application, both scientific such as atomic and molecular Physics, as well as optical telecommunications. The currently employed commercial solution is on single sideband modulators (SSB), which are ubiquitous in optical telecommunications. They consist of two Mach-Zehnder amplitude modulators inside an interferometer and provide broadband, frequency agile, single sideband generation, with high carrier suppression ratio (>99%).

The approach presented by the Loncar group is based on coupled resonators. Experimentally the authors show both up-shifting and down-shifting by a single modulation frequency with this approach. The scheme is elegant and shows the advantage of using low loss, high Q resonators in Lithium Niobate. It is a beautiful demonstration of the novel complexity – and novel device architectures – that are possible using integrated electro-optical device technology.

Yet the results are misleading in a number of ways, and the functionality that the approach offers does not match that of conventional single sideband modulator, used for frequency shifting.

First, in their manuscript heavy emphasis is put on describing the configurability of the device, i.e. the tuning of the splitting ratio between the fundamental and the sideband by tuning the RF power and the tuning of the frequency difference between by the RF frequency. However, it should be
noted that essentially all frequency shifters (i.e. single sideband modulators, SSB) based both on quadrature modulators, which are commercialized in the SOI platform and ubiquitous in 100G and 400G optical transceivers, as well as acoustic-optical modulators (within the resonant bandwidth of the crystal) share this property. This is nothing new, nor particularly outstanding.

Second, the manuscript appears to suggest that the implementation of the frequency shifter via the electro-optical platform is more efficient than the state of the art. However, this is not the case, and comes from an incorrect way to define the “efficiency” of the device.

Specifically, I find the definition of conversion efficiency chosen by Hu and colleagues problematic. It is common for second order nonlinear processes to define the conversion efficiency as function of the input power (here the microwave power) in the unit [%/W]. Instead, the definition of the authors of conversion efficiency is instead to compare the relative power of carrier and sideband at the output. This in fact has already a name: it is called the carrier suppression ratio instead. A 99% carrier suppression ratio is easily achieved with standard off dual Mach-Zehnder based SSB. There is no improvement over the state of the art.

Lastly, the definition of conversion efficiency chosen here obscures the fact that the bona fide efficiency, i.e. output power divided by input power, of the presented device is "efficiency * insertion loss", which means that 99% efficiency and 0.5 dB insertion loss equates to a true efficiency of around 90%, not accounting for fiber input-output coupling efficiencies.

In fairness, it should be noted that the insertion loss of a dual Mach Zehnder with sinusoidal modulation has a fundamental insertion loss limit of 4.7 dB and the present device is advantageous for many loss sensitive applications, especially in the domain of quantum information technology. However, the current abstract and introduction fail to emphasize the loss and instead focus on the carrier suppression ratio which is state-of-the-art at best.

Third, the conventional SSB allow frequency agility and have a broad bandwidth, which is key to modulations (e.g. in QAM). The authors approach is inherently narrowband and not suited to data-communication.

Last, I would like to point the authors to Savchenkov and colleagues work on optical frequency shifting using crystalline LN microresonators. The higher Q in the crystalline WGM allows it to operate with only 2 mW of RF power, compared to the 100s of mW reported here and similar tunability over many GHz is demonstrated. The concept of [1], i.e. using multiple spatial modes of a lithium niobate resonator that couple differently to the applied external field, is largely similar to the presented work.

Overall we find that the manuscript could profit by discussing parts of the theory in the main manuscript instead of the supplementary information. The trade-off between nonlinear conversion efficiency and instantaneous bandwidth, as well as the tradeoff between the DC tunability of the RF shift frequency by tuning the resonators out of degeneracy. Lastly there exists a trade-off between the instantaneous bandwidth and the appearance of parasitic off-resonant sidebands (cf. SI Fig 1), that appear because the modulation frequency is only four times larger than the external coupling rate.

On the other hand, the experiments in Fig. 3 lack quantitative description. What is the used / possible bandwidth of the swap operation? How faithful is the data swap operation and what sources of loss and noise limit this operation? The transmission of low bandwidth signals (audio, with kHz bandwidth) hardly compares to the coherent communication experiments of the same authors in their prior work, that benchmarked the results against state of the art. One cannot escape the impression that the chosen application is ill-suited to highlight the technological capability of the resonant modulation approach. The authors could e.g. use demonstrate channel swapping on an actual data-stream, and characterize the minimum switching time and BER (which will be limited by the resonator bandwidth). They have already engaged in similar experiments.
with the Winzer group. It is surprising to see that this was not demonstrated here, given the dominant motivation of telecommunication.

To me the most exciting aspect is the demonstration of a high carrier suppression shifter for high frequencies, using a cascade of coupled EO resonators driven by a subharmonic. This scheme is clever, novel and has major potential to significantly improve the RF power required to shift an optical frequency, as it alleviates complexity of generating signals at 100 GHz or above. Moreover, this scheme would also be a leap beyond prior work of the authors, in which the Loncar group reported coupled photonic molecules Ref. 27 – the very device architecture used for this experiment.

As such, the proposed system in Fig. 4 for more than 100 GHz level frequency shift is exciting indeed and lies well outside the capabilities of contemporary SSB, and would represent a unique advantage and use of EO integrated photonics.

However, to this reviewer, it was disappointing and rather surprising to not see any device implemented. Clearly, what is lacking is presenting a physical implementation, and demonstrate that the approach actually works, that is, having successfully navigated the pitfalls of the proposed device such as the problems of tuning four resonances with three voltages and the increased electrode size and capacity on a 30 GHz resonator.

In summary, to this reviewer without this demonstration, the manuscript has not risen to the level that would be expected in a Nature publication. While the exceptionally on chip “low insertion loss” of the demonstrated device certainly merits attention from the integrated photonics community, the latter is an artificial metric, as it is not the true insertion loss (light-in vs. light-out) and I find that the present work establishes an incremental improvement over previous implementations both from the authors, i.e. Refs. 27 (photonic molecules) and 30 and Savchenkov’s work [1] to merit publication in Nature. The lack of actual demonstration of the proposed device in figure 4 will leave readers puzzled. To this reviewer, a manuscript that includes proper definitions of efficiency (and carrier suppression rate), a discussion on the tradeoff of resonant modulation i.e. bandwidth/RF efficiency, and generally a fair comparison to the state of the art, and above all, a manuscript that demonstrates the concept of cascaded modulation (Figure 4) would represent the sort of advancement one expects from Nature. With such revisions I would strongly endorse the manuscript for Nature.

Furthermore, I would like authors to answer/consider the following questions/comments to improve the manuscript for the specialist readers in the integrated photonics and quantum optics communities:

· Fig 2b,c) should show a logarithmic scale to properly highlight the carrier suppression and the emergence of unwanted higher order sidebands due to non-resonant coupling

· Fig 2f) The y-Axis should denote the RF power coupled to the chip, not the power before the RF amplifier, which is irrelevant for actual device performance. The amplifier gain is not mentioned in the Methods section.

· What is the capability for optical tuning of the input output frequencies of the devices?

· How much can the RF frequency be tuned by the inter-resonator detuning of the device before the conversion efficiency breaks down?

· What is the fiber to chip coupling loss. Is it included in the as-defined insertion loss?

· What is the parasitic coupling loss for the 30x over-coupled resonator pair? It would be also quite helpful for the reader to supply the amplitude and phase transmission curve of the overcoupled
resonator pair.

- Please comment on the fundamental trade-off between the insertion loss, which is maximized by overloading the resonators and the emergence of higher order sidebands (see Extended data Fig.1), which escape the overloaded resonator despite being off-resonant.

- More details on the fabrication should be given. Does the change of the electrode layouts compared to Ref. 27 minimize capacity? The Methods section on fabrication is too short and lacks references altogether.


Author Rebuttals to Initial Comments:
Referees’ comments:

Referee #1 (Remarks to the Author):

Dramatic advances in thin-film lithium niobate photonics have been reported in the last couple of years, with several papers in high profile journals such as Nature. The Harvard group of Prof. Marko Loncar, who is the senior author of this submission, is at the lead of such advances. Lithium niobate has long been considered the go-to material for optical phase and intensity modulation, due to its high electro-optic coefficient, but was not capable of supporting complex integrated systems due to the large size of the waveguides and optical mode. Recent advances allowing fabrication of low loss, high confinement waveguides in thin film lithium niobate material has fundamentally changed the situation. Recent reports include a number of very exciting device demonstrations: phase modulators with record bandwidth, on-chip electro-optic cavity comb generators, record efficiency second harmonic generation, and others. The current work reports a highly efficient, low loss optical frequency shifter that currently operates in the multi-GHz up to few tens of GHz regime. Although efficient acousto-optic devices that provide near complete optical frequency shifting exist in lower frequency bands, to date there have been no satisfactory solutions applicable to tens of GHz frequency shifts – a regime that has important established applications in classical optical communications and RF systems, and potential applications in quantum technologies.

The work reported is high quality and impressive, and the functionality is indeed unique. Therefore, I do believe this report is worth considering for publication in Nature.

We thank the reviewer for the very positive assessment of our work and for supporting its publication in Nature.

That said, my biggest question concerns the relation to the group’s previous work on an “Electronically programmable photonic molecule” published in Nature Photonics (2018). The basic device structure, a pair of coupled electro-optic microresonators with hybridized resonances, is the same. The concept of coupling the hybridized resonances through a lumped electro-optic modulation is also the same.

We agree with the referee that there are some similarities between our current manuscript and our Nature Photonics publication (Ref. 27) that also uses a coupled-ring resonator platform. In fact, the idea of using coupled resonators to realize a photonic two-level system has been widely explored in photonics for more than 20 years, starting with the initial proposal and demonstration in 1998 [Bayer et al. Phys. Rev. Lett. 81, 2582 (1998)]. Our own work (Ref. 27) builds on these ideas and introduces the electro-optic “control knob” that allows for controlled coupling between these photonic levels using electrical signals (DC and microwave). However, as we discuss below, this work was limited to pulsed microwave and optical operation, which is a significant limitation for broad impact and utility of the coupled-ring platform.

Our current manuscript pushes the photonic molecule platform to a new regime of operation, allowing unprecedented performance that goes well beyond what has been accomplished during the last 20 years, in our opinion. This has been accomplished by developing a new understanding of the system, specifically by exploring and leveraging the interplay between discrete and a
continuum of modes supported by our platform. By precisely engineering coupling rates between these modes, we were able to demonstrate high-performance frequency-domain mode shifting and beam splitting at tens of GHz frequency. This alone, we think, represents a significant advancement over the state of the art (including our past work). We also go a step further, and generalize the proposed concept to novel, cascaded, and efficient frequency shifters.

Already in the 2018 paper, the authors report “We demonstrate that the photonic molecule can be used for unitary transformation of light in the frequency domain by controlling the dispersive and dissipative coupling between the two optical modes.” Although they did not demonstrate unidirectional frequency shifting or a frequency beam splitter in the 2018 paper, these operations can be anticipated, as they are among the most commonly invoked unitary transformations (for example, they are named X-gate and Hadamard gate in the quantum community).

While the referee is correct, we would like to point out that the approach we pursued in Ref. 27 has several fundamental limitations that render it impractical and unsuitable for applications:

1. In Ref. 27, the frequency-domain conversion of light is performed using the Rabi oscillations induced by microwave driving. Thus, to perform a unitary transformation in the frequency domain the Rabi cycle needs to be interrupted, which requires the use of pulsed and carefully tailored microwave control signals (π or π/2 pulses). This is both challenging and costly since expensive high-bandwidth equipment needs to be used.

2. Since pulsed microwave control signals are used, the unitary transformation is possible only during certain time intervals - when the microwave is on - and thus optical signals need to be pulsed as well. In other words, our old approach cannot be applied to modulated continuous-wave (CW) optical signals. While this pulsed regime is of interest for envisioned applications of microwave-to-optical conversion and optical memory presented in Ref. 27, it is not suitable for realization of arbitrary unitary transformations on arbitrary optical signals. Moreover, pulsed operation requires synchronization between optical and microwave pulses. For example, this would rely on monitoring the arrival time of optical pulses in order to apply microwave pulses at the right time. This, however, can be impractical for quantum information applications where photons may not be measured, or where photonic quantum memories will be required (in addition to feed-forward), adding an additional restriction.

3. Finally, in Ref. 27 the bandwidth of the optical signal that is being converted is limited by the high-Q of the optical cavity needed to achieve efficient frequency conversion. Although this bandwidth is sufficient for modulated CW signals, it restricts utility for signals encoded in the time domain, a necessary encoding method due to the required use of microwave pulses.

In contrast, our current work demonstrates a practical and novel approach for controlling the frequency of any (pulsed or CW) optical signal with high efficiency and low loss. In our new devices, both the microwave and optical inputs can be continuous. Thus, light arriving at the device at any time can be shifted or splitted in frequency domain. This is achieved by exploiting the clever interplay between discrete modes of a coupled resonator system and continuum modes provided by a waveguide which interrupts the Rabi oscillation cycle. As a result, a simple, CW, harmonic microwave control signal can be used to realize unitary transformations in the frequency domain for nearly arbitrary optical signals: pulsed or CW. Moreover, the use of a strongly over-coupled
resonator system results in a cavity linewidth one order of magnitude higher than that used in Ref. 27, resulting in a much larger bandwidth of the device. Specifically, in our current work, we demonstrated the ability to convert optical signals of > 3 GHz microwave bandwidth, while our theoretical predictions estimate the 3-dB bandwidth to be as large as ~8 GHz (shift efficiency is > 50% from 7 GHz to 15 GHz).

In summary, Ref. 27 demonstrates a very nice and versatile platform - an optical two-level system that can be controlled using microwave signals - and uses it for several proof-of-principle demonstrations. However, the design strategy used in Ref. 27 results in a device that is fundamentally limited in its ability to control optical signals. Our current work provides a novel design strategy, and leverages precisely engineered couplings between different modes to allow for efficient and practical frequency shifting and beam splitting, as well as arbitrary unitary transformations on an optical signal in frequency domain.

In my view the main new result in the current paper is that authors worked out the coupling conditions needed to obtain complete frequency conversion with low loss and successfully demonstrated such operation in a very convincing way. A second new result is a concept to use multiple coupled electro-optic rings to achieve larger net frequency shifts and simulations showing the possibility of reaching 100 GHz or more. These are both significant results, so I see the question of how to decide on the current manuscript given the 2018 publication as a policy call on the part of the Nature editors.

The referee is correct in their assessment of the novelty of our work and its distinction from our previous work. Also, we would like to thank the referee for recognizing the importance and significance of these results.

At a minimum though, I would call on authors to more clearly acknowledge the relationship to the 2018 Nature Photonics paper and to add discussion that clearly identifies the new features in the current submission, compared to their previous paper.

We agree with the reviewer that we could have done a better job at distinguishing this work from our previous work. In the revised manuscript we made clear distinctions between the old and new work, identified shortcomings of the old work, and emphasized the novelty with respect to scientific and technological advancements made in the new work. Briefly, these are:

1. **Technological advancement:** Experimental demonstration of an integrated, electro-optic frequency shifter and beam splitter that simultaneously features high efficiency, low loss, small footprint, and the ability to operate at tens of GHz frequency. Taken together, these are important advancements over the state-of-the-art and, combined together, are unique to our device.

2. **Scientific advancement:** A novel approach for controlling the flow of light in the frequency domain that leverages precisely engineered coupling rates between different modes of the system. We believe that this concept is original and very powerful, as demonstrated by our results. Moreover, we were able to generalize this concept to propose a cascaded frequency shifter. We expect that this concept could be used as a powerful tool to control the light dynamics in a complex system involving multiple resonators, and may stimulate additional high-impact works in the future.
We have added the following revisions to the conclusion of the manuscript to distinguish our work from previous work more clearly and clarify the novelty of our work (changes are shown in red):

“In summary, we proposed and demonstrated an integrated, efficient, and low-loss electro-optic frequency shifter and frequency beam splitter operated at tens of GHz frequency, enabled by recent breakthroughs in integrated lithium niobate photonics [24,27,30]. In contrast to our previous work [27], that was limited to operation with pulsed optical and microwave signals, and thus requires precise timing between the two, here we can use simple sinusoidal CW microwave signals to control both pulsed and CW optical signals. This significantly simplifies the control of the device since precise timing is not needed. Furthermore, current devices operate in a strongly over-coupled limit, which increases the device bandwidth. Leveraging this, efficient and low loss frequency shifting and beam splitting is demonstrated. To this end, we engineer the coupling rates between different modes of the system to control the flow of light in the frequency domain. Moreover, we generalize our approach to propose a cascaded frequency shifter. Improvements to the quality factor of the optical resonators and the use of a microwave cavity can further reduce the insertion loss and drive voltage required, respectively. For example, increasing optical intrinsic Q to $10^7$ [24] will reduce the insertion loss to 0.04 dB, or can reduce both insertion loss and drive voltage to 0.2 dB and 2 V, respectively (see Methods). Notably, dynamic control of the shifted light can be achieved by replacing the coupling gap with a microwave-driven Mach-Zehnder interferometer [Soltani et al, Phys. Rev. A 96, 043808 (2017)] and by applying broadband microwave signals. Moreover, our method for controlling the flow of light in the frequency domain could be applied to other systems, such as mechanics, superconducting qubits, quantum dots, or atomic systems which contain discretized and a continuum of energy levels. The ability to process information in the frequency domain in an efficient, compact, and scalable fashion has the potential to significantly reduce the resource requirements for linear-optical quantum computing$^{11,12}$ and multiplexed quantum communication$^{31}$. Efficient and on-demand shifting of light may also allow for control of the emission spectrum of solid-state single-photon emitters to create indistinguishable single photons or to produce deterministic single photons from probabilistic emitters$^{32,33}$. Our reconfigurable frequency shifter could become a fundamental building block for frequency-encoded information processing that offers benefits to telecommunications$^7$, radar$^{34}$, optical signal processing$^{25}$, spectroscopy$^{35}$, and laser control$^{36}$. “

Otherwise, I have just a few small points.

Please comment on the optical power handling. This will not be an issue for quantum applications, where low power is expected, but may be important for classical applications such as lidar or radar signal processing. Even though the output light from the device can be amplified, the power has to be high enough to achieve amplification without excessive addition of noise – that will a problem if the power is excessively low.

In our experiments, we use hundreds of microwatts of power in a bus waveguide, which translates to several milliwatts of power inside the ring (due to the modest finesse ~50 of our strongly over-coupled ring resonators). One potential issue for lithium niobate ~50 of our strongly over-coupled ring resonators). One potential issue for lithium niobate rings operating at higher pump powers is photo-refractive effects that can detune the resonances and cause electro-optic response to uncontrollably vary when a DC voltage is applied, which affects the bias point of our devices. In our experiments we did observe these issues. Yet, as discussed in literature, LN rings are known to be able to handle large optical powers. For example, our group has previously demonstrated tens of Watts (~50 W) of circulating optical power inside a ring, for > 50 mW of power in the bus
waveguide [Wang et al, *Nature Communications* 10, 978 (2019)]. At high optical powers, photorefractive and thermo-optic effects can be combined to stabilize the ring resonance [He et al, *Optica* 6, 1138 (2019)]. Finally, there are strategies to mitigate the negative impact of the photorefractive effect on the DC bias stability by doping or utilizing feedback control, for example. In addition, our device does not have to operate exactly at the frequency-degenerate point of the two rings to have high performance. The device can maintain a high shift efficiency even if the DC voltage drifts (Please see Tunability of the shift frequency through DC tuning in the Methods section as well as the Extended Data Figure 6). We added the following discussion (in red) about the high power handling ability of our devices, including potential problems and solutions to the Methods section:

“In the measurement we use hundreds of microwatts of power in a bus waveguide, which translates to several milliwatts of power inside the rings due to the modest finesse of our strongly over-coupled cavities. Handling of optical powers as high as ~50 W have been demonstrated in LN ring resonators [Wang et al, *Nature Communications* 10, 978 (2019)]. However, with high optical powers, lithium niobate rings can suffer from resonance shifts, as well as drifts when a DC voltage is applied, due to the photorefractive effect. This can be mitigated by doping or using feedback control. Moreover, our device can maintain high performance under large frequency detuning of the two rings (see Extended Data Fig. 6 and the section of tunability of the shift frequency through DC tuning in Methods), which also helps reduce the negative effect of DC bias drift.”

**Figure 2f y-axis shows “MW power before the amp” with relatively low powers: -25 dBm to – 50 dBm. This is a very strange way to label the axis, especially since I do not recall seeing the amplification factor specified. It is easy for the reader to get the wrong impression that it works at very low power and voltage. But later an example voltage is listed as ~3V, not unreasonable, but not extraordinarily low either. The dissipated power on chip may be low, but only because most of the power is reflected. Please modify the labeling of the y-axis so that is not likely to leave readers with the wrong impression about the power.**

We thank the reviewer for pointing this out. Indeed, showing the power generated by the microwave source before amplification can be misleading. Thus, we have modified the y-axis label in Fig. 2f to indicate the on-chip microwave power. Moreover, we have added the microwave power for each device in the main text, figure captions and the Methods section, and we have also summarized them in an added Table 1 of device parameters.

As a reference, the microwave driving powers used to achieve the largest shift efficiency for devices with 12.5 GHz, 11.0 GHz, and 28.2 GHz doublet splittings are 102 mW (20.1 dBm), 288 mW (24.6 dBm), and 316 mW (25 dBm), respectively. The source power used for those three devices are 0.8 dBm, 0 dBm, and -23 dBm with amplifier gains of 19.3 dBm, 24.6dBm, and 48 dBm, respectively (including microwave cable losses).

**Please give more explanation about the electrode geometry and why the rather complicated looking geometry shown was adopted.**

To achieve high frequency operation (e.g. 30 GHz) of our device, we had to minimize both the capacitance and parasitic inductance of our electrodes. (This is explained in the “Ultimate limit of the magnitude of frequency shift” section in Methods.) Our numerical modeling indicates that the dominant parasitic capacitance in our system is formed between electrodes at two different layers, i.e. top and bottom electrodes. To minimize this, the electrode design was chosen to minimize the direct-overlap between these electrodes. Furthermore, we found that by making the top electrode
narrower, the capacitance formed between the electrodes at that layer can be reduced without affecting the microwave power handling capability. These clarifications are included in the Device Fabrication section in the Methods (also shown below for reference, with new changes labelled in red color):

“Device fabrication. Devices are fabricated from a commercial x-cut lithium niobate (LN) on insulator wafer (NANOLN), with a 600 nm LN layer, 2 μm buried oxide (thermally grown), on a 500 μm Si handle. Electron-beam lithography with hydrogen silsesquioxane (HSQ) resists followed by Ar+-based reactive ion etching (350 nm etch depth) are used to pattern the optical layer of the device, including the rib waveguides and micro-ring resonators. The device is cleaned and microwave electrodes (15 nm of Ti, 300 nm of Au, and 15 nm of Ti) are defined by photolithography followed by electron-beam evaporation and a bilayer lift-off process. These “bottom electrodes” provide electric fields across the rings to perform electro-optic modulation. Two layers of SiO2 (0.8 μm+0.8 μm) using plasma-enhanced chemical vapor deposition (PECVD) are used to clad the devices. Vias are subsequently patterned using photolithography and etched through the oxide using hydrofluoric acid. Finally, another layer of metal (15 nm of Ti and 500 nm of Au) is patterned by photolithography, electron-beam evaporation and lift-off. These “top electrodes” are used to route microwave signals and deliver them to the bottom electrodes. The crossovers are needed to ensure the desired polarities for microwave modulation. In the case of the ~ 28 GHz device (Fig. 2a), the shape of the top electrode is chosen to minimize its overlap with the bottom electrode, and thus minimize the parasitic capacitance formed between them. Furthermore, the top electrode is also narrow in order to reduce the parasitic capacitance formed between electrodes in that layer without affecting the microwave power handling capability. These design choices reduce the RC constant of the electrodes and allow for efficient modulation at high microwave frequencies. Lower frequency devices, with 12.5 GHz and 11.0 GHz doublet splitting, use the top electrode structure similar to that in Ref. 27. An illustration of the cross-section of the device is shown in Extended Data Fig. 1a. The inclined sidewall of vias (Extended Data Fig. 1a) due to the wet-etch process ensures that two layers of metal can connect to each other through electron-beam evaporation.”

We also added a figure to illustrate the cross section of the device as Extended Data Figure 1a:

Extended Data Fig. 1 | Illustration of the cross section of the device, setup of frequency shift measurements, and optical frequency spectra and transmission spectra. a, the cross section of the device. The parameters labeled in the cross section are w=1.2 um, h=350 nm, t=250 nm, d1=300 nm, d2=500 nm, and h1=h2=800 nm. b, [...]


We thank the reviewer for mentioning this paper. We have added it to the references in the revised version of the manuscript.

Referee #2 (Remarks to the Author):

This manuscript, entitled “Reconfigurable electro-optic frequency shifter,” describes a new scheme for high-efficiency, electro-optic frequency conversion. The scheme involves engineering resonant structures and their coupling to a continuum of states. By achieving an effective critical coupling condition, the frequency of incident light can be shifted with near unity conversion efficiency. The authors present measurements from devices and theoretical modeling to explain the effects. They also describe applications and extensions, such as using the device as a tunable beamsplitter, swapping frequency channels and extending the device to larger frequency shifts by coupling a cascade of resonances together. The performance of their devices is impressive, and I believe their ideas are creative and impactful. However, I found the manuscript difficult to follow, requiring several repeated readings to understand the meaning and relationships between certain statements. I’ve tried to describe these points of confusion below. After improving the clarity, I believe the manuscript deserved publication in a high-profile journal.

We thank the reviewer for the favorable and encouraging review despite the lack of clarity. We believe that we have addressed all the points of confusion in the revised version of manuscript, as discussed below.

The work described in this manuscript is part of a family of impressive devices pioneered by the authoring research group in thin-film lithium niobate. Their fabrication expertise has allowed the realization of devices demonstrating highly efficient electro-optic conversion.

We thank the reviewer for the kind words and recognizing the accomplishments of our group!

The centerpiece of this manuscript is the near unity conversion efficiency obtained by engineering couplings between a pair of resonances and a continuum. The data (Fig 2b and 2c) show >99% conversion efficiency. However, I found it puzzling that the actual required microwave (MW) driving voltage to achieve this conversion is not mentioned anywhere in the main text or figures, and not until line 458 in the methods section.

This is a very good point – we thank the reviewer for catching this. In the revised manuscript, both in the main text and in the caption of Fig. 2, we have now added the microwave power used to achieve > 99% shift efficiency, i.e. to achieve the results shown in Figs. 2b and 2c. Furthermore, we have changed the y-axis of Fig. 2f to indicate the microwave power delivered to the chip after the RF amplifier, as opposed to the power produced by the microwave source(before the amplifier). We hope that this will further clarify the power levels required for efficient frequency shifting.

Moreover, we have added the microwave power for each device in the main text, figure captions, and the Methods section. We have also summarized them in Table 1.
As a reference, the microwave driving powers to achieve the largest shift efficiency for devices with 12.5 GHz, 11.0 GHz, and 28.2 GHz doublet splittings are 102 mW (20.1 dBm), 288 mW (24.6 dBm), and 316 mW (25 dBm), respectively. The source power used for those three devices are 0.8 dBm, 0 dBm, and -23 dBm with amplifier gains of 19.3 dBm, 24.6dBm, and 48 dBm, respectively (including microwave cable losses).

Also, the authors seek to highlight the “reconfigurability” of their device, particularly in the title of the manuscript, but I would argue the device performance is more impressive and perhaps more novel since four-wave mixing Bragg scattering beamsplitters (Raymer, et al Optics Communications 283, 747 (2010)) and other nonlinear beamsplitters (Pelc, et al, Optics Express 20, 19075 (2012)) have similar reconfigurability capabilities.

We agree with the referee that when compared to other approaches, our device stands out in terms of its high performance. We also agree that the “reconfigurability” is not unique to our platform. However, we do feel that it is an important aspect of our work. To better emphasize the performance of our device, we propose to change the title to ‘Efficient and reconfigurable electro-optic frequency shifter’. Alternatively, we are happy to remove ‘reconfigurable’ from the title if the reviewer feels strongly about de-emphasizing this aspect of our work. Furthermore, we have added the following paragraph (in red) to the main text to place the reconfigurability of our device into context with other platforms, such as Bragg-scattering four-wave mixing, and have included the references mentioned by the referee.

“It should be noted that a frequency beam splitter, as the frequency-domain counterpart of a spatial beam splitter, needs to be bi-directional (can achieve up- and down-shift simultaneously), its outputs should be a coherent combination of its inputs when both frequency channels are present, and it should not affect other degrees-of-freedom such as polarization or spatial modes. Taking these into account, it can be seen that frequency shifters based on the IQ modulators, serrodyne method, adiabatic tuning, spectral shearing, and acousto-optic modulators cannot be reconfigured as frequency beam splitters, while nonlinear frequency shifters [Pele et al. Optics Express 20, 19075 (2012)] such as those based on Bragg-scattering four-wave mixing [Raymer et al. Optics Communications 283, 747 (2010)] can.”

My main concern with this manuscript is its clarity. The body of the text describes the operation at a high level (as an analogy to energy levels in an atomic system coupled to a continuum), but I did not understand the mapping until I carefully read the model described in the “numerical simulation” and “theoretical analysis” sections and the end of the paper. For instance, throughout the discussion on page 3, I was confused by the relationship between Omega (Rabi frequency), the doublet splitting and the MW drive (both MW frequency and MW amplitude). With the suggestive language used (Rabi frequency), I had the image of Autler-Townes splitting, where the doublet splitting depends on the MW drive (which is NOT the case here). It only became clear to me what was going on after I read the theoretical analysis section at the end of the paper.

We thank the reviewer for pointing this omission out. Indeed, with so many coupling rates and frequencies, it is important to define things clearly. We have attempted to do so in the revised manuscript, and have addressed the points raised by the referee, as discussed below.
Can you summarize the explicit relationships between Omega, doublet splitting, and microwave drive in the body of the text? Also, the main text does not mention mu, the coupling between the two physical rings.

In the revised manuscript we have added a paragraph to clearly define $\Omega$, the doublet splitting, and microwave drive, as well as to describe relationships between them. The following text was added to the fifth paragraph of the main text where we discussed our experimental implementation:

“Microwave driving induces a coherent coupling $\Omega$ between the S and AS modes, that is proportional to the peak-voltage of the applied microwave control signal. The doublet splitting (frequency differences between S and AS modes) is $2|\mu|$, where $\mu$ represents the coupling strength between two evanescently coupled rings (in the absence of an applied microwave signal). The microwave frequency $\omega_m$ is matched to or detuned from the doublet splitting $2|\mu|$, depending on the experiment we perform.”

I think you should mention that the two physical rings are strongly coupled to each other and must be thought of as a single device (the two rings are strongly coupled with delta frequency = 2 mu = 11 to 28 GHz, which exceeds gamma, the coupling rate to the waveguide). Then it would make more sense why the continuum waveguide only needs to couple to one ring.

Another very good point. In the revised manuscript we emphasized that the two physical rings are strongly coupled and therefore should be thought of as a single device. We also provided a clear explanation of why physical access (using a waveguide) to only one ring is sufficient to couple a continuum of modes to both resonances of our strongly coupled ring system. Specifically, we added the following (in red) to the fifth paragraph of the main text:

“The two physical rings are strongly coupled even in the absence of microwave drive (through evanescent coupling) and therefore can be seen as a single device. As a result, both (super-) modes supported by this strongly coupled system can be accessed using a single waveguide placed in the proximity of one ring only. Furthermore, the coupling rate $\gamma$ between the waveguide and the left cavity (Fig. 1e and 2a) is 31 times higher than the intrinsic loss $\kappa_{int}$ of the cavity, yielding two strongly over-coupled modes with balanced effective mode-waveguide coupling of $\kappa_{\text{eff}} = \kappa_{\text{v1}} = \kappa_{\text{v2}} = \gamma/2$ that are needed to satisfy for the generalized critical coupling condition (see Methods).”

Thirdly, in lines 109-110, the authors speak about "the cavity" while there are actually two cavities/resonances. Saying the waveguide couples to only one cavity adds to the confusion. The waveguide couples to both A and AS resonances, and the rate is 30x higher than the intrinsic loss of both resonances (not the loss of just one cavity).

We thank the reviewer for catching this. The waveguide is close to one of the rings that form our strongly coupled system but indeed it can couple to both the Sand AS resonances. Please see the text we included in response to your previous point.

Another area that I believe could be clarified is explaining better how the insertion loss and MW drive voltage depend on device parameters. Some limited hand-waving arguments are presented in the methods section titled “characterization and limitation of insertion loss”. Is there a theoretical expression upon which Extended Data Fig 3 is based? Does the insertion loss also depend on mu? In this section, it is also mentioned that the MW voltage should decrease with smaller gamma. Is
there a theoretical formula for the MW drive voltage, or some intuition as to how MW drive voltage depends on gamma and other parameters (eg omega_m, FSR, etc)?

We agree that more clarification is warranted. Therefore we added a paragraph to the Methods section “Characterization and limitation of insertion loss” to explain the dependence of the insertion loss and microwave driving voltage on parameters such as $\gamma$, $\kappa_{int}$, and $\mu$. We also provided a theoretical formula describing insertion loss, with explanation. Moreover, we added a few sentences to emphasize that the insertion loss and shift efficiency do not depend on $\mu$, which is one of the biggest advantages of our device. The added text is shown in red for the reviewers convenience:

**Theoretical expressions of microwave power, coupling rates, and insertion loss**

Microwave power and coupling rate $\Omega$:

When the intrinsic loss is non-zero, the generalized critical coupling condition is $\kappa_e = \kappa_i + \frac{\gamma^2}{\kappa}$ with $\kappa = \kappa_e + \kappa_{int}$, corresponding a coupling rate $\Omega = \sqrt{\kappa_e^2 - \kappa_{int}^2}$ to achieve the generalized critical coupling condition. Thus, the required microwave driving power is

$$P_0 = \frac{1}{R} \left( \frac{V_o}{\sqrt{2}} \right)^2 = \frac{1}{2} \left( \frac{V_c}{k_{RC}} \right)^2 = \frac{1}{2} \left( \frac{\Omega}{k_{RC} G_V} \right)^2 = \frac{1}{2} \left( \frac{1}{k_{RC} G_V} \right)^2 (\kappa_e^2 - \kappa_{int}^2)$$

where $V_o$ is the peak-voltage at the 50 $\Omega$ probe, $R$ is the resistance of the probe, $V_c$ is the voltage on the capacitor, $k_{RC} = V_c/V_o$ is determined by the RC limit of the electrode and is frequency-dependent, $G_V = 0.5$ GHz/V is the electro-optic coefficient of our device.

Since $\kappa_e = \gamma/2$, decreasing the waveguide-cavity coupling rate $\gamma$ can reduce the required microwave power for efficient frequency shifting (i.e. to reach the critical coupling condition). Higher microwave powers are required for increased microwave frequency $\omega_m$ because $k_{RC}$ will simultaneously decrease due to the RC limit of the electrode (discussed in section “ultimate limit of the shift frequency” in Methods).

Device insertion loss $IL$:

The power of the output signal $a_{out} = A_0 e^{-i\omega t} + A_+ e^{-i\omega t} e^{-i\omega_m t}$ is determined by $A_0$ and $A_+$. So the insertion loss is

$$IL = |A_0|^2 + |A_+|^2 = \left( \frac{\kappa_i + \frac{\Omega^2}{\kappa} - \kappa_e}{\kappa_i + \frac{\Omega^2}{\kappa} + \kappa_e} \right)^2 + \frac{4\Omega^2 \kappa_e^2}{(\kappa_i + \frac{\Omega^2}{\kappa} + \kappa_e)^2}$$

where we use the fact that we are measuring the average power, therefore the interference term of the output signal vanishes. When the generalized critical coupling condition is achieved, $A_0$ will vanish. Therefore, the insertion loss is purely given by the value of $A_+$:
\[ IL = |A_x|^2 = \frac{4\Omega^2\kappa_e^2}{(\kappa^2 + \Omega^2)^2} = \frac{4(\kappa_e^2 - \kappa_{\text{int}}^2)\kappa_e^2}{(\kappa^2 + \kappa_e^2 - \kappa_{\text{int}}^2)^2} \]

where we use \( \Omega = \sqrt{\kappa_e^2 - \kappa_{\text{int}}^2} \) at the generalized critical coupling condition. Importantly, it can be seen that the \( IL \) does not depend on the doublet splitting \( 2\mu_d \), which determines the magnitude of the frequency shift, and is only determined by the ratio \( \frac{\kappa_e}{\kappa_{\text{int}}} = \frac{\gamma/2}{\kappa_{\text{int}}} \). The device will become lossless \( (IL = 0 \text{ dB}) \) when \( \kappa_{\text{int}} \to 0 \).

I also have several specific questions and areas for improved clarity:

- Page 3. How do you control the direction of the coupling to the continuum? The continuum is kind of like a blackbody that both absorbs and emits radiation. Would it be better to draw double-ended arrows for the coupling? Or at least mention in the text that the direction comes from whether you populate the levels omega_1 or omega_2.

We thank the reviewer for pointing this out. The coupling is indeed bi-directional. In fact, we spent a lot of time thinking of how to illustrate the bi-directionality without making Fig. 1 too confusing. One approach we considered is to use two different colors for up- and down-conversion as illustrated below (panel d).

However, we thought that additional red arrows may imply Rabi oscillations, which is not what happens in our system. For this reason, we decided not to modify the original figure, but rather to emphasize the bi-directionality in the text and to clarify that the direction of energy flow in frequency domain depends on which level we populate first. Specifically, the following is added to the caption of Fig. 1:
“Note that the direction of energy flow is determined by which level is populated first, and transitions indicated by the coupling rates $\kappa_{e1}$, $\kappa_{e2}$, and $\Omega$ are bi-directional in nature.”

- Paragraph starting line 116 and Figs 2b,c. Conversion efficiency depends on MW drive power (Omega). What MW powers are used to achieve the conversion efficiencies for up- and down-conversion?

We carefully re-measured the microwave power needed to achieve a maximum shift efficiency using the device with 12.5 GHz doublet splitting. We find the microwave power required to generate the data shown in Figs. 2b and 2c is 102 mW. We also updated Figs. 2b and 2c with new data taken using this microwave power. Both up- and down-conversion use the same microwave power. These, as well as other microwave powers used for other devices, have been added in the figure captions, main text, and Methods.

- Fig 2d and discussion starting line 129. Why is the y-axis of Fig 2e “MW frequency”? I would have expected the y-axis to be shifted optical power (a.u.) It looks like the 8 - 11 GHz is the label of each curve (which should be a legend), not the actual y-axis. Also, when you give an eta value, it is the peak efficiency right?

We thank the reviewer for pointing this out. We have changed the y-axis to indicate normalized optical power (a.u.) and moved the labels “8-11 GHz” to each curve. Here, $\eta$ is defined as the power at the shifted frequency divided by the total output power, and is unique to each of the spectra shown in Figure 2d. The maximum $\eta$ is obtained when the microwave frequency is 11 GHz, that is, when it matches the doublet splitting of the device, and when the microwave power is optimized (i.e. critical coupling is reached). Other spectra are obtained by varying the microwave frequency while keeping all the other conditions the same. Consequently, except for the case when $\omega_{\text{in}} = 11$ GHz, $\eta$ for all other microwave detunings can be further increased by increasing the microwave power (to compensate for the fact that the shifted mode is detuned from optical resonance). We clarified these measurements in the seventh paragraph of the revised manuscript. Changes are shown in red:

“The microwave power is kept at 288 mW as we vary the microwave frequency from 11.0 GHz to 8.0 GHz. Accordingly, $\eta$ reduces from 97.7% to 78.4%, indicating a 3-dB bandwidth of >3 GHz that is currently limited by the bandwidth of our microwave amplifier (Figs. 2d and e). The bandwidth of the shifter benefits from the strong over-coupling of the optical resonators to the optical waveguide and strong microwave modulation, yielding a bandwidth that is larger than the unmodulated cavity linewidth (see Methods).”

- What is the meaning of the dashed line in Fig 2e? I don't see any mention of it in the text or caption.

The dashed line used to indicate the 3-dB bandwidth. However, we realized this dashed line is not useful so we deleted it in the revised version.

- Fig 3 and discussion starting line 149. There is only one tunable filter in Fig 3a (not a dichroic beam splitter), so the experiment doesn't seem to show SIMULTANEOUS swapping of the two channels (you seem to be checking only one channel at a time). Is this correct? Also, what is the filter and what is its extinction ratio? Do you observe cross-talk (perhaps due to imperfect extinction of the filter)?
Yes we only measure one channel at a time for this experiment, due to availability of only one filter in our lab that has the required specifications. Specifically, we use EXFO model XTM-50 ultrafine, XTM-50-SCL-U-58-A, with the bandwidth set to 4 GHz, and an extinction ratio \(~40\) dB. The experiment is performed as follows. We send both modulated laser beams into the device, each laser beam resonant with either the S or AS mode, and tune the resonance of the filter to match the resonances of the S mode, and take the first set of data. Next, we immediately tune the filter to be resonant with the AS mode without making any changes to our experimental conditions, and take the second set of data. We believe that this approach is sufficient to claim the swap operation.

However, we do agree with the reviewer that the primary reason for simultaneously measuring both channels is to quantify cross-talk in real time, not simply to observe the data swapping simultaneously (which occurs due to the unitarity of our splitter). Thus, to precisely determine cross-talk, and also to reconcile our lack of simultaneous measurement of both channels, we performed the following experiment. We use two modulated laser beams as two frequency channels. Specifically, we modulated one of the optical beams (matching the S resonance, and which we refer to as channel 1 here) with a sinusoidal signal of which the frequency is swept from 200 MHz to 2.8 GHz and the other (matching the AS resonance, channel 2) with a 1 GHz sinusoidal signal (Extended Data Fig. 5a). The swap operation was then performed, and the filter was tuned to pass light first from the S resonance (channel 1) and then from the AS resonance (channel 2). The transmitted signals were detected by a photodiode and their spectra are analyzed using a real-time spectrum analyzer to quantify the cross-talk. The results are shown in the figure below, and also included in the manuscript as Extended Data Fig. 5 along with a corresponding description in the section “Measurement of swap operation” in Methods.

We plot the RF spectra when the (swept) modulation frequency in channel 1 is set to 2.6 GHz (the modulation frequency in channel 2 is fixed at 1 GHz) as an example. It shows that, after the swap operation, the spectrum is clean in both channel 1 and channel 2 (Extended Data Fig. 5b). The frequency component of 1.6 GHz that appears in channel 1 is the beat note between the shifted frequency and the residual frequency. The 2 GHz frequency is the second harmonic signal that is generated by the amplitude modulator, which is verified beforehand. We define the cross-talk as the ratio between the shifted frequency and residual frequency and find that crosstalk is very low (< -35 dB) when the swept modulation frequency of channel 1 is at the several hundreds of MHz level, and are \(~-25\) dB when using a 2.8 GHz signal (Extended Data Fig. 5c). The cross-talk measurement is performed using the device same as the modulation bandwidth measurement and channel shifting with pseudorandom bit sequences measurement at the same optical wavelength and microwave driving power (see the question of acceptance bandwidth later). The cross-talk can be reduced further by improving the shift efficiency, see “Limitation of the shift efficiency” in the Methods, as well as improving the device optical bandwidth (see the question of acceptance bandwidth later).
Extended Data Fig. 5 | Crosstalk measurement for channel swapping. a, Experimental setups for crosstalk measurement. Two input laser beams are each independently modulated by a sinusoidal signal as two frequency channels, sent into the device, and detected by an OSA and a PD followed by an RSA. Sinusoidal signal applied to the input beam of channel 1 (match the S resonance) is swept from 200 MHz to 2.8 GHz while sinusoidal signal on the input beam of channel 2 (match the AS resonance) is kept at 1 GHz. Each channel is selected by a tunable filter. b, radio-frequency spectrum for output channel 1 and channel 2 on the RSA after the swap when the modulation frequency in channel 1 is set to 2.6 GHz, showing low crosstalk in the swap measurements. The crosstalk is defined as the ratio between the shifted frequency and the residual frequency. The frequency component of 1.6 GHz that appears in channel 1 is the beat note between the shifted frequency and the residual frequency. The 2 GHz frequency is the second harmonic signal that is generated by the amplitude modulator, which is verified beforehand. c, Measured crosstalk for two channels when sweeping the modulation frequency in channel 1 from 200 MHz to 2.8 GHz. We find the crosstalk is \(-35\) dB at low frequency (several hundreds of MHz) and \(-25\) dB at 2.8 GHz. PC, polarization controller; AM, amplitude modulator; EDFA, erbium-doped fiber amplifier; OSA, optical spectrum analyzer; PD, photodetector; RSA, real-time spectrum analyzer.

We have added the following in the main text related to the question of crosstalk (We also added descriptions about device modulation bandwidth, motivation of the swap measurements, and future improvement of bandwidth that arises from other questions, please see detail about those in other related questions). Please see below (red color):

"In addition, we also modulated two different songs to the two frequency channels and verified the swap operation by sending signals from the photodetector to a speaker (see supplementary for a video file). However, note that the 3-dB modulation-bandwidth for the frequency channels is limited to 2.2 GHz in current devices and will broaden to 4.1 GHz when increasing the microwave power to overdrive the device (see methods). The frequency shifting with pseudorandom bit sequences
are also performed to further verify the device performance at GHz-bandwidth frequency channels (see methods). In addition, the cross-talks of the swap operation are characterized as ~35 dB to -25 dB for sinusoidal modulations on channels from several hundreds MHz to 2.8 GHz (see methods). Improving the device optical bandwidth to ~14GHz could fit the device to future telecommunication applications (see methods)."

We have also added the following text to Methods (red color):

“**Measurement of swap operation.** The experimental demonstration of the swap operation is performed at a wavelength of 1560.6 nm (setup shown in Fig. 3a). We first set the frequency of two laser beams to be far detuned from the doublet resonance and measure the time-domain audio signals as references. This corresponds to the case in which the signals are not swapped. We then tune the frequency of each laser beam to be on resonance with one of the modes of the doublet, i.e. laser 1 (2) in S (AS) mode. In this case, frequency components around laser beam 1 are up-shifted and components around the frequency of laser beam 2 are down-shifted. The amplitudes of the time domain signal before and after swapping are renormalized for comparison in Fig. 3b.

Another experiment of swap operation is performed to quantitatively characterize the cross-talk of the swap operation (Extended Data Fig. 5). Laser beams 1 and 2 are respectively modulated by two sinusoidal signals as two frequency channels. The sinusoidal signal in channel 1 is swept from 200 MHz to 2.8 GHz while the signal in channel 2 is fixed at 1 GHz (Extended Data Fig. 5a). Swap operation is then performed, filter is tuned to pass first channel 1 and then channel 2, and the transmitted signals are detected by a photodiode followed by a real-time spectrum analyzer. The radio frequency (RF) spectra are analyzed to obtain the cross-talk, which is defined as the ratio between the shifted frequency and residual frequency. An example of the RF spectra when the swept modulation frequency in channel 1 is set to 2.6 GHz (the modulation frequency in channel 2 is fixed at 1 GHz) are plotted and it shows that the spectrum is clean and the cross-talk is low in both channels (Extended Data Fig. 5b). The frequency component that shows up at 1.6 GHz in channel 1 could be the beat note between the shifted (1 GHz) and residual frequency (2.6 GHz). The frequency at 2 GHz in channel 1 is the second harmonic signal generated by the amplitude modulator we used, which is verified before the swap measurement. By sweeping the modulation frequency of channel 1 from 200 MHz to 2.8 GHz, we find the cross-talks for both channels are low (~ -35 dB) when the modulation frequency of channel 1 is at several hundreds of MHz and the cross-talks gradually increase to ~ -25 dB at 2.8 GHz (Extended Data Fig. 5c). The cross-talk measurement is performed using the device same as the modulation bandwidth measurement and channel shifting with pseudorandom bit sequences measurement at the same optical wavelength and microwave driving power.”

- Also, regarding Fig 3 and the discussion, what is the MW drive power? Is it obvious that up- and down-shifting would require identical MW power? Even independent of the filter, why isn't there cross-talk? I could imagine if you accidentally over- or under-drive the system, you could have information on the wrong output channel (which would negate the claim of information exchange without detection).

We thank the reviewer for mentioning this. The microwave drive power used to perform the swap operation is 24.6 dBm (288 mW). And yes, it is true that the up- and down-shift require identical microwave power. In fact, this is one of the advantages of our approach: once the generalized critical coupling condition is reached, this frequency shifter is bi-directional! Then, simply changing
the pump frequency from $\omega_1$ to $\omega_2$ (i.e. S to AS) changes the directionality of the frequency shifting: up-shift or down-shift. Nothing else needs to be changed in our device or experimental apparatus.

As discussed in the previous reply, we agree that there is cross-talk due to imperfections of the frequency shift. The reason that the data in Fig. 3b is clean is the high shift efficiency of our device, which yields cross-talk to be at least 25 dB lower than the signal.

We agree that if we accidentally over- or under-drive the system, we could have non-ideal frequency shifting/swapping with significant cross-talk. However, simulations show that the shift efficiency is not overly sensitive to variations of the drive RF power, as illustrated in the figure below. Specifically, changes in the microwave powers in the range 20 dBm - 23.5 dBm vary the efficiency by no more than 5 percent. We note that this simulation is performed based on the parameters of our 11.0 GHz device which we used to perform the swap operation.

![Simulated shift efficiency as a function of microwave power on the chip](image)

Simulated shift efficiency as a function of microwave power on the chip. High shift efficiency, with a variation of <5%, can be achieved over a power range of 20 dBm - 23.5 dBm, indicating a good tolerance of shift efficiency with microwave power.

Note that we performed all swap measurements described above (and in the manuscript) with near-optimum microwave powers.

- How do you increase the modes $n$ in the cascading scheme? By changing size of ring 3 to have larger FSR?

  Yes, the number of modes for the cascading scheme is defined by the size of ring 3 and ring 1. Please see the added text in the following reply.

- For the cascaded device (Fig 4), how do you tune the resonances of rings 1,2 & 3 to be degenerate at the correct frequencies?
We can use a DC voltage to tune the cavity resonances through the electro-optic effect of LiNbO₃. The tuning rate is typically 0.5 GHz/V and our device can handle at least 60 V without destroying the electrode.

We have added the corresponding revisions related to this and the last question into the tenth paragraph of the main text (also posted below in red).

“Therefore the number of modes n of such a device is determined by the size of ring 1 and ring 3. DC voltage or thermal tuning can be used to tune the resonances of all rings.”

- **Line 190**, is there a reference paper describing dynamic coupling (microwave MZI)?


- **In the conclusion**, what is the acceptance bandwidth of omega_L (the laser to be shifted), and how does this affect your claim that your device can frequency shift quantum dots or probabilistic quantum emitters (which may have 10s GHz or even nm-wide spectra)?

The acceptance bandwidth of the input laser is a few GHz. We have performed additional measurement to confirm the acceptance bandwidth of optical signals. In particular, measured the modulation bandwidth of our device with a 12.5 GHz doublet splitting. Here, one laser beam was modulated with a sinusoidal signal from a vector network analyzer (VNA), and light was then up-shifted. The output light is detected by a photodetector and sent back to the VNA. The measured modulation bandwidth is shown below (also attached to Methods as Extended Data Fig. 3). We found that the 3-dB modulation bandwidth is as large as 2.2 GHz (Extended Data Fig. 3b), corresponding to a 4.4 GHz optical bandwidth. Specifically, we demonstrate that this bandwidth can be broadened by increasing the microwave driving power on the device. We show that by increasing the microwave power from 126 mW to 398 mW, the 3-dB modulation bandwidth can be increased to 4.1 GHz, which is due to the microwave-induced linewidth broadening effect that is discussed in the theoretical analysis in Methods. The electro-optic S21 for both microwave critical-drive and over-drive are normalized to the electro-optic S21 of the microwave critical-drive at lowest frequency (10 MHz) and the instrument responses (including amplitude modulator, photodetector, and filter bandwidths) are calibrated. From the electro-optic S21 at lowest frequency (10 MHz), we found that the optical power loss is -1.15 dB, which is consistent with the device insertion loss (-0.96 dB).

Moreover, as requested by the referee 3, we measured the eye diagram by creating pseudorandom bit sequences via an arbitrary waveform generator (AWG), using it to modulate the input laser beam, and performing up-shift of the input light. Data rates at 1.000 Gbit/s and 3.125 Gbit/s are measured (Extended Data Fig. 3c and 3d). The data rates in this experiment are limited by the sampling rate of the AWG that we used. By comparing the amplitude of the eye diagrams before and after up-shifts, we confirmed that the loss (~1 dB) is consistent with the measured 0.96 dB device insertion loss for the data in Fig. 2 of the main text, and we did not observe added noise from our device. The eye diagrams before the swap are measured by tuning the input laser off-resonance and the center of the filter window is set to the input laser wavelength. For the case of before and after shift, the bandwidth of the filter is kept the same and the microwave driving powers are kept at 126 mW (the case of microwave critical drive in the modulation bandwidth measurement, Extended Data
Fig. 3b). The switching time in the current eye diagrams is limited by the AWG and oscilloscope bandwidth.

Extended Data Fig. 3 | Device modulation bandwidth and frequency channel shifting with pseudorandom bit sequences. a, Experimental setups. The input laser beam is modulated by either a sinusoidal signal from the port 1 of a vector network analyzer (VNA) (bandwidth measurement) or an actual data stream that is generated by an arbitrary waveform generator (AWG) (eye diagram measurement). The input light is up-shifted and detected by a photodetector (PD) followed by either port 2 of the VNA (bandwidth measurement) or an oscilloscope (eye diagram measurement). The measurements are performed at a wavelength of 1560 nm on the device in Fig. 2b and 2c in the main text, in which the doublet splitting is 11.3 GHz due to optical dispersion (doublet splitting is 12.5
GHz at 1601 nm). b, Measured modulation bandwidth of the device. The 3-dB modulation bandwidth is 2.2 GHz, corresponding to an optical bandwidth of 4.4 GHz. Specifically, the modulation bandwidth is broadened to 4.1 GHz by increasing the microwave driving power from 126 mW to 398 mW. c, Measured eye diagrams when using actual data streams to modulate the input laser beam. The eye diagrams before shift are measured by setting the input laser beam off-resonance with the filter window centered to the input wavelength (filter bandwidth unchanged). By comparing the amplitude of the eye diagrams before and after swap, we found the loss is ~1 dB which is consistent with the device insertion loss (0.96 dB).

We also show that the device optical bandwidth can be broadened to 10s GHz. Specifically, we simulate the effect of varying device parameters on the instantaneous optical bandwidth. An increase of the bandwidth can be achieved by increasing the external coupling rate $\kappa_e$ while keeping all the other parameters the same as our 28.2 GHz device. For example, device parameters can be: $\kappa_e = 2\pi \times 10$ GHz, $\kappa_{int} = 2\pi \times 170$ MHz (1.1 million intrinsic Q), and $\omega_m = 2\pi \times 28.2$ GHz, which leads to a 3-dB optical bandwidth of ~14 GHz (Extended Data Fig. 4b) with a driving microwave power of 1.35 W for a full frequency shift (238 mW for 50-50 split), a suppression of 26.7 dB with respect to parasitic sidebands, and a device insertion loss of 0.13 dB.

![Extended Data Fig. 4 | Simulated shift efficiency as a function of the detuning of the laser.](image)

Optical bandwidth of a device optimized for high bandwidth. Design parameters: $\gamma = 2\pi \times 20$ GHz (leads to a $\kappa_e = 2\pi \times 10$ GHz), $\kappa_{int} = 2\pi \times 170$ MHz, $\omega_m = 2\pi \times 28.2$ GHz. A 3-dB optical bandwidth of ~14 GHz can be achieved using a critical-drive microwave power of 1.35 W with a 26.7 dB suppression of parasitic sidebands and 0.13 dB device insertion loss. The microwave power for a 50-50 split on such a device is expected to be 238 mW.

Finally, the acceptance modulation/optical bandwidth does not affect our claim that our device can shift photons originating from quantum emitters. The reviewer is correct to say that dots typically have very large bandwidths (which is partially why they are so heavily investigated). However, other promising emitters, such as silicon vacancies in diamond or silicon carbide, have bandwidth of hundreds of MHz to GHz in cavities [Zhang et al. *Nano Lett.* 18, 2, 1360–1365, 2018; Lukin et al. *Nature Photonics* **14**, 330–334, 2020, Evans et al. *Science* **362**, 662–665, 2018]. In addition, it is interesting to consider emitters that can be embedded into lithium niobate [Saglamyurek et al, *Nature*, **469**, 512-515, 2011]. To this point, let us consider rare-earth-ions or single photons generated by spontaneous parametric down conversion (SPDC). Rare-earths have shown
emission bandwidths of no more than MHz [Kindem et al., *Nature* 580, 201-204, 2020], and would be of similar order in lithium niobate under the same experimental conditions (e.g. Purcell enhancement), which is well below the acceptance bandwidth of the shifter. SPDC produces broadband photon pairs as the reviewer pointed out, however these photons are often strongly filtered to GHz bandwidths in applications to purify their spectra [Sun et al., *Optica* 4, 10, 1214-1218, 2017]. Moreover, photons from SPDC can be used for frequency-multiplexed schemes that require filtering to less than GHz (and with GHz-range shifts) to gain an advantage [Sinclair et al., *Phys. Rev. Lett.* 113, 053603, 2014], or to generate near-deterministic single photons [Grimeau Puigibert et al., *Phys. Rev. Lett.* 199, 083601, 2017, Joshi et. al., *Nature Communications* 9, 847, 2018].

Related to the bandwidth question, we have added the following text to the paragraph about the swap operation in the main text, in which the channel bandwidth is an important metric. Please see below (in red color):

“In addition, we also modulated two different songs to the two frequency channels and verified the swap operation by sending signals from the photodetector to a speaker (see supplementary for a video file). However, note that the 3-dB modulation-bandwidth for the frequency channels is limited to 2.2 GHz in current devices and will broaden to 4.1 GHz when increasing the microwave power to overdrive the device (see methods). The frequency shifting with pseudorandom bit sequences are also performed to further verify the device performance at GHz-bandwidth frequency channels (see methods). In addition, the cross-talks of the swap operation are characterized as ~35 dB to -25 dB for sinusoidal modulations on channels from several hundreds MHz to 2.8 GHz (see methods). Improving the device optical bandwidth to ~14 GHz could fit the device to future telecommunication applications (see methods).”

We have also added the following text (in red color) to Methods:

“**Device optical and modulation bandwidth.** Additional experiments are performed to verify the device optical bandwidth. The input laser beam is first modulated with a single sinusoidal signal from a vector network analyzer (VNA) and then passes through the device to perform a frequency up-shift. The output light is sent back to the vector network analyzer (Extended Data Fig. 3a). The 3-dB modulation bandwidth for the frequency channel is 2.2 GHz, corresponding to a 4.4 GHz optical bandwidth (Extended Data Fig. 3b). Specifically, we find that by increasing the microwave power from 126 mW to 398 mW, the modulation bandwidth can be broadened to 4.1 GHz, which is due to the microwave-induced linewidth broadening effect discussed in the theoretical analysis in Methods. The electro-optic S21 for both microwave critical-drive and over-drive are normalized to the electro-optic S21 of the microwave critical-drive at lowest frequency (10 MHz) and the instrument responses (including amplitude modulator, photodetector, and filter bandwidths) are calibrated. From the electro-optic S21 at lowest frequency (10 MHz), we found that the optical power loss is ~1.15 dB, which is consistent with the device insertion loss (~0.96 dB).

The frequency channel is also encoded by actual data streams to further demonstrate the device performance for GHz-scale channel bandwidths. We generate the pseudorandom bit sequences at 1.000 Gbit/s and 3.125 Gbit/s by an arbitrary waveform generator (Extended Data Fig. 3a). Eye diagrams are measured to characterize the device performance (Extended Data Fig. 3c and 3d). The data rates that we used are currently limited by the sampling rate of the arbitrary waveform generator. By comparing the amplitude of the eye diagrams before and after up-shifts, we confirmed that the loss (~ 1 dB) is consistent with the measured 0.96 dB device insertion loss for
the data in Fig. 2 of the main text, and we did not observe added noise from our device. The eye
diagrams before shift are measured by tuning the laser beam off-resonance and setting the center
of the filter window at the frequency of the laser beam. For the case of before and after shift, the
bandwidth of the filter is kept the same and the microwave driving powers are kept at 126 mW (the
case of microwave critical drive in the modulation bandwidth measurement, Extended Data Fig.
3b).

Both the measurement of modulation bandwidth and channel shifting with pseudorandom bit
sequences are performed on the device with 12.5 GHz doublet splitting (Fig. 2b, 2c in the main
text). The optical wavelength is chosen at 1560.7 nm in which the doublet splitting changed to 11.3
GHz due to the optical dispersion.

In addition, to fit some telecommunication applications that require a higher bandwidth, we show
that the device optical bandwidth can be further improved by increasing the waveguide-cavity
coupling gamma. For example, improving the waveguide-cavity coupling gamma to \( \gamma = 2\pi \times 20 \text{ GHz} \) (leads to a \( \kappa_c = 2\pi \times 10 \text{ GHz} \)) while keeping other parameters same as the current
28.2 GHz device (\( \kappa_{\text{int}} = 2\pi \times 170 \text{ MHz} \), \( \omega_m = 2\pi \times 28.2 \text{ GHz} \)) can result in a 3-dB optical
bandwidth of \( \sim 14 \text{ GHz} \) (simulation, Extended Data Fig. 4) with a driving microwave power of 1.35
W for full frequency shift (238 mW for 50-50 split), a suppression of 26.7 dB on parasitic sidebands
(see section limitation of the shift efficiency for discussion on parasitic sidebands), and a device
insertion loss of 0.13 dB.”

- In the simulation of cascaded frequency shift, is it reasonable to assume the Q of all three
resonators is the same? Generally speaking, Q is proportional to \(1/FSR\) and there are different FSRs.

The referee is correct that in the absence of intrinsic losses, the Q of the resonator is directly
proportional to its size (length), that is inversely proportional to FSR. However, in our devices we
are typically limited by absorption due to material imperfections or scattering due to fabrication
imperfections [please see Zhang et al. Optica 4, 1536 (2017)]. In fact, we can now readily make
resonators of varying length with \( Q_{\text{intrinsic}} \) on the order of several million. Therefore, we believe that
it is reasonable to assume that the intrinsic quality factor is the same for all three resonators.

- Line 417. It says TM light is unshifted, but in extended fig 2, it looks like the TM light does have a
Stokes shifted but no anti-Stokes. That doesn't seem like unshifted.

We thank the reviewer for pointing this out. Previously we said it is unshifted because the TM mode
is shifted with a low shift efficiency (~50%) compared to that of the TE mode (~99%). We now
modify the sentence to say the “TM mode is not efficiently shifted”.

- Line 512-514 (and 500-501). The notation kappa_i and kappa_j seem confusing (especially in close
proximity to each other). It seems j=1 or 2 but i=intrinsics (and is NOT an index). Maybe you should
call intrinsic kappa something else (kappa_int or kappa_0). Also, why would the intrinsic loss of the
two rings be the same? Is that a law, or just an assumption from fabrication?

We thank the reviewer for mentioning this. We have changed \( \kappa_i \) to \( \kappa_{\text{int}} \) in all of the manuscript to
avoid any confusion.
As we mentioned above, we assume two rings to have identical intrinsic losses. Based on our experience, this is typically true. More importantly, even if the two rings have different intrinsic losses, the S and AS modes will share the same intrinsic losses because both hybrid modes equally occupy both rings. Thus, the assumption of identical intrinsic losses of both rings will not affect the outcome of our work.

Referee #3 (Remarks to the Author):

The current manuscripts build on the very new and promising technology of photonic integrated circuits based on LiNbO3 – which the Loncar group and others pioneered in recent years. In the current manuscript Hu and colleagues present work on photonic integrated electro-optic frequency shifters with high efficiency and low-loss. This is achieved using a new architecture of resonant modulation using a pair of coupled resonators and electro optic modulation on the novel lithium niobate on insulator platform.

Frequency shifting is important in a number of applications, both scientific such as atomic and molecular Physics, as well as optical telecommunications. The currently employed commercial solution is on single sideband modulators (SSB), which are ubiquitous in optical telecommunications. They consist of two Mach-Zehnder amplitude modulators inside an interferometer and provide broadband, frequency agile, single sideband generation, with high carrier suppression ratio (>99%). The approach presented by the Loncar group is based on coupled resonators. Experimentally the authors show both up-shifting and down-shifting by a single modulation frequency with this approach. The scheme is elegant and shows the advantage of using low loss, high Q resonators in Lithium Niobate. It is a beautiful demonstration of the novel complexity – and novel device architectures – that are possible using integrated electro-optical device technology.

We thank the reviewer for the kind words and recognizing the importance of the platform we, and others, have been developing. We also thank them for reading our manuscript carefully and providing a very thorough and detailed review. While it took some time to address all the comments, it did force us to dig even deeper into the literature and carefully compare our platform to previous work. We truly believe that this resulted in a much stronger manuscript, and we hope that the reviewer will be of the same opinion.

Yet the results are misleading in a number of ways, and the functionality that the approach offers does not match that of conventional single sideband modulator, used for frequency shifting.

We regret to hear that the reviewer finds our work misleading. We, however, respectfully disagree with the assessment that our work is inferior to a single sideband modulator. Our arguments are discussed below.

First, in their manuscript heavy emphasis is put on describing the configurability of the device, i.e. the tuning of the splitting ratio between the fundamental and the sideband by tuning the RF power and the tuning of the frequency difference between by the RF frequency. However, it should be noted that essentially all frequency shifters (i.e. single sideband modulators, SSB) based both on quadrature modulators, which are commercialized in the SOI platform and ubiquitous in 100G and
400G optical transceivers, as well as acoustic-optical modulators (within the resonant bandwidth of the crystal) share this property. This is nothing new, nor particularly outstanding.

We thank the reviewer for this comment. We now see that there is a misunderstanding in the interpretation of the term “reconfigurable” in our title.

Indeed, most single sideband modulators can control the modulation efficiency by changing the RF power. However, our intention of using the term “reconfigurable” is to emphasize that our device can be configured either as a frequency shifter or frequency beam splitter, which are the two fundamental elements needed to construct a photonic circuit that can perform frequency-domain information processing. This “reconfigurability” does not refer to “tunable efficiency.” It is worth noting that conventional frequency shifters with tunable shift efficiencies are not equivalent to a frequency beam splitter.

There are important distinctions between our device and the other on-chip approaches mentioned by the referee.

1. Our device is bi-directional and is capable of up- and down-shifting. This is the key attribute of a frequency-beam splitter.
2. The shifting/beam-splitting operation acts on two and only two (frequency) degrees of freedom without altering other properties such as spatial and polarization modes or invoking additional frequencies.

Let us elaborate further regarding point 1. Tuning the power ratio, while required, is not sufficient for realization of a frequency domain beam splitter. A frequency beam splitter, like its spatial counterpart, needs to be bi-directional and capable of up- and down-shifting simultaneously. In other words, when excited with an optical signal of frequency $f_1$, a 50:50 frequency beam splitter will produce an output with 50% of signal at $f_1$ and 50% of signal at frequency $f_2 = f_1 + \text{fm}$ (where fm is microwave frequency). However, at the same time, if it is excited with light at $f_2$, it should produce an output with 50% of light at $f_2$ and 50% at $f_1$. Finally, if both $f_1$ and $f_2$ signals are present, a frequency beam splitter should be able to produce outputs that coherently mix these two signals. These functionalities in the frequency domain are analogous to those of a spatial beam splitter. Importantly, all of these functions should be possible without changing the configuration of the device or driving signal. That is, a frequency beam splitter must not require prior/additional knowledge of the frequency of the input signal (in analogy, a conventional beam splitter works regardless of which of the two input ports are excited). Similar arguments apply if the shift efficiency is not set to be 50:50.

Frequency shifters based on quadrature and acoustic modulators mentioned by the referee, as well as those based on the serrodyne technique, adiabatic tuning, and spectral shearing, cannot achieve this beam splitter functionality. For example the IQ modulator, when excited by $f_1$ will indeed produce $f_1$ and $f_2 = f_1 + \text{fm}$. However, when excited with light at $f_2$, it will continue up-shifting and produce $f_2$ and $f_3 = f_2 + \text{fm}$. In other words, the IQ-based shifter, as well as the aforementioned on-chip frequency shifter concepts, do not act on a two-by-two frequency-subspace, which precludes them to be frequency-domain beam splitters. Of course, an IQ modulator (as well as serrodyne, etc.) can be driven with different sets of microwave signals to produce the desired output of 50:50 $f_2$ and $f_1$ when input is $f_2$ (when configured as a 50:50 beam splitter). This however means that the device needs to have the knowledge of the frequency of the incoming signal to perform the correct shift. This, while possible for classical signals (e.g. use a tap in, followed by a filter and an
on-chip detector), adds loss, requires more complexity, and is less elegant. However, this approach would not work in scenarios where frequency-domain coherent beam combining is needed (e.g. want to combine signals at f1 and f2), nor for channel swapping as we demonstrated. Finally, this approach would not work for quantum signals, in which measurements are not possible (and additional loss restricts utility). More philosophically, since spatial mode beam splitters also do not require the knowledge of which input port light came from to perform their functionality, neither should their frequency-domain counterparts.

Regarding point 2, our device is simple, efficient, and directly analogous to a spatial mode beam-splitter because it distributes power between only two frequency modes. Other on-chip frequency shifters either require a new spatial mode/port (acousto-optic modulator), use a method that sends light to a second output spatial mode/port or a radiation port in the case of a Y-junction (IQ, Mach-Zehnder), or distributes light to additional frequency modes that subsequently need to be filtered to produce an output that mimics a frequency-domain beam splitter (phase modulator). Notably, all of these methods are fundamentally lossy (see discussion regarding the carrier suppression and shift efficiency below). Moreover, conditions for quantum interference on-chip are ideal using our shifter since we only change the frequency degree-of-freedom of light.

In summary, we hope to have clarified what we mean by “reconfigurable” and that the referee agrees with our assessment that conventional IQ and acousto-optic modulators cannot perform true frequency-domain beam splitting functionality - a frequency analog of spatial-domain beam splitter. In fact, this feature is uncommon in nearly all frequency shifter platforms including IQ modulators, acousto-optic modulators, frequency shifting based on serrodyne and adiabatic tuning, with the exception of nonlinear frequency beam splitters that use e.g. the four-wave mixing Bragg scattering, as pointed out by Referee 2.

We do think that addressing this point raised by Referee 3 clearly in our manuscript is important and further distinguishes our work from past accomplishments. Thus, we have added the following text to the third paragraph of the manuscript:

“It should be noted that a frequency beam splitter, as the frequency-domain counterpart of a spatial beam splitter, needs to be bi-directional (can achieve up- and down-shift simultaneously), its outputs should be a coherent combination of its inputs when both frequency channels are present, and it should not affect other degrees-of-freedom such as polarization or spatial modes. Taking these into account, it can be seen that frequency shifters based on the IQ modulators, serrodyne method, adiabatic tuning, spectral shearing, and acousto-optic modulators cannot be reconfigured as frequency beam splitters, while nonlinear frequency shifters [Pele et al. Optics Express 20, 19075 (2012)] such as those based on Bragg-scattering four-wave mixing [Raymer et al. Optics Communications 283, 747 (2010)] can.”

Second, the manuscript appears to suggest that the implementation of the frequency shifter via the electro-optical platform is more efficient than the state of the art. However, this is not the case, and comes from an incorrect way to define the “efficiency” of the device.

Specifically, I find the definition of conversion efficiency chosen by Hu and colleagues problematic.

We thank the reviewer for pointing out this problem, which comes from the different definitions of efficiency used in different communities. We actually considered these points extensively while writing the manuscript, and have picked the figures of merits in a way that would allow for fair and
easy comparison between a variety of approaches used by different communities. Clearly, some additional clarifications and improvements are needed. Please see below.

It is common for second order nonlinear processes to define the conversion efficiency as a function of the input power (here the microwave power) in the unit [%/W].

Indeed, in all-optical wave mixing, the normalized conversion in unit of %/W is often used. While this metrics is valid in the linear regime, where both pump power and conversion efficiency are low, it is not very relevant in our device operation regime, where conversion efficiency approaches 100% and the scaling with microwave power becomes highly nonlinear. For example, the microwave powers required to achieve 50% and ~100% shift efficiency do not follow 1:2 ratio but rather 1:30 (on our 28.2 GHz device). A %/W metrics for the low efficiency regime does not provide meaning information to evaluate our device performance. In addition, there exists an optimal microwave power required to reach the critical coupling condition and achieve an efficient frequency shift. This is illustrated by the theoretical curve shown below. If this optimal microwave power is exceeded, the efficiency of frequency shifting is reduced. For these reasons, we choose not to use the metric suggested by the Referee, which is typically used to characterize the conversion efficiency in linear region for $\chi^{(2)}$ nonlinear all-optical frequency conversion.

Simulated shift efficiency as a function of microwave power on the chip. High shift efficiency with variation of <5% can be achieved over a power range of 20 dBm - 23.5 dBm, indicating a good tolerance of the shift efficiency to the microwave power.

Instead, the definition of the authors of conversion efficiency is instead to compare the relative power of carrier and sideband at the output. This in fact has already a name: it is called the carrier suppression ratio instead. A 99% carrier suppression ratio is easily achieved with standard off dual Mach-Zehnder based SSB. There is no improvement over the state of the art.

Indeed, our “shift efficiency $\eta$” is defined as the power ratio between light at shifted frequency and total output light. We agree that the “carrier suppression ratio”, which quantifies the ratio of energy of the carrier to that of a single sideband, is a term commonly used in the RF photonics and communication communities, and that it can be close to 99%. However, it is important to note that
a 99% carrier suppression ratio can be achieved by using a conventional modulator together with a filter, which induces significant loss of energy. Conventional (electro- and acousto-optical) approaches to single sideband modulation all result in either additional frequency modes (sidebands), or spatial modes, that then need to be eliminated, which introduces loss. Using conventional modulation approaches, additional sidebands are either filtered out or dropped into the additional spatial modes/ports (additional waveguide in the case of a directional coupler or “vacuum” port in the case of a Y-combiner). In other words, in conventional approaches, additional degrees of freedom, beyond the two frequency modes of interest, are needed to achieve a high sideband suppression ratio which results in additional loss that is fundamental in nature and cannot be avoided (more on the losses below). In our approach on the other hand, a near-unity amount of energy can be shifted from the carrier to a single sideband without additional losses. This is possible since our device - by design - operates on two frequency modes only and does not require additional frequency or spatial modes that would require spectral or spatial filtering. To illustrate this key point, and to separate the efficiency from the intrinsic loss, we employ the shift efficiency and device insertion loss metrics rather than the carrier suppression ratio.

In our manuscript, we separate between on-chip loss induced by the device itself from on/off coupling loss. This is (for better or for worse) a common practice in the integrated photonics community that is used to separate fiber coupling loss (which can be a challenge for integrated photonics) from intrinsic device loss (which are often the focus of the work). Furthermore, we believe that on-chip loss is a more appropriate figure of merit for large optical systems integrated on the same chip, which consists of a large number of daisy-chained devices with a single fiber input/output.

To address on-chip insertion loss, we have defined a figure of merit called the "device insertion loss DIL" defined as the power of output of the device divided by the power at the input of the device (on chip). In our current devices, DIL = 0.45 dB and is limited by the intrinsic Q (\(Q_{\text{intrinsic}} = 1\,\text{million}\)) of the resonators used, which is in turn limited by fabrication imperfections. Theoretically, if the intrinsic Q of the resonators could be increased to infinity (or exceed e.g. 10,000,000 as already demonstrated, DIL \(\sim\) 0 dB can be achieved. We note that ultra-high intrinsic Q does not reduce the bandwidth of our device since we operate in the over-coupled limit, where bandwidth is determined by external-coupling Q (<100,000). This is illustrated in the Extended Data Fig. 3 that shows the relationship between device insertion loss and intrinsic Q. This is in stark contrast to IQ based shifters that have a theoretical DIL fundamentally limited to \(\text{DIL} = 4.7\,\text{dB}\), even in the absence of all other loss (fiber coupling, scattering, material absorption, etc).

Indeed, the ability of our approach to achieve DIL \(\sim\) 0 dB is its distinguishing feature, and is essential for applications that require large numbers of frequency beam splitters to be cascaded, e.g. quantum information processing. For example, the total insertion loss of 10 optimized frequency beam splitters would result in an overall on-chip loss of 4.5 dB whereas the same loss for 10 IQ based frequency beam splitters would be 47 dB (not including material and scattering loss). Additionally, our cascaded frequency shifter (Figure 4) also benefits from very low DIL.

In the revised manuscript we have added the following text to address this point (changes in red) and have changed all mentions of ‘insertion loss’ to ‘device insertion loss’:

“In-phase and quadrature (IQ) modulators can eliminate symmetric sidebands via destructive interference among multiple modulators\(^{22}\), but they are limited by a fundamental device insertion loss of 4.7dB and are accompanied by higher-order sidebands.”
Lastly, the definition of conversion efficiency chosen here obscures the fact that the bona fide efficiency, i.e. output power divided by input power, of the presented device is “efficiency * insertion loss”, which means that 99% efficiency and 0.5 dB insertion loss equates to a true efficiency of around 90%, not accounting for fiber input-output coupling efficiencies.

As mentioned above, we separate the overall shift efficiency (output power/input power) and the device insertion loss (not accounting for fiber input-output coupling efficiencies) to allow for comparison between different platforms. Indeed, as we clearly noted in the manuscript, and as pointed out by the Referee, the “overall on-chip device efficiency” can be written as \( \eta \times \text{DIL} \).

This approach is common practice in the literature: the “efficiency” defined as the power at the shifted frequency divided by the output power, is widely used in other electro-optic methods to perform frequency shifting, including the dual MZI-based single sideband (IQ modulator) method that the reviewer has mentioned. The spirit of using the output power in the denominator for defining efficiency is to distinguish losses due to the fabrication imperfections (scattering loss due to sidewall roughness, material absorption) when light passes through the device, which are not fundamental to the conversion process, from the losses due to the inherent nature of the shifter design.

We acknowledge that conversion efficiency could also be defined as the ratio between the power at the shifted frequency with microwave on \( P_{\text{out, shifted}}(\text{microwave on}) \) and the output power of light when driving is off \( P_{\text{out, total}}(\text{microwave off}) \), as used for characterizing the adiabatic tuning method [Preble et al. *Nature Photonics* 1, 293 (2007)], the serrodyne method [Johnson et al. *Optics Letters* 35, 745 (2010), Houtz et al. *Optics Express* 17, 19235 (2009)], and the IQ modulator method [Lo et al. *Optica* 4, 919 (2017)]. However, this definition is not suitable for our system: the transmission through the device increases when the microwave drive is turned on (please see our transmission spectrum when microwave is turned on and off in Extended Data Fig. 1, and the discussion about this later in the reply), and thus \( P_{\text{out, shifted}}(\text{microwave on})/P_{\text{out, total}}(\text{microwave off}) > 1 \) in our case! For this reason we defined the shift efficiency as \( P_{\text{out, shifted}}(\text{microwave on})/P_{\text{out, total}}(\text{microwave on}) \).

To provide a fair comparison, we calculated the performance of the IQ modulator approach from Lo et al. *Optica* 4, 919 (2017) using our figure of merit, and we found \( \eta = P_{\text{out, shifted}}(\text{microwave on})/P_{\text{out, total}}(\text{microwave on}) = 97.2\% \) (theory) and \( \text{DIL} = 4.7 \text{ dB} \) (theoretical, in the absence of all other losses). The shift efficiency is calculated using \( J_{-1}/(J_{-1} + J_{-2}) \) where \( J \) is the Bessel function when the conversion efficiency is maximized, according to the theory of Lo et al. *Optica* 4, 919 (2017).

This is to be compared with our device that has experimental efficiency > 99% and experimental DIL = 0.45 dB which includes scattering losses already. (We note that in theory, our device has efficiency = 100 % and DIL = 0 dB). *Clearly, our device outperforms the IQ modulator approach.*

Based on the above discussion, we believe that it is important to separate two figures - DIL and shift efficiency - in order to provide the most complete information to the readers. For this reason, we kept these definitions in the revised manuscript and have added the text (in the end of this question) to clarify the choice of figures of merits and provide comparison with IQ modulator. The overall on-chip conversion efficiency can then be easily obtained as \( \eta \times \text{DIL} \).
We also note that using these two figures of merit allows readers to understand various trade-offs in our design because the shift efficiency and device insertion loss are two independent variables that can be independently controlled in our design. For example, in Extended Data Fig. 7a we show how the insertion loss can be improved while maintaining a high shift efficiency. This may be useful for readers who care about microwave power consumption but do not worry about the device insertion loss, for example. In this case, one could use a lower waveguide-cavity coupling rate gamma to obtain a lower microwave power with a slightly higher device insertion loss. This kind of intuition would be obscured if we did not separate those two parameters.

In our work we indeed do not consider the fiber input-output coupling losses, which is not uncommon in the integrated photonics community. Having said that, we note that our group has already demonstrated fiber coupling losses <1.7 dB/facet for the same thin-film lithium niobate platform as the one used in our current work [He et al. Optics Letters 44, 2314 (2019)]. Furthermore, we have also demonstrated adiabatic fiber couplers that can achieve experimental coupling efficiency > 95% (-0.22 dB) for free-standing diamond couplers [Burek et al. Phys. Rev. Applied 8, 024026 (2017)], and the NIST Boulder team has recently demonstrated good efficiencies for supported couplers [Khan et al, arXiv:2002.00729 (2020)]. Importantly, both of these approaches are directly applicable to the LN platform, but are beyond the scope of our current work.

However, for transparency reasons and to avoid confusion between facet loss and device loss, in the revised manuscript we added a sentence to clarify that the “device insertion loss” does not include facet loss (see below).

Finally, we would like to emphasize that even considering the overall on-chip efficiency of our device, that is DIL * shift_efficiency = 90% in our case, as Referee pointed out, our devices are still much more efficient than the state-of-the-art IQ shifters. We performed an extensive literature survey of the field over the last 30 years and we report three best results below (happy to share the complete analysis if needed, too)

<table>
<thead>
<tr>
<th>Paper</th>
<th>Overall Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Izutsu et al. Journal of Quantum Electronics 17, 2225 (1981)</td>
<td>32%</td>
</tr>
<tr>
<td>Lauermann et al. Optics Express 24, 11694 (2016)</td>
<td>33.8%</td>
</tr>
<tr>
<td>Lo et al. Optica 4, 919 (2017)</td>
<td>6.2%</td>
</tr>
</tbody>
</table>

Note: following papers do not report the efficiency, unfortunately.
Higuma et al. Electronics Letters 37, 515 (2001)
It can be seen that the best result reports efficiency is 33.81% which is the same as the fundamental limit of 33.81%. However, it should be noted that these conversion efficiencies do not include on-chip insertion loss because they define conversion efficiency as the ratio of transmitted power with microwave on and off (as explained before), and insertion loss is cancelled out. Their definition of efficiency is the reason that the theoretical limit is reached in their experiment. In contrast, our device features ~90% efficiency including device insertion loss! Moreover, our efficiency is not fundamentally limited and it can be increased by improving fabrication to reduce optical losses and increase optical Q. As mentioned above, the state of the art Q in LN integrated photonics, reported by our team, is 10 times better than the Q of devices reported here, which would already allow the overall efficiency to be ~99%.

To address the reviewer’s concern, we have included the following discussion to the sixth paragraph of the main text where we define our figures of merits for the first time. Please also see below (changes in red color):

“Note that the definition of our on-chip insertion loss does not include the fiber-to-chip coupling loss, which is currently ~5 - 10 dB/facet. Spot size converters [He et al. Optics Letters 44, 2314-2317 (2019)] and adiabatic couplers [Khan et al. arXiv: 2002.00729 (2020)] could be used to reduce this efficiency to below 1.7 dB/facet and 1.1 dB/facet, respectively. We choose to use two separate figures of merit, η and DIL, to characterize our device performance because they can be independently controlled by tuning different device parameters, and are related to different trade-offs (see Methods). The amount of energy that is transferred to the target frequency is captured by eta, while DIL represents the optical loss due to the propagation of light in the device. Combining them together, the overall on-chip conversion efficiency of our device is therefore η × DIL = P_{shift}/P_{in}. Using these figures of merit, frequency shifters based on IQ modulators have an intrinsic device insertion loss of at least -4.7 dB (not including propagation loss due to scattering or material absorption) with an theoretically limited shift efficiency of 97.2% [Lo et al. Optica 4, 919 (2017)]. It is also worth noting that in our approach the device transmission increases as microwave power increases (Extended Data Fig. 1), which precludes the use of the shift efficiency definition η = P_{shift}(MW on)/P_{out}(MW off) that is commonly used in electro-optics.”

In fairness, it should be noted that the insertion loss of a dual Mach Zehnder with sinusoidal modulation has a fundamental insertion loss limit of 4.7 dB and the present device is advantageous for many loss sensitive applications, especially in the domain of quantum information technology. However, the current abstract and introduction fail to emphasize the loss and instead focus on the carrier suppression ratio which is state-of-the-art at best.

We thank the reviewer for mentioning this very important problem of a dual Mach Zehner modulator — the fundamental insertion loss of 4.7 dB (assuming zero propagation loss of the device), which ultimately limits its η × DIL to a low value (much lower than what we achieved).

However, we disagree with the reviewer that we emphasize efficiencies over the loss. In fact, these two figures of merit are always mentioned together: In the previous manuscript, please see line 25 in the abstract, line 67-68 in the introduction, the paragraph started at line 116, the paragraph started at line 129, and line 184 in the conclusion. However, to address the point raised by the Referee, we have included the value of insertion loss for each device in the caption of Fig. 2.
Moreover, in the revised abstract we have further emphasized the (fundamentally) low loss of our design by adding following statement:

“Our device provides frequency shifts as high as 28 GHz with a measured shift efficiency of ~99% and on-chip insertion loss of ~0.45 dB, corresponding to an overall on-chip conversion efficiency of ~90%, that is conversion loss of ~0.5 dB.”

Third, the conventional SSB allow frequency agility and have a broad bandwidth, which is key to modulations (e.g. in QAM). The authors approach is inherently narrowband and not suited to data-communication.

We agree with the Referee. In fact, we now realize that referring to our device as a single sideband (SSB) modulator was an unfortunate oversight, since indeed it would imply/require significant bandwidth for data transfer. Having said that, we note that the current microwave bandwidth of our device is > 3 GHz, and we have performed additional measurements to verify that the modulation bandwidth of input optical signals is 2.2 GHz and 4.1 GHz (see questions on swap operation later). Such GHz-level bandwidth could be increased to ~14 GHz by further over-coupling the device with the same shift efficiency (see questions on swap operation later). At that point, the device could be of interest as a SSB modulator for data rates ~10 GHz. In fact, the bandwidth could be further increased by increasing the waveguide-ring coupling, without sacrificing the loss. This is due to the fact that the insertion loss of the system is determined by an intrinsic quality factor of the resonator, which can be very large, while the bandwidth is set by the overall (loaded) quality factor, determined by the waveguide-ring coupling. Nonetheless, we have modified the manuscript to emphasize the device performance as a frequency shifter and beam splitter, of relevance for laser frequency control, atomic-molecular optics, and quantum photonics.

Last, I would like to point the authors to Savchenkov and colleagues work on optical frequency shifting using crystalline LN microresonators. The higher Q in the crystalline WGM allows it to operate with only 2 mW of RF power, compared to the 100s of mW reported here and similar tunability over many GHz is demonstrated. The concept of [1], i.e. using multiple spatial modes of a lithium niobate resonator that couple differently to the applied external field, is largely similar to the presented work.

We thank the reviewer for pointing out this excellent work. In their work, Savchenkov and colleagues achieve partial (50%) frequency shifts between TE and TM modes as well as SSB generation using cavity modes to suppress additional sideband generation. We have added the following text (shown in red):

“Single sideband modulation using TE and TM modes of a high-Q micro-disk has been demonstrated, albeit with limited shift efficiency of 50% and MHz-level bandwidth [Savchenkov et al. Optics Letters 34, 1300 (2009)].”

However, we do not agree with the reviewer that our work is largely similar to this work, nor that it is inferior in our performance. The reasons are stated below.

Efficiency: The shift efficiency we demonstrated is >99% (together with low on-chip device insertion loss) while a ~50% efficiency (with unknown device insertion loss) was measured in Ref. [1]. Furthermore, in Fig. 2b of Ref. [1], they demonstrated the pump-maximized or sideband-maximized cases by using a polarizer to remove one of the sidebands, obscuring the fact that their demonstrated shift efficiency is the aforementioned ~50%. This is important because a 50% shift
efficiency can be easily achieved using other methods such as IQ or serrodyne modulation. (Since very little information was given about the device insertion loss in Savchenkov’s work, we cannot compare our low-loss device with theirs, unfortunately).

*Microwave power:* we used to achieve 50:50 split ratio is 10 mW while that used in their work is 2 mW. The microwave power of 100 mW that Referee mentions is used to achieve full conversion, which Savchenkov and colleagues never demonstrate.

*Bandwidth:* The reason that the authors in Ref. [1] can use only 2 mW driving power for generating a 50% shift efficiency is the use of a high-Q optical cavity, resulting in a linewidth of only 1 and 20 MHz, for the two modes that they used, respectively. In our work we have linewidths on the order of several GHz with an instantaneous 3-dB microwave bandwidth >3 GHz (7 to 15 GHz from theoretical estimation). In addition, we also measured the 3-dB modulation bandwidth of the optical input and show that it can be 4.1 GHz (see questions on the swap operation later), which further verified the GHz-level bandwidth of our device. In other words, we are able to realize a 50:50 power splitter with at least 100 times the instantaneous bandwidth using only 5 times the power compared to Ref. [1].

*Tunability:* While we agree with the Referee’s comment that “similar tunability over many GHz is demonstrated”, that are very important differences between our and their work. In Ref. [1] the authors use thermal or DC tuning to tune the mode resonances from 11 GHz to 15 GHz. In contrast, our devices do not require any DC or thermal tuning, and feature instantaneous bandwidth of >3 GHz by design (Figs. 2d and 2e). If we were to use thermal or DC tuning like in Ref. [1], we estimate our tuning range to be much larger than that of Ref [1], spanning tens of GHz while keeping the shift efficiency >90%. For additional details, please see our reply to the tunability question that was discussed later. Finally, as mentioned in the main text, our device can be upgraded to that with a variable coupling gap, offering an even greater tuning range.

*The concept:* Ref. [1] uses two specific cavity modes to suppress other frequency modes and achieve a single-sideband modulation, i.e. eliminate sidebands other than pump and shifted frequency. In contrast, the key point of our work is investigating a generalized critical coupling condition to realize a unidirectional flow of energy between two cavity modes, which underpins efficiency shifting and beam splitting configurability, and of which we extend to cascaded shifts. In addition, the scheme from Ref. [1] employs additional degrees of freedom (polarization). In our approach we demonstrate true beam splitting without utilizing additional degree of freedom other than frequency. “Philosophy” aside, unnecessary changes in the polarization state may not be desired in integrated optics applications, where many devices are to be integrated on the same chip. For example, realizing cascaded frequency shifters, like the one we demonstrate in Figure 4, would be difficult using two polarization states that have different dispersion and FSR. Moreover, a change in polarization of light is not suitable for quantum applications that rely on interference of indistinguishable photons. Of course, additional polarization rotators can compensate for this, but add extra complexity, loss and hamper scaling efforts.

In summary, while we do agree the work by Savchenkov et al. is excellent and achieves a clear SSB modulation, we believe that our work is very different, and more importantly offers several advantages.

*Overall we find that the manuscript could profit by discussing parts of the theory in the main manuscript instead of the supplementary information. The trade-off between nonlinear conversion*
efficiency and instantaneous bandwidth, as well as the tradeoff between the DC tunability of the RF shift frequency by tuning the resonators out of degeneracy. Lastly there exists a trade-off between the instantaneous bandwidth and the appearance of parasitic off-resonant sidebands (cf. SI Fig 1), that appears because the modulation frequency is only four times larger than the external coupling rate.

We thank the reviewer for these helpful suggestions. We addressed the trade-off between the tuning of the magnitude of frequency shift (through an applied DC voltage) and the shift efficiency, as well as instantaneous bandwidth versus the parasitic sidebands later in the text (there are specific questions related to these topics raised by the Referee).

Here we address the trade-off between nonlinear conversion efficiency and instantaneous bandwidth. We start by saying that our approach does not suffer from an efficiency-bandwidth tradeoff, which we think is an important and distinguishing feature. Even though we reach 99% shift efficiency, the overall efficiency ($\eta \times DIL$) can be further improved by reducing the device insertion loss, by increasing the waveguide-cavity coupling rate $\gamma$ or by realizing a smaller intrinsic resonator loss rate $k_{int}$ (we changed the symbol of intrinsic loss rate from $k_i$ to $k_{int}$ as suggested by reviewer 2). Importantly, both methods will not decrease the bandwidth because an increase in $\gamma$ will be accompanied by a drop in $Q$, and a smaller $k_{int}$ will not affect the device bandwidth as it is already 31 times smaller than $\gamma$. This is because our bandwidth is determined by the total Q (not intrinsic), that is by waveguide-cavity coupling rate and not intrinsic Q. Since intrinsic loss rate is already 31 times smaller than the waveguide-cavity coupling rate, further reduction in $k_{int}$ will have little impact on the bandwidth.

In response to the reviewer’s suggestion to improve the manuscript, and to address the efficiency-bandwidth trade-off, we have added the following section into the seventh paragraph of the main text:

“In addition, our device does not suffer from a typical conversion efficiency-bandwidth trade-off. Since the shift efficiency is high once the generalized critical coupling condition is satisfied, the overall conversion efficiency is mainly limited by the DIL. For example, a 10-fold reduction in the resonator loss rate (that is an increase in the intrinsic quality factor) will lead to a tenfold decrease in DIL (from 0.45 dB to 0.045 dB) while having a minimal impact on the bandwidth, which is dominated by a waveguide-cavity coupling rate $\gamma$ (already 31 times larger than intrinsic loss rate). On the other hand, improving the DIL by increasing $\gamma$ leads to even larger bandwidth. Both of these effects benefit from the strongly over-coupled regime that our device operates in (see Methods).”

As for the added text in the main text and Methods related to other trade-offs, please see the replies shown later.

On the other hand, the experiments in Fig. 3 lack quantitative description. What is the used / possible bandwidth of the swap operation? How faithful is the data swap operation and what sources of loss and noise limit this operation? The transmission of low bandwidth signals (audio, with kHz bandwidth) hardly compares to the coherent communication experiments of the same authors in their prior work, that benchmarked the results against state of the art. One cannot escape the impression that the chosen application is ill-suited to highlight the technological capability of the resonant modulation approach. The authors could e.g. use demonstrate channel swapping on an actual data-stream, and characterize the minimum switching time and BER (which will be limited
by the resonator bandwidth). They have already engaged in similar experiments with the Winzer group. It is surprising to see that this was not demonstrated here, given the dominant motivation of telecommunication.

As mentioned earlier in the response, we now regret the analogies we made between our device and SSB modulators, which correctly lead the Referee to infer intended application in telecommunications. Nonetheless, we will try to address the comment by providing additional insight below.

We used kHz-bandwidth audio signals to modulate the light. The goal of this experiment was to demonstrate the bidirectionality of our platform, which confirms that it can be used as frequency beam splitter. In order to easily distinguish between two channels and confirm the swap, we decided to use modulated signals instead of simple unmodulated CW beams. This was a simple way to demonstrate proof-of-concept frequency beam splitting. Specifically, we swapped a Chinese- with an English-language song, discriminating the two with the filter, and listened to the results with a speaker connected to our photodetector. We recorded the demonstration on video, which we now include in the supplementary material, and hope it can attract the attention of a broad audience.

Nevertheless, the more pertinent use of our device is for broadband signals. Thus, we have performed an additional measurement to confirm the instantaneous bandwidth of our device. Here, one laser beam was modulated with a sinusoidal signal from a vector network analyzer (VNA), and light was then up-shifted. The output light is detected by a photodetector and sent back to the VNA. The measured modulation bandwidth is shown below (also attached to Methods as Extended Data Fig. 3). We found that the 3-dB modulation bandwidth is as large as 2.2 GHz (Extended Data Fig. 3b), corresponding to a 4.4 GHz optical bandwidth. Specifically, we demonstrate that this bandwidth can be broadened by increasing the microwave driving power on the device. We show that by increasing the microwave power from 126 mW to 398 mW, the 3-dB modulation bandwidth can be increased to 4.1 GHz, which is due to the microwave-induced linewidth broadening effect that is discussed in the theoretical analysis in Methods. The electro-optic S21 for both microwave critical-drive and over-drive are normalized to the electro-optic S21 of the microwave critical-drive at lowest frequency (10 MHz) and the instrument responses (including amplitude modulator, photodetector, and filter bandwidths) are calibrated. From the electro-optic S21 at lowest frequency (10 MHz), we found that the optical power loss is -1.15 dB, which is consistent with the device insertion loss (-0.96 dB). From the measured bandwidth, we estimated the fastest rising/switching time of the shifted signal to be \( \frac{1}{2.2 \text{ GHz}} = 0.45 \text{ ns} \) for 2.2 GHz modulation bandwidth and \( \frac{1}{4.1 \text{ GHz}} = 0.24 \text{ ns} \) for 4.1 GHz modulation bandwidth.

Moreover, as requested by the referee, we measured the eye diagram by creating pseudorandom bit sequences via an arbitrary waveform generator (AWG), using it to modulate the input laser beam, and performing up-shift of the input light. Data rates at 1.000 Gbit/s and 3.125 Gbit/s are measured (Extended Data Fig. 3c and 3d). The data rates in this experiment are limited by the sampling rate of the AWG that we used. By comparing the amplitude of the eye diagrams before and after up-shifts, we confirmed that the loss (~1 dB) is consistent with the measured 0.96 dB device insertion loss for the data in Fig. 2 of the main text, and we did not observe added noise from our device. The eye diagrams before the swap are measured by tuning the input laser off-resonance and the center of the filter window is set to the input laser wavelength. For the case of before and after shift, the bandwidth of the filter is kept the same and the microwave driving powers are kept at 126 mW.
(the case of microwave critical drive in the modulation bandwidth measurement, Extended Data Fig. 3b). Finally, we determined the bit error rate (BER) from the eye diagram by fitting the noise distribution and estimated the BERs to be $1.30 \times 10^{-7}$ and $3.35 \times 10^{-5}$ for the 1 and 3.125 Gbit/s signals before shift, respectively. And the BERs become $1.07 \times 10^{-6}$ and $1.2 \times 10^{-3}$ for the 1 and 3.125 Gbit/s signals after shift due to the decrease of signal-to-noise ratio (SNR) from the ∼1 dB device insertion loss DIL.

Extended Data Fig. 3 | Device modulation bandwidth and frequency channel shifting with pseudorandom bit sequences. a, Experimental setups. The input laser beam is modulated by either a sinusoidal signal from the port 1 of a vector network analyzer (VNA) (bandwidth measurement) or an actual data stream that is generated by an arbitrary waveform generator (AWG) (eye diagram measurement). The input light is up-shifted and
detected by a photodetector (PD) followed by either port 2 of the VNA (bandwidth measurement) or an oscilloscope (eye diagram measurement). The measurements are performed at a wavelength of 1560 nm on the device in Fig. 2b and 2c in the main text, in which the doublet splitting is 11.3 GHz due to optical dispersion (doublet splitting is 12.5 GHz at 1601 nm). b, Measured modulation bandwidth of the device. The 3-dB modulation bandwidth is 2.2 GHz, corresponding to an optical bandwidth of 4.4 GHz. Specifically, the modulation bandwidth is broadened to 4.1 GHz by increasing the microwave driving power from 126 mW to 398 mW. c, Measured eye diagrams when using actual data streams to modulate the input laser beam. The eye diagrams before shift are measured by setting the input laser beam off-resonance with the filter window centered to the input wavelength (filter bandwidth unchanged). By comparing the amplitude of the eye diagrams before and after swap, we found the loss is ~1 dB which is consistent with the device insertion loss (0.96 dB).

Measuring the effect of imperfections of the swap operation is an important point of this experiment, so we performed additional experiments to quantify such imperfections for a broad range of modulation frequencies of the channels. To this end, we use two modulated laser beams as two frequency channels. Specifically, we modulated one of the optical beams (matching the S resonance, and which we refer to as channel 1 here) with a sinusoidal signal of which the frequency is swept from 200 MHz to 2.8 GHz and the other (matching the AS resonance, channel 2) with a 1 GHz sinusoidal signal (Extended Data Fig. 5a). The swap operation was then performed, and the filter was tuned to pass light first from the S resonance (channel 1) and then from the AS resonance (channel 2). The transmitted signals were detected by a photodiode and their spectra are analyzed using a real-time spectrum analyzer to quantify the cross-talk. The results are shown in the figure below, and also included in the manuscript as Extended Data Fig. 5 along with a corresponding description in the section “Measurement of swap operation” in Methods.

We plot the RF spectra when the (swept) modulation frequency in channel 1 is set to 2.6 GHz (the modulation frequency in channel 2 is fixed at 1 GHz) as an example. It shows that, after the swap operation, the spectrum is clean in both channel 1 and channel 2 (Extended Data Fig. 5b). The frequency component of 1.6 GHz that appears in channel 1 is the beat note between the shifted frequency and the residual frequency. The 2 GHz frequency is the second harmonic signal that is generated by the amplitude modulator, which is verified beforehand. We define the cross-talk as the ratio between the shifted frequency and residual frequency and find that crosstalk is very low (< -35 dB) when the swept modulation frequency of channel 1 is at the several hundreds of MHz level, and are ~ -25 dB when using a 2.8 GHz signal (Extended Data Fig. 5c). The cross-talk measurement is performed using the device same as the modulation bandwidth measurement and channel shifting with pseudorandom bit sequences measurement at the same optical wavelength and microwave driving power. The cross-talk can be reduced further by improving the shift efficiency, see “Limitation of the shift efficiency” in the Methods, as well as improving the device optical bandwidth (see below).
Extended Data Fig. 5 | Crosstalk measurement for channel swapping. a, Experimental setups for crosstalk measurement. Two input laser beams are each independently modulated by a sinusoidal signal as two frequency channels, sent into the device, and detected by an OSA and a PD followed by an RSA. Sinusoidal signal applied to the input beam of channel 1 (match the S resonance) is swept from 200 MHz to 2.8 GHz while sinusoidal signal on the input beam of channel 2 (match the AS resonance) is kept at 1 GHz. Each channel is selected by a tunable filter. b, radio-frequency spectrum for output channel 1 and channel 2 on the RSA after the swap when the modulation frequency in channel 1 is set to 2.6 GHz, showing low crosstalk in the swap measurements. The crosstalk is defined as the ratio between the shifted frequency and the residual frequency. The frequency component of 1.6 GHz that appears in channel 1 is the beat note between the shifted frequency and the residual frequency. The 2 GHz frequency is the second harmonic signal that is generated by the amplitude modulator, which is verified beforehand. c, Measured crosstalk for two channels when sweeping the modulation frequency in channel 1 from 200 MHz to 2.8 GHz. We find the crosstalk is ~ -35 dB at low frequency (several hundreds of MHz) and ~ -25 dB at 2.8 GHz. PC, polarization controller; AM, amplitude modulator; EDFA, erbium-doped fiber amplifier; OSA, optical spectrum analyzer; PD, photodetector; RSA, real-time spectrum analyzer.

To further address the referee’s comment about the relevance of our device for telecommunication applications, we simulate the effect of varying device parameters on the instantaneous optical bandwidth. An increase of the bandwidth can be achieved by increasing the external coupling rate \( \kappa_e \), while keeping all the other parameters the same as our 28.2 GHz device. For example, device parameters can be: \( \kappa_e = 2 \pi \times 10 \text{ GHz} \), \( \kappa_{\text{int}} = 2 \pi \times 170 \text{ MHz} \) (1.1 million intrinsic Q), and \( \omega_m = 2 \pi \times 28.2 \text{ GHz} \), which leads to a 3-dB optical bandwidth of ~ 14 GHz (Extended Data Fig. 4b) with a driving microwave power of 1.35 W for a full frequency shift (238 mW for 50-50 split), a suppression of 26.7 dB with respect to parasitic sidebands, and a device insertion loss of 0.13 dB.
Extended Data Fig. 4 | Simulated shift efficiency as a function of the detuning of the laser. Optical bandwidth of a device optimized for high bandwidth. Design parameters: $\gamma = 2\pi \times 20 \text{ GHz}$ (leads to a $\kappa_x = 2\pi \times 10 \text{ GHz}$), $\kappa_{int} = 2\pi \times 170 \text{ MHz}$, $\omega_m = 2\pi \times 28.2 \text{ GHz}$. A 3-dB optical bandwidth of $\sim 14 \text{ GHz}$ can be achieved using a critical-drive microwave power of 1.35 W with a 26.7 dB suppression of parasitic sidebands and 0.13 dB device insertion loss. The microwave power for a 50-50 split on such a device is expected to be 238 mW.

In summary, we believe that the experimental results in Figure 3 show what we intended: our device can perform bi-directional swap and thus indeed behaves as a frequency beam splitter.

We have added the following in the main text to clarify the motivation of the swap measurement, add discussion of crosstalk and bandwidth. Please see below (red color):

"In addition, we also modulated two different songs to the two frequency channels and verified the swap operation by sending signals from the photodetector to a speaker (see supplementary for a video file). However, note that the 3-dB modulation-bandwidth for the frequency channels is limited to 2.2 GHz in current devices and will broaden to 4.1 GHz when increasing the microwave power to overdrive the device (see Methods). Frequency shifting with pseudorandom bit sequences are also performed to further verify the device performance for GHz bandwidth modulation (see Methods).The cross-talk of the swap operation is characterized as $\sim$ -35 dB to -25 dB for sinusoidal modulations on channels from several hundreds MHz to 2.8 GHz (see Methods). Improving the device optical bandwidth to $\sim 14 \text{ GHz}$ could allow applications for telecommunication applications (see Methods)."

We have also added the following paragraph to Methods:

"**Device optical and modulation bandwidth.** Additional experiments are performed to verify the device optical bandwidth. The input laser beam is first modulated with a single sinusoidal signal from a vector network analyzer (VNA) and then passes through the device to perform a frequency up-shift. The output light is sent back to the vector network analyzer (Extended Data Fig. 3a). The 3-dB modulation bandwidth for the frequency channel is 2.2 GHz, corresponding to a 4.4 GHz optical bandwidth (Extended Data Fig. 3b). Specifically, we find that by increasing the microwave power from 126 mW to 398 mW, the modulation bandwidth can be broadened to 4.1 GHz, which is due to the microwave-induced linewidth broadening effect discussed in the theoretical analysis.
in Methods. The electro-optic S21 for both microwave critical-drive and over-drive are normalized to the electro-optic S21 of the microwave critical-drive at lowest frequency (10 MHz) and the instrument responses (including amplitude modulator, photodetector, and filter bandwidths) are calibrated. From the electro-optic S21 at lowest frequency (10 MHz), we found that the optical power loss is -1.15 dB, which is consistent with the device insertion loss (-0.96 dB).

The frequency channel is also encoded by actual data streams to further demonstrate the device performance for GHz-scale channel bandwidths. We generate the pseudorandom bit sequences at 1.000 Gbit/s and 3.125 Gbit/s by an arbitrary waveform generator (Extended Data Fig. 3a). Eye diagrams are measured to characterize the device performance (Extended Data Fig. 3c and 3d). The data rates that we used are currently limited by the sampling rate of the arbitrary waveform generator. By comparing the amplitude of the eye diagrams before and after up-shifts, we confirmed that the loss (~ 1 dB) is consistent with the measured 0.96 dB device insertion loss for the data in Fig. 2 of the main text, and we did not observe added noise from our device. The eye diagrams before shift are measured by tuning the laser beam off-resonance and setting the center of the filter window at the frequency of the laser beam. For the case of before and after shift, the bandwidth of the filter is kept the same and the microwave driving powers are kept at 126 mW (the case of microwave critical drive in the modulation bandwidth measurement, Extended Data Fig. 3b).

Both the measurement of modulation bandwidth and channel shifting with pseudorandom bit sequences are performed on the device with 12.5 GHz doublet splitting (Fig. 2b, 2c in the main text). The optical wavelength is chosen at 1560.7 nm in which the doublet splitting changed to 11.3 GHz due to the optical dispersion.

In addition, to fit some telecommunication applications that require a higher bandwidth, we show that the device optical bandwidth can be further improved by increasing the waveguide-cavity coupling gamma. For example, improving the waveguide-cavity coupling $\gamma$ to $\gamma = 2\pi \times 20$ GHz (leads to a $\kappa_p = 2\pi \times 10$ GHz) while keeping other parameters same as the current 28.2 GHz device ($\kappa_{int} = 2\pi \times 170$ MHz, $\omega_m = 2\pi \times 28.2$ GHz) can result in a 3-dB optical bandwidth of ~ 14 GHz (simulation, Extended Data Fig. 4) with a driving microwave power of 1.35 W for full frequency shift (238 mW for 50-50 split), a suppression of 26.7 dB on parasitic sidebands (see section limitation of the shift efficiency for discussion on parasitic sidebands), and a device insertion loss of 0.13 dB.

**Measurement of swap operation.** The experimental demonstration of the swap operation is performed at a wavelength of 1560.6 nm (setup shown in Fig. 3a). We first set the frequency of two laser beams to be far detuned from the doublet resonance and measure the time-domain audio signals as references. This corresponds to the case in which the signals are not swapped. We then tune the frequency of each laser beam to be on resonance with one of the modes of the doublet, i.e. laser 1 (2) in S (AS) mode. In this case, frequency components around laser beam 1 are up-shifted and components around the frequency of laser beam 2 are down-shifted. The amplitudes of the time domain signal before and after swapping are renormalized for comparison in Fig. 3b.

Another experiment of swap operation is performed to quantitatively characterize the crosstalk of the swap operation (Extended Data Fig. 5). Laser beams 1 and 2 are respectively modulated by two sinusoidal signals as two frequency channels. The sinusoidal signal in channel 1 is swept from 200 MHz to 2.8 GHz while the signal in channel 2 is fixed at 1 GHz (Extended Data Fig. 5a). Swap operation is then performed, filter is tuned to pass first channel 1 and then channel 2, and the
transmitted signals are detected by a photodiode followed by a real-time spectrum analyzer. The radio frequency (RF) spectra are analyzed to obtain the crosstalk, which is defined as the ratio between the shifted frequency and residual frequency. An example of the RF spectra when the swept modulation frequency in channel 1 is set to 2.6 GHz (the modulation frequency in channel 2 is fixed at 1 GHz) are plotted and it shows that the spectrum is clean and the cross talk is low in both channels (Extended Data Fig. 5b). The frequency component that shows up at 1.6 GHz in channel 1 could be the beat note between the shifted (1 GHz) and residual frequency (2.6 GHz). The frequency at 2 GHz in channel 1 is the second harmonic signal generated by the amplitude modulator we used, which is verified before the swap measurement. By sweeping the modulation frequency of channel 1 from 200 MHz to 2.8 GHz, we find the cross-talks for both channels are low (~ -35 dB) when the modulation frequency of channel 1 is at several hundreds of MHz and the cross-talks gradually increase to ~ -25 dB at 2.8 GHz (Extended Data Fig. 5c). The cross-talk measurement is performed using the device same as the modulation bandwidth measurement and channel shifting with pseudorandom bit sequences measurement at the same optical wavelength and microwave driving power.”

To me the most exciting aspect is the demonstration of a high carrier suppression shifter for high frequencies, using a cascade of coupled EO resonators driven by a subharmonic. This scheme is clever, novel and has major potential to significantly improve the RF power required to shift an optical frequency, as it alleviates complexity of generating signals at 100 GHz or above. Moreover, this scheme would also be a leap beyond prior work of the authors, in which the Loncar group reported coupled photonic molecules Ref. 27– the very device architecture used for this experiment.

As such, the proposed system in Fig. 4 for more than 100 GHz level frequency shift is exciting indeed and lies well outside the capabilities of contemporary SSB, and would represent a unique advantage and use of EO integrated photonics.

We thank the reviewer for recognizing the novelty and appeal of the proposed cascaded frequency shifter. This cascaded process is exactly enabled by the concept we proposed in this work.

We acknowledge that there are some similarities between our current manuscript and our Nature Photonics publication (Ref. 27) that also uses a coupled-ring resonator platform. However, we do believe that the concept we used, and the functionality we achieved, is significantly different from that in Ref. 27. This was summarized in our response to Referee 1, as shown below.

The idea of using coupled resonators to realize a photonic two-level system has been widely explored in photonics for more than 20 years, starting with the initial proposal and demonstration in 1998 [Bayer et al. Phys. Rev. Lett. 81, 2582 (1998)]. Our own work (Ref. 27) builds on these ideas and introduces the electro-optic “control knob” that allows for controlled coupling between these photonic levels using electrical signals (DC and microwave). However, as we discuss below, this work was limited to pulsed microwave and optical operation, which is a significant limitation for broad impact and utility of the coupled-ring platform.

Our current manuscript pushes the photonic molecule platform to a new regime of operation, allowing unprecedented performance that goes well beyond what has been accomplished during the last 20 years, in our opinion. This has been accomplished by developing a new understanding of the system, specifically by exploring and leveraging the interplay between discrete and a continuum of modes supported by our platform. By precisely engineering coupling rates between these modes, we were able to demonstrate high-performance frequency-domain mode shifting and
beam splitting at tens of GHz frequency. This alone, we think, represents a significant advancement over the state of the art (including our past work). We also go a step further, and generalize the proposed concept to novel, cascaded, and efficient frequency shifters.

We would also like to point out that the approach our group pursued in Ref. 27 has several fundamental limitations that renders it impractical and unsuitable for applications:

1. In Ref. 27, the frequency-domain conversion of light is performed using the Rabi oscillations induced by microwave driving. Thus, to perform a unitary transformation in the frequency domain the Rabi cycle needs to be interrupted, which requires the use of pulsed and carefully tailored microwave control signals ($\pi$ or $\pi/2$ pulses). This is both challenging and costly since expensive high-bandwidth equipment needs to be used.

2. Since pulsed microwave control signals are used, the unitary transformation is possible only during certain time intervals - when the microwave is on - and thus optical signals need to be pulsed as well. In other words, our old approach cannot be applied to modulated continuous-wave (CW) optical signals. While this pulsed regime is of interest for envisioned applications of microwave-to-optical conversion and optical memory presented in Ref. 27, it is not suitable for realization of arbitrary unitary transformations on arbitrary optical signals. Moreover, pulsed operation requires synchronization between optical and microwave pulses. For example, this would rely on monitoring the arrival time of optical pulses in order to apply microwave pulses at the right time. This, however, can be impractical for quantum information applications where photons may not be measured, or where photonic quantum memories will be required (in addition to feed-forward), adding an additional restriction.

3. Finally, in Ref. 27 the bandwidth of the optical signal that is being converted is limited by the high-Q of the optical cavity needed to achieve efficient frequency conversion. Although this bandwidth is sufficient for modulated CW signals, it restricts utility for signals encoded in the time domain, a necessary encoding method due to the required use of microwave pulses.

In contrast, our current work demonstrates a practical and novel approach for controlling the frequency of any (pulsed or CW) optical signal with high efficiency and low loss. In our new devices, both the microwave and optical inputs can be continuous. Thus, light arriving at the device at any time can be shifted or splitted in frequency domain. This is achieved by exploiting the clever interplay between discrete modes of a coupled resonator system and continuum modes provided by a waveguide which interrupts the Rabi oscillation cycle. As a result, a simple, CW, harmonic microwave control signal can be used to realize unitary transformations in the frequency domain for nearly arbitrary optical signals: pulsed or CW. Moreover, the use of a strongly over-coupled resonator system results in a cavity linewidth one order of magnitude higher than that used in Ref. 27, resulting in a much larger bandwidth of the device.

In summary, Ref. 27 demonstrates a very nice and versatile platform - an optical two-level system that can be controlled using microwave signals - and uses it for several proof-of-principle demonstrations. However, the design strategy used in Ref. 27 results in a device that is fundamentally limited in its ability to control optical signals. Our current work provides a novel design strategy, and leverages precisely engineered coupling between different modes to allow for
efficient and practical frequency shifting and beam splitting, as well as arbitrary unitary transformations on an optical signal in frequency domain.

We have added the following revisions to the conclusion of the manuscript to distinguish our work from previous work more clear and clarify the novelty of our work (changes labeled in red color):

“In summary, we proposed and demonstrated an integrated, efficient, and low-loss electro-optic frequency shifter and frequency beam splitter operated at tens of GHz frequency, enabled by recent breakthroughs in integrated lithium niobate photonics [24,27,30]. In contrast to our previous work [27], that was limited to operation with pulsed optical and microwave signals, and thus requires precise timing between the two, we can use simple sinusoidal CW microwave signals to control both pulsed and CW optical signals. This significantly simplifies the control of the device since precise timing is not needed. Furthermore, current devices operate in a strongly over-coupled limit, which increases the device bandwidth. Leveraging this, efficient and low loss frequency shifting and beam splitting is demonstrated. To this end, we engineer the coupling rates between different modes of the system to control the flow of light in the frequency domain. Moreover, we generalize our approach to propose a cascaded frequency shifter. Improvements to the quality factor of the optical resonators and the use of a microwave cavity can further reduce the insertion loss and drive voltage required, respectively. For example, increasing optical intrinsic Q to $10^7$ [24] will reduce the insertion loss to 0.04 dB, or can reduce both insertion loss and drive voltage to 0.2 dB and 2 V, respectively (see Methods). Notably, dynamic control of the shifted light can be achieved by replacing the coupling gap with a microwave-driven Mach-Zehnder interferometer [Soltani et al, Phys. Rev. A 96, 043808 (2017)] and by applying broadband microwave signals. Moreover, our method for controlling the flow of light in the frequency domain could be applied to other systems, such as mechanoelectric, superconducting qubits, quantum dot, or atomic systems which contain discretized and a continuum of energy levels. The ability to process information in the frequency domain in an efficient, compact, and scalable fashion has the potential to significantly reduce the resource requirements for linear-optical quantum computing$^{11,12}$ and multiplexed quantum communication$^{31}$. Efficient and on-demand shifting of light may also allow for control of the emission spectrum of solid-state single-photon emitters to create indistinguishable single photons or to produce deterministic single photons from probabilistic emitters$^{32,33}$. Our reconfigurable frequency shifter could become a fundamental building block for frequency-encoded information processing that offers benefits to telecommunications$^7$, radar$^{34}$, optical signal processing$^{28}$, spectroscopy$^{35}$, and laser control$^{38}$. “

However, to this reviewer, it was disappointing and rather surprising to not see any device implemented. Clearly, what is lacking is presenting a physical implementation, and demonstrate that the approach actually works, that is, having successfully navigated the pitfalls of the proposed device such as the problems of tuning four resonances with three voltages and the increased electrode size and capacity on a 30 GHz resonator.

In summary, to this reviewer without this demonstration, the manuscript has not risen to the level that would be expected in a Nature publication. While the exceptionally on chip “low insertion loss” of the demonstrated device certainly merits attention from the integrated photonics community, the latter is an artificial metric, as it is not the true insertion loss (light-in vs. light-out) and I find that the present work establishes an incremental improvement over previous implementations both from the authors, i.e. Refs. 27 (photonic molecules) and 30 and Savchenkov’ s work [1] to merit publication in Nature. The lack of actual demonstration of the proposed device in figure 4 will leave readers puzzled. To this reviewer, a manuscript that includes proper definitions of efficiency (and
carrier suppression rate), a discussion on the tradeoff of resonant modulation i.e. bandwidth/RF efficiency, and generally a fair comparison to the state of the art, and above all, a manuscript that demonstrates the concept of cascaded modulation (Figure 4) would represent the sort of advancement one expects from Nature. With such revisions I would strongly endorse the manuscript for Nature.

While we share the Reviewer's enthusiasm about the cascaded shifter, which is the topic of our ongoing activities, we do believe that current manuscript not only presents novel concept used to realize an efficient frequency shifter and true, bi-directional, frequency beam splitter, but also already presents significant improvement over the state of the art when it comes to frequency shifters (as discussed above).

We hope that our answers to the Referee's questions help emphasize this. We believe that the revised manuscript is significantly improved, in large part due to very detailed review performed by all referees. It is thus our hope that the Referee will agree with us that the revised manuscript is worthy of publication in Nature, even without the experimental implementation of Figure 4.

We briefly answer a few specific points mentioned in the Reviewer's summary:

- We now clearly distinguish that we are talking about “on-chip insertion loss” and not “overall insertion loss” that includes fiber coupling.
- Fiber-coupling aside, we do believe, and hope that the reviewer is now convinced, that our “shift efficiency” * DIL is a true light-out vs light-in metric, and is not “artificial”.
- The main, and extremely important, difference between our previous (Ref. 27) and present work is that due to clever and novel design (while using similar topology, indeed) we can now use simple RF signals (sine wave) instead of RF pulses. This is an important and non-trivial feature in our opinion, since not only simplifies the electronics needed for the experiments, but also allows the shifter to be applied to both CW and pulsed optical signals that do not have to be synchronized with the RF signal (as it was the case in Ref. 27).
- We believe that our concept is different from that of Savchenkov's (Ref. [1]), and importantly, it allows realization of true beam splitter. Also, our work stands out since it combines the 99% shift efficiency with low device insertion loss, features 2 - 3 orders-of-magnitude larger bandwidth with a similar required-microwave power, proposes new concept for controlling the flow of energy between two modes (compared with their concept of using two modes to suppress other sidebands), tens of GHz tuning range while maintaining high shift efficiency (this tunability is shown in a specific question from the reviewer later), and ability of integration.
- We hope to have convinced the reviewer that our definition of shift efficiency (and carrier suppression rate) is proper.
- As pointed out, our platform does not suffer from the trade-off between the resonant modulation bandwidth and optical efficiency: optical losses could in theory be reduced to 0 dB while modulation bandwidth either remains the same or increases. This is due to the strongly overcoupled nature of the waveguide-cavity system.
- We do acknowledge the tradeoff between the resonant modulation and RF bandwidths. We have performed measurements to confirm the GHz-level modulation bandwidth for optical signals and using pseudorandom bit sequences in frequency channels to show the device performance under actual data streams. We also measured the crosstalk of the swap operation for different bandwidth of channels to qualify the imperfection of this
operation. Finally, we provided device parameters that could extend the optical bandwidth to tens of GHz.

- We clarified that the motivation for the swap measurement with audio signal is to demonstrate and illustrate a direct frequency-domain swap operation using a single device.
- Based on our extensive literature survey, we concluded that our overall on-chip efficiency (on-chip loss * shift efficiency) is 90% and is nearly a factor of 3 better than state of the art of 33.8%. Furthermore, we emphasize that this 33.8% efficiency does not include the device insertion loss (and thus it should be compared to our shift efficiency of 99%).
- We do recognize the additional insertion losses due to fiber coupling, which plagues all integrated photonic platforms, and summarized approaches to address this.

In summary, we believe our work is novel for the following achievements and we hope the reviewer will agree that this is significant achievements after the discussion:

- **Technological advancement:** Experimental demonstration of an integrated, electro-optic frequency shifter and beam splitter that simultaneously features high efficiency, low loss, small footprint, single-polarization, desired bandwidth (GHz-scale), and the ability to operate at tens of GHz frequency. Taken together, these are important advancements over the state-of-the-art and combined together are unique to our device.
- **Scientific advancement:** A novel approach for controlling the flow of light in the frequency domain that leverages precisely engineered coupling rates between different modes of the system. We believe that this concept is non-trivial and very powerful, as demonstrated by our results. Moreover, we were able to generalize this concept to propose a cascaded frequency shifter. We expect that this concept could be used as a powerful tool to control the light dynamics in a complex system involving multiple resonators, and may stimulate additional high-impact works in the future.

Furthermore, I would like authors to answer/consider the following questions/comments to improve the manuscript for the specialist readers in the integrated photonics and quantum optics communities:

- Fig 2b,c) should show a logarithmic scale to properly highlight the carrier suppression and the emergence of unwanted higher order sidebands due to non-resonant coupling

  We have added the logarithmic scale to Figs. 2b and c in the revised manuscript, and for convenience below.
Fig 2f) The y-Axis should denote the RF power coupled to the chip, not the power before the RF amplifier, which is irrelevant for actual device performance. The amplifier gain is not mentioned in the Methods section.

We thank the reviewer for pointing this out. We realized this omission and fixed it now. Moreover, we have added an individual section called “Microwave driving power” in the Methods section to clarify the microwave powers used for driving our devices. We also quantify the microwave powers used for all devices in the main text and figure captions as well as in Table 1, which summarizes the device parameters.

As a reference, the microwave driving powers used to achieve the largest shift efficiency for devices with 12.5 GHz, 11.0 GHz, and 28.2 GHz doublet splitting are 102 mW (20.1 dBm), 288 mW (24.6 dBm), and 316 mW (25 dBm), respectively. The source powers used for those three devices are 0.8 dBm, 0 dBm, and -23 dBm with amplifier gains 19.3 dBm, 24.6 dBm, and 48 dBm, respectively (including microwave cable losses).

What is the capability for optical tuning of the input output frequencies of the devices?

We can tune the optical resonances with a DC voltage, with a tuning rate of 0.5 GHz/V. Our device can handle at least 60 V without destroying the electrode, thus allowing 30 GHz tunability.

Note that the frequencies can also be tuned by varying the doublet splitting by way of a coupled Mach Zehnder modulator, as we indicated in the conclusion of the main text. With this method we expect to detune by ~ 40 GHz with 30 V on a MZI with 200um length [Soltani et al, Phys. Rev. A 96, 043808 (2017)].

How much can the RF frequency be tuned by the inter-resonator detuning of the device before the conversion efficiency breaks down?

We thank the reviewer for pointing out this method of tuning. We investigated the case where modes of the two rings are degenerate and studied the efficiency for different microwave
frequencies. And yes, resonances of the two rings can be detuned to obtain a larger frequency
difference between the two hybrid modes, but this will reduce the effective coupling strength
(Omega) if the microwave drive power is held constant.

We performed simulations to investigate such an effect, along with additional measurements to
support the simulation. We have added the following text (red color) to the seventh paragraph of
the main text:

“Note that the shift efficiency for different microwave detunings can be further optimized by varying
the microwave power. In addition, the microwave operating frequency can be varied by detuning
the optical modes through a DC voltage. We show that the device with 12.5 GHz doublet splitting
can be tuned to 16 GHz with 99.1% shift efficiency and without changing the operating microwave
power. Theoretical simulation shows that the device can be tuned to >23 GHz while maintaining a
shift efficiency of >90% (See Extended Data Fig. 5 in Methods).”

We have added the following text (red color) as an individual section in the Methods:

“**Controlling the shift frequency with DC voltage.** The shift frequency can be controlled by
detuning the optical resonances of the two ring resonators, resulting in a different splitting between
two hybrid modes. However, these detuned coupled resonators will experience a reduced coherent
(Fig. 2b and 2c) is used to investigate such a phenomenon by measurement and simulation. We
find that the device maintains high shift efficiencies even for large detuning (Extended Data Fig. 5).
Theory suggests a shift efficiency of >90% is achievable for shift frequencies of more than 20 GHz,
while the measurement is limited by the gain-bandwidth product of the microwave amplifier used.
In simulation and experiment, the two optical resonators are frequency-detuned by δω from each
other by a DC voltage therefore providing a variation of the two-mode splitting $2\sqrt{(δω)^2 + μ^2}$ in
which $μ$ is the evanescent coupling between the two rings (Doublet splitting is $2|μ|$). For each two-
mode splitting, the frequencies of the applied microwave signals are changed to match the two-
mode splitting, while the powers of the microwave signals are invariant from the case that the
frequencies of two optical resonators are matched (Fig. 2b and 2c).
Extended Data Fig. 6 | Varying the shift frequency with DC voltage. The two optical resonators are detuned from each other using a DC voltage to provide a variation of the frequency difference between the two hybrid modes. A device with 12.5 GHz doublet splitting (Fig. 2b and 2c) is used to investigate this effect. For each frequency difference between two modes, the microwave frequency is changed to match this difference, while the powers of the microwave signals are kept constant and equal to that used when the resonances of each ring are degenerate (Fig. 2b and 2c). The shift efficiency remains >90% when the shift frequency is detuned >20 GHz.

· What is the fiber to chip coupling loss. Is it included in the as-defined insertion loss?

The fiber-chip coupling loss is ~10 dB/facet, resulting in total fiber-to-fiber loss of ~20 dB. This fiber-chip coupling loss is not included in our definition of device insertion loss (DIL) based on our previous discussions. By polishing the facets, coupling efficiency can be improved to ~5 dB/facet. Further reduction of coupling loss, to <1.7 dB/facet, can be achieved by using a mode-converter on the facets [please see previous work of our group: He et al. Optics Letter 44, 2314 (2019)].

We have added the following to the main text for clarification:

“Note that the definition of our on-chip insertion loss does not include the fiber-to-chip coupling loss, which is currently ~5 - 10 dB/facet. Spot size converters [He et al. Optics Letters 44, 2314-2317 (2019)] and adiabatic couplers [Khan et al. arXiv: 2002.00729 (2020)] could be used to reduce this efficiency to below 1.7 dB/facet and 1.1 dB/facet, respectively .”

· What is the parasitic coupling loss for the 30x over-coupled resonator pair? It would be also quite helpful for the reader to supply the amplitude and phase transmission curve of the overcoupled resonator pair.

We thank the reviewer for bringing this up. The parasitic loss is included in the intrinsic quality factor of our cavities, which is 1 million, corresponding to a 190 MHz intrinsic loss rate (see Device Parameter in the Methods section). This is also one of the challenges that we resolved over the
recent years - achieving a desired and strong over-coupling rate while maintaining a high intrinsic quality factor.

We have added the measurement of the optical transmission spectrum with microwave modulation on and off for the 12.5 GHz device (Fig. 2b and 2c) in the Methods as Extended Data Fig. 1c. We also include a simulation of the power and phase spectra in the case of microwave modulation on and off in the Methods as Extended Data Fig. 1d, based on the parameters of the 12.5 GHz device. Those figures are also shown below. For simplicity we did not copy Extended Data Fig. 1a and 1b here and also removed the corresponding description about Extended Data Fig. 1a and 1b in the caption shown here.

Extended Data Fig. 1 | Illustration of the cross section of the device, setup of frequency shift measurements, and optical frequency spectra and transmission spectra. a, […] c, Measured transmission spectrum of the 12.5 GHz device (Fig. 2b and c, as well as Extended Data Fig. 1c and 1d) when the microwave drive is turned off (left panel) and on (right panel). d, Simulation of the transmission and phase spectra of the 12.5 GHz device in the presence and absence of the microwave drive.

· Please comment on the fundamental trade-off between the insertion loss, which is maximized by overloading the resonators and the emergence of higher order sidebands (see Extended data Fig.1), which escape the overloaded resonator despite being off-resonant.

Indeed, increasing the waveguide-cavity coupling rate gamma will also increase the power of the parasitic sidebands (which include unintended down- or up-shifts or higher-order sidebands). However, the intensity of these sidebands can be mitigated at a larger shift frequency. To investigate this effect, we simulate the power of parasitic sidebands with varied frequency shift for different waveguide-cavity coupling rates and added the following section (red color) to the main text and Methods:

In the sixth paragraph main text:
"Note that two parasitic sidebands, with a suppression of >25 dB (inset of Fig. 2b and 2c), are due to the imperfect suppression of the over-coupled hybrid pairs. These sidebands limit the shift
efficiency and can be further reduced by a lower waveguide-cavity coupling rate or increasing the shift frequency (see Methods).

In the Methods:

**Limitation of the shift efficiency.** The shift efficiency in this work is currently limited by the parasitic sidebands of the pump and shifted frequencies (e.g. Extended Data Fig. 7b). Such parasitic sidebands originate from the Lorentzian shape of the over-coupled hybrid modes. For example, for the device with 12.5 GHz doublet splitting (Fig. 2b and 2c), one of the parasitic sidebands is at a frequency detuning of 25 GHz while the other is at -12.5 GHz detuning. This 25 GHz sideband detuning is 5 times larger than the resonance linewidth. The generation of the two parasitic sidebands can be further suppressed by increasing the shift frequency or reducing the waveguide-cavity coupling rate \( \gamma \). A theoretical simulation (Extended Data Fig. 7b) is performed to investigate the power of the parasitic sidebands with varied shift frequency for different waveguide-cavity coupling rates \( \gamma \). The results show that waveguide-cavity coupling rates up to \( 2\pi \times 7 \) GHz can still ensure sideband power suppression of at least 20 dB below that of the shifted light for a range of shift frequencies >10 GHz and below 30 dB for a range that is >30 GHz. Note that decreasing the waveguide-cavity coupling \( \gamma \) will cause a reduction of the microwave bandwidth. Therefore a proper choice of the waveguide-cavity coupling rate \( \gamma \) and the shift frequency is required to achieve a high shift ratio and large bandwidth simultaneously. In this work, a 25 dB suppression of the parasitic sidebands below that of the shifted light with a microwave bandwidth of several GHz is achieved in all devices for shift frequencies of 10 - 30 GHz.

![Graph showing normalized power on parasitic sidebands vs. magnitude of frequency shift](image)

**Extended Data Fig. 7 | Ultimate limitation of the device insertion loss and parasitic sidebands.** a, [...] b, Simulation of the normalized power of the parasitic sidebands as a function of the shift frequency. The waveguide-cavity coupling rate \( \gamma \) is varied from \( 2\pi \times 1 \) GHz to \( 2\pi \times 7 \) GHz. Waveguide-cavity coupling rates that are as high as \( 2\pi \times 7 \) GHz can still keep the parasitic sidebands suppressed below 20 dB for shift frequencies >10 GHz and below 30 dB for shifts that are >30 GHz. In this work, the parasitic sidebands are all lower than 25 dB in devices at shift frequencies of 10 - 30 GHz.

Of course, one can reduce the intrinsic loss rate \( k_{\text{int}} \) to acquire a better device insertion loss, as discussed in the "limitation of device insertion loss" section in Methods.
More details on the fabrication should be given. Does the change of the electrode layouts compared to Ref. 27 minimize capacity? The Methods section on fabrication is too short and lacks references altogether.

We have added more content to the fabrication section in the Methods along with an illustration of the device cross-section (we added this illustration to Extended Data Fig. 1a). The added text (in red) and figure is shown below:

“Device fabrication. Devices are fabricated from a commercial x-cut lithium niobate (LN) on insulator wafer (NANOLN), with a 600 nm LN layer, 2 μm buried oxide (thermally grown), on a 500 μm Si handle. Electron-beam lithography with hydrogen silsesquioxane (HSQ) resists followed by Ar+-based reactive ion etching (350 nm etch depth) are used to pattern the optical layer of the device, including the rib waveguides and micro-ring resonators. The device is cleaned and microwave electrodes (15 nm of Ti, 300 nm of Au, and 15 nm of Ti) are defined by photolithography followed by electron-beam evaporation and a bilayer lift-off process. These “bottom electrodes” provide electric fields across the rings to perform electro-optic modulation. Two layers of SiO2 (0.8 μm+0.8 μm) using plasma-enhanced chemical vapor deposition (PECVD) are used to clad the devices. Vias are subsequently patterned using photolithography and etched through the oxide using hydrofluoric acid. Finally, another layer of metal (15 nm of Ti and 500 nm of Au) is patterned by photolithography, electron-beam evaporation and lift-off. These “top electrodes” are used to route microwave signals and deliver them to the bottom electrodes. The crossovers are needed to ensure the desired parallelism for microwave modulation. In the case of the ~ 28 GHz device (Fig. 2a), the shape of the top electrode is chosen to minimize its overlap with the bottom electrode, and thus minimize the parasitic capacitance formed between them. Furthermore, the top electrode is also narrow in order to reduce the parasitic capacitance formed between electrodes in that layer without affecting the microwave power handling capability. These design choices reduce the RC constant of the electrodes and allow for efficient modulation at high microwave frequencies. Lower frequency devices, with 12.5 GHz and 11.0 GHz doublet splitting, use the top electrode structure similar to that in Ref. 27. An illustration of the cross-section of the device is shown in Extended Data Fig. 1a. The inclined sidewall of vias (Extended Data Fig. 1a) due to the wet-etch process ensures that two layers of metal can connect to each other through electron-beam evaporation.”

![Extended Data Fig. 1](image-url) | Illustration of the cross section of the device, setup of frequency shift measurements, and optical frequency spectra and transmission spectra. a, the cross section of the device. The parameters labeled in the cross section are w=1.2 um, h=350 nm, t=250 nm, d1=300 nm, d2=500 nm, and h1=h2=800 nm. b, [...]

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*Note: The image and extended data figure are not included in the text. The text refers to an image and a diagram that are not provided here.*
Reviewer Reports on the First Revision:

Referee #1 (Remarks to the Author):

Authors have written a long response, have given more attention to differentiating their current work from that reported in their 2018 Nature Photonics paper as requested (this was my most important comment), and have satisfactorily addressed my other points. So there is no question that the manuscript is improved. And as I hope I made clear before, this is very nice work.

Bottom line: although it is good enough to publish in Nature, I believe the question whether the work is sufficiently different from the 2018 Nature Photonics paper remains a judgment call for the editors. I am on the fence regarding this point.

Referee #2 (Remarks to the Author):

I have been asked to re-review the manuscript “Electro-optic frequency shifter and beam splitter,” which describes a highly efficient frequency shifter with tunable conversion efficiency. The authors draw an analogy to a four-port beamsplitter and show that their device can perform the routing (shifting) functions with near 100% efficiency and low cross-talk. In the initial review, I found the results impressive, but the clarity in the manuscript was lacking. In the revision, there is now a more thorough description of the physical parameters and their relationships. The authors have performed an improved experiment studying the cross-talk of their channel-swapping device and presented it in Extended Figure 5. The new discussion of bandwidth and overdriving is important for real-world implementation of this device. Overall, after reviewing the revised manuscript, I am satisfied with the improvements and I believe the manuscript deserved publication in a high-profile journal.

I have a few additional questions:

- \( \Gamma \) is called frequency of Rabi Oscillation on line 95, but is called coupling rate on lines 660, 662. I would recommend more careful choice of words since the rate of oscillation is not the same as a coupling (or decay) rate.

- In Fig 3 and extended fig 5, why is SWAP capitalized in the figure? It is not an abbreviation.

- On page 17 of the rebuttal, the authors present a graph of the dependence of efficiency on microwave power and argue that their device is not “overly sensitive” to variations in power. Perhaps it is not necessary to include this figure in the manuscript, but is the statement of insensitivity to microwave power (for perfect swapping of channels) stated in the manuscript?

Referee #3 (Remarks to the Author):

First of all this reviewer would like to thank the authors for their long and careful answer. However this reviewer would like to express surprise about the format of the reply. While carefully prepared and voluminous with 50 pages, its length does not hide the core fact that the authors have not included any fundamentally new data into the manuscript. To the regret of this reviewer that was hoping to see new measurements provided.

The reply to this reviewer’s criticism is mostly a reply letter.
In the original review it was stated:
to this reviewer, above all, a manuscript that demonstrates the concept of cascaded modulation (figure 4) would represent the sort of advancement one expects from Nature. With such revisions I would strongly endorse the manuscript.

Given that the authors have not chosen to pursue this route, i.e. to turn their proposed device in figure 4, into an actual device, the manuscript has to the regret of this reviewer still the same shortcoming as in the original version. As such this manuscript does not rise to the same level as prior work of the authors, or as expected to read in a publication in Nature.

As pointed out in the original review the current experiment – that of an electro-optical photonic molecule – is very similar to prior work, and this impression is equally shared by Referee 1. The current work is using a different operating regime of their prior device of a photonic molecule, investigated in detail in an “Electronically programmable photonic molecule” in Nature Photonics 2019. In this former work the operating regime was pulsed, and led to Ramsey spectroscopy of photons, whereas here it is CW microwave driven and employs overcoupled devices. However apart from this there is no novelty, neither conceptually nor from a device side.

This view can also be corroborated by the authors own appreciation of their work “Our current manuscript pushes the photonic molecule platform to a new regime of operation […]. This has been accomplished by developing a new understanding of the system, and […]. By precisely engineering coupling rates between these modes we were able to demonstrate high performance frequency domain mode shifting and beam splitting […]. We also go a step further and generalize the proposed concept to a novel cascaded and efficient frequency shifter”.

First, to this reviewer the new understanding is rather exaggerated. While the previous scheme on Ramsey spectroscopy was subtle and required both optical and microwave pulses (and lead to beautiful ‘classical’ Ramsey fringes), the current scheme is simple and follows straightforwardly. Also, there is literature on the topic (simply continuous RF excitation, between two optical modes as studied by the work of Matkso and Ilchenko on photonic receivers). As such there is not much novelty or insight to this reviewer associated with continuous RF driving – the Physics is expected. For example the conversion follows directly from https://advances.sciencemag.org/content/4/8/eaar4994 - but there are many other papers on this subject of two coupled optical resonances subject to a time periodic modulation.

Second, the authors comment specifically on the novel concept of a cascaded and efficient frequency splitter. Given the large degree of overcoupling this schemes become realistic – but remains not shown.

Third, the reviewer understands the reply to extend the novelty claim to “frequency beamsplitting”, which indeed is an interesting new twist, and which is novel. However, the application of frequency shifting remains weak in this reviewer’s opinion. What is demonstrated in this manuscript, conversion of music streams is to this reviewer rather a “contrived” application and in stark contrast to the author’s prior work that demonstrated actual system laboratory demonstrations relevant to optical communication systems (e.g. PAM 4 and phase shift keying modulation formats). The frequency shifting with a low (kHz) bandwidth music data stream is not so convincing, and adds no real technological value to the manuscript. In contrast to the authors impressive and leading demonstrations in the past on this new platform.

Overall, despite the very long and detailed response, I regret to notice that the authors have not undertaken efforts to refute the key core criticism of this reviewer. While the authors have tried to strengthen the manuscripts core message by introducing the concept of a “beam splitter” (which is novel), the overall manuscript still suffers from the cascaded frequency shifting (an entire figure in the manuscript) being a concept. As such this reviewer is afraid that the manuscript will not lead to the same excitement and interest as prior work of the authors. The reviewer therefore regrets that the manuscript has not rise to the level of Nature - which new measurements would have allowed.

Minor comments: the discussion of “on chip” insertion loss remains confusing, as the terms or not
standard practice in the field. The coupling to resonators is mostly expressed as the degree of overcoupling, or "mirror input coupling efficiency" for Fabry Perot type cavities. The input insertion loss is very high with 5-10 dB per facet.

Author Rebuttals to First Revision:
Response to Referees’ comments:

Based on the referees’ suggestions we have fabricated and experimentally demonstrated the cascaded frequency shifter. These results are added as a new Fig. 5 in the manuscript, with accompanying explanation in the Main text and Methods.

Overall, we thank each of the referees for their helpful comments and detailed assessments of our manuscript. We have followed all their suggestions and made the corresponding changes to our manuscript. We hope these changes have addressed the concerns of each referee and, in conjunction with the cascaded shifter demonstration, have improved their opinion of the manuscript.

Please see our point-by-point response to all the referee comments below.

Note that we have made several editorial changes to the manuscript to increase clarity and readability, especially due to the inclusion of the cascaded shifter demonstration. These, along with additional scientific content, are shown in the manuscript in red font.

Referee #1 (Remarks to the Author):

Authors have written a long response, have given more attention to differentiating their current work from that reported in their 2018 Nature Photonics paper as requested (this was my most important comment), and have satisfactorily addressed my other points. So there is no question that the manuscript is improved. And as I hope I made clear before, this is very nice work.

Bottom line: although it is good enough to publish in Nature, I believe the question whether the work is sufficiently different from the 2018 Nature Photonics paper remains a judgment call for the editors. I am on the fence regarding this point.

Our response: We thank the referee for their positive comments and the support of publication in Nature from a scientific point of view. We hope that our demonstration of the cascaded frequency shifter (see comments to Referee #3) will tip the balance in favor of publishing this work in Nature.

Referee #2 (Remarks to the Author):

I have been asked to re-review the manuscript “Electro-optic frequency shifter and beam splitter,” which describes a highly efficient frequency shifter with tunable conversion efficiency. The authors draw an analogy to a four-port beamsplitter and show that their device can perform the routing (shifting) functions with near 100% efficiency and low cross-talk. In the initial review, I found the results impressive, but the clarity in the manuscript was lacking. In the revision, there is now a more thorough description of the physical parameters and their relationships. The authors have performed an improved experiment studying the cross-talk of their channel-swapping device and presented it in Extended Figure 5. The new discussion of bandwidth and overdriving is important for real-world implementation of this device. Overall, after reviewing the revised
manuscript, I am satisfied with the improvements and I believe the manuscript deserved publication in a high-profile journal.

**Our response:** We thank the reviewer for positive comments and the support of publication.

I have a few additional questions:

- $\Gamma$ is called frequency of Rabi Oscillation on line 95, but is called coupling rate on lines 660, 662. I would recommend more careful choice of words since the rate of oscillation is not the same as a coupling (or decay) rate.

**Our response:** We thank the reviewer for helping us improve the clarity. Indeed, we should be careful about the differences between Rabi Oscillation and coupling rate. Therefore, we have made the following changes (in red) to clarify this confusion in the fourth paragraph of the revised manuscript (Line 95 in previous version):

“When driven, e.g., using coherent microwave signals and the electro-optic effect considered in this work, the two levels are coupled with a coupling rate of $\Omega$, resulting in Rabi oscillation.”

We have modified the remainder of the manuscript to ensure the coupling rate $\Omega$ only refers to the coupling between the two levels and not Rabi Oscillation.

- In Fig 3 and extended fig 5, why is SWAP capitalized in the figure? It is not an abbreviation.

**Our response:** We thank the reviewer for pointing out this omission. We changed “SWAP” to “Swap” in the revised manuscript.

- On page 17 of the rebuttal, the authors present a graph of the dependence of efficiency on microwave power and argue that their device is not “overly sensitive” to variations in power. Perhaps it is not necessary to include this figure in the manuscript, but is the statement of insensitivity to microwave power (for perfect swapping of channels) stated in the manuscript?

**Our response:** We added additional statements in the manuscript to clarify this insensitivity to microwave power. Please see below for added text to ‘Measurement of swap operation’ in the Methods:

“Note that simulations show that the shift efficiency of the swap measurement is not overly sensitive to variations of the drive RF power. Specifically, changes in the microwave powers in the range of $\sim$3 dBm vary the efficiency by no more than 5 percent.”
Referee #3 (Remarks to the Author):

First of all this reviewer would like to thank the authors for their long and careful answer. However this reviewer would like to express surprise about the format of the reply. While carefully prepared and voluminous with 50 pages, its length does not hide the core fact that the authors have not included any fundamentally new data into the manuscript. To the regret of this reviewer that was hoping to see new measurements provided.

The reply to this reviewer’s criticism is mostly a reply letter.

In the original review it was stated:

"to this reviewer, above all, a manuscript that demonstrates the concept of cascaded modulation (figure 4) would represent the sort of advancement one expects from Nature. With such revisions I would strongly endorse the manuscript”.

Given that the authors have not chosen to pursue this route, i.e. to turn their proposed device in figure 4, into an actual device, the manuscript has to the regret of this reviewer still the same shortcoming as in the original version. As such this manuscript does not rise to the same level as prior work of the authors, or as expected to read in a publication in Nature.

Our response: We would like to thank the reviewer for reading our detailed response and for providing detailed comments. We are also thankful for their insisting on an experimental demonstration of the cascaded shifter concept, which provided much needed motivation 😊. After several months spent in cleanroom and doing measurements, we are excited to share that we achieved cascaded frequency shifting of 120 GHz with a three-resonator device using only a continuous and single-tone microwave signal of 30 GHz. We believe that this result provides the requested experimental verification of the proposed concept, and thus differentiate the current work from our previous work. We hope that the reviewer shares our excitement and will agree this is a significant breakthrough and suitable for publication in Nature.

The added Figure 5 of experimental demonstration and added paragraph are shown below (in red):

Added paragraph in main text:

Finally, we demonstrate a cascaded frequency shifter using a device consisting of three mutually coupled resonators (Fig. 5a): a small ring resonator (Ring 1) is used for coupling to selected mode of the racetrack resonator (Ring 2), and a rectangular-shaped resonator (Ring 3) that provides a frequency boundary. Telecommunication wavelength light resonant with Rings 1 and 2 is directed to the device using a waveguide adjacent to the Ring 1. The waveguide also serves as the continuum of modes. A 29.805 GHz microwave tone is applied to, and matches the FSR of, the Ring 2 (racetrack). This results in a four-mode cascade and a frequency down-shift of 119.22 GHz, equal to the FSR of the Ring 1, owing to the boundary created by a Ring 3. The output optical spectrum (Fig. 5b) reveals $\eta = 80.9\%$, a carrier suppression ratio of 17 dB, and a device insertion loss of 6.17 dB, corresponding to 1.54 dB per mode in a four-step cascade. Improving the shift
efficiency and device insertion loss can be achieved by reducing the coupling strength $\mu_1$ and $\mu_2$ which currently distorts the FSR of the racetrack resonator through a non-resonant perturbation, leading to non-ideal match of the GCC condition (see Methods). A full set of parameters inferred from this device is outlined in the Methods.

**Fig. 5 | Demonstration of electro-optic cascaded frequency shifting.** a, Device optical image (false color). Three resonators, a small ring (Ring 1), a racetrack (Ring 2) and rectangular-shaped (Ring 3) resonator, are evanescently coupled to form a single device. The racetrack is used to provide a family of frequency modes that are coupled using electro-optic modulation. Ring 1 is used to over-couple two modes (frequency detuning $\omega_1$ and $\omega_2$ in inset) of Ring 2, and Ring 3 is used to define the boundaries of the cascading process. The resonance frequencies of Rings 1 and 3 are adjusted using resistive heaters. A bus waveguide coupled to Ring 1 provides the input and output ports as well as serves as the continuum. A weakly coupled auxiliary waveguide is used to monitor the resonances of Rings 2 and 3 during tuning process (using the heaters). b, Output spectrum of the cascaded frequency shifter. Continuous-wave light of 1628.5 nm wavelength (corresponding to zero detuning), resonant with Ring 1 and 2, is directed to the device. A continuous and single-tone microwave signal of $\omega_m = 2\pi \times 29.805$ GHz is applied to the electrode and results in a four-mode cascaded frequency down-shift of 119.22 GHz. The shift efficiency is measured to be 80.9% and a device insertion loss of 6.17 dB. The latter corresponds to 1.54 dB loss per each of the four frequency shifts.
**Added text in Methods:**

**Simulation of cascaded frequency shifting.** The numerical simulation is performed based on the equations of motion for the cascaded frequency shift system. They are derived using a similar approach (Heisenberg-Langevin equation) to that discussed above:

\[
\dot{a}_q = \left( -i(\omega_q - \omega_L) - \frac{\kappa_{\text{int}1} + \kappa_e}{2} \right) a_q - i\mu_1 b_1 \delta_{q,1} - i\mu_1 b_5 \delta_{q,2} - \sqrt{\kappa_e} \alpha_{in}
\]

\[
\dot{b}_j = \left( -i(\omega_j - \omega_L) - \frac{\kappa_{\text{int}2} + \kappa_{\text{aux}}}{2} \right) b_j - i\Omega \cos(\omega_m t + \varphi) (b_{j+1} + b_{j-1}) - i\mu_1 a_1 \delta_{j,1} - i\mu_1 a_2 \delta_{j,5} - i\mu_2 c_1 \delta_{j,0} - i\mu_2 c_2 \delta_{j,6}
\]

\[
\dot{c}_p = \left( -i(\omega_p - \omega_L) - \frac{\kappa_{\text{int}3}}{2} \right) c_p - i\mu_2 b_0 \delta_{p,1} - i\mu_2 b_6 \delta_{p,2}
\]

where \( a_q, b_j, c_p \) represents the annihilation operators of modes in Rings 1, 2, 3, respectively \((q = 1,2; j = 0,1,2,3,4,5,6; p = 1,2)\). In Ring 2, the modes \( b_1, \ldots, b_5 \) corresponds to modes 1 to 5 in Fig. 4b. In Ring 1, \( a_1 \) and \( a_2 \) are the input and output modes that couple to \( b_1 \) and \( b_5 \), respectively. In Ring 3, \( c_3 \) and \( c_2 \) are the modes that couple to \( b_0 \) and \( b_6 \), which creates boundaries for the cascaded process. The Kronecker delta \( \delta_{i,j} \) gives 1 when \( i = j \) and 0 when \( i \neq j \). The effective intrinsic loss rate \( \kappa_{\text{aux}} \) for Ring 2 is induced by the coupling to the auxiliary waveguide (Fig. 5a) while \( \kappa_{\text{int}1}, \kappa_{\text{int}2} \), and \( \kappa_{\text{int}3} \) represent the intrinsic loss rate of Ring 1, Ring 2, and Ring 3, respectively. The simulations are performed using similar methods described in the section “Numerical simulation of the two-resonator device”.

For the simulations, we assume all three cavities to have an intrinsic \( Q \sim 1.8 \times 10^6 \), which corresponds to an intrinsic loss rate \( \kappa_{\text{int}} = 2\pi \times 100 \text{ MHz} \). The waveguide-mode coupling of Ring 1 is \( \kappa_e = 2\pi \times 3 \text{ GHz} \), the Ring 1-Ring 2 evanescent coupling is \( \mu_1 = 2\pi \times 1.5 \text{ GHz} \), and the Ring 2-Ring 3 coupling is \( \mu_2 = 2\pi \times 3 \text{ GHz} \). The coupling induced by microwave modulation is \( \Omega = 2\pi \times 3 \text{ GHz} \), which is similar to that used in our current devices.

**Device parameters of the cascaded frequency shifter.** The device parameters of the cascaded frequency shifter are extracted from the transmission spectrum of the device, as measured using the bus and auxiliary waveguide. The parameters are summarized in Table 2. The shift efficiency and device insertion loss are mainly limited by the mismatch of the FSRs of Ring 1 \((2\pi \times 123.9 \text{ GHz})\) and Ring 2 \((2\pi \times 29.825 \text{ GHz})\). This mismatch originates from the strong evanescent coupling, \( \mu_1 \) and \( \mu_2 \), which distorts the FSR of Ring 2 through a non-resonant perturbation. For example, while \( \mu_2 \) provides a strong boundary by forming a doublet splitting through the coupling of modes \( c_1 \) and \( b_0 \) (Fig. 4b), mode \( c_1 \) also couples to \( b_1 \) off-resonantly and leads to a frequency changes of mode \( b_1 \) on the order of \( \sim \frac{\mu_2^2}{\text{FSR}_{\text{original},2}} = \sim 2\pi \times 1.5 \text{ GHz} \) (second-order perturbation theory), where \( \text{FSR}_{\text{original},2} = \sim 2\pi \times 30.925 \text{ GHz} \) is the designed FSR of Ring 2 without coupling to other rings. Reducing the coupling strength of \( \mu_1 \) and \( \mu_2 \) to \( \sim 2\pi \times 1 \text{ GHz} \) will allow matching of the FSRs to satisfy the GCC condition without affecting the
boundary. Finally, the FSR of Ring 3 is not precisely extracted given that there is not an auxiliary waveguides on Ring 3. However, this parameter does not affect the cascaded process since Ring 3 is only used break the cascade.

![Extended Data Fig. 9 | Output spectrum of the cascaded frequency shifter. Spectrum of Fig. 5b in dB scale](image)

**Table 2. Parameters of the cascaded frequency shifter**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Cascaded frequency shifter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shift efficiency $\eta$</td>
<td>80.9%</td>
</tr>
<tr>
<td>Device insertion loss $DIL$</td>
<td>6.17 dB</td>
</tr>
<tr>
<td>Microwave power</td>
<td>550 mW</td>
</tr>
<tr>
<td>External coupling to bus waveguide of ring 1 $\kappa_e$</td>
<td>$2\pi \times 2.20$ GHz</td>
</tr>
<tr>
<td>Coupling rate between ring 1 and ring 2 $\mu_1$</td>
<td>$2\pi \times 2.49$ GHz</td>
</tr>
<tr>
<td>Coupling rate between ring 2 and ring 3 $\mu_2$</td>
<td>$2\pi \times 6.86$ GHz</td>
</tr>
<tr>
<td>Intrinsic loss rate of ring 1 $\kappa_{int1}$</td>
<td>$2\pi \times 0.14$ GHz</td>
</tr>
<tr>
<td>Intrinsic loss rate of ring 2 $\kappa_{int2}$</td>
<td>$2\pi \times 0.10$ GHz</td>
</tr>
<tr>
<td>Effective intrinsic loss rate of ring 2 induced by auxiliary waveguide $\kappa_{aux}$</td>
<td>$2\pi \times 0.10$ GHz</td>
</tr>
<tr>
<td>Intrinsic loss rate of ring 3 $\kappa_{int3}$</td>
<td>$2\pi \times 0.17$ GHz</td>
</tr>
<tr>
<td>Ring 1 FSR</td>
<td>$2\pi \times 123.9$ GHz</td>
</tr>
<tr>
<td>Ring 2 FSR</td>
<td>$2\pi \times 29.825$ GHz</td>
</tr>
<tr>
<td>Ring 3 FSR</td>
<td>$\sim 2\pi \times 180$ GHz</td>
</tr>
</tbody>
</table>

As pointed out in the original review the current experiment – that of an electro-optical photonic molecule – is very similar to prior work, and this impression is equally shared by Referee 1. The current work is using a different operating regime of their prior device of a photonic molecule, investigated in detail in an “Electronically programmable photonic molecule” in Nature Photonics 2019. In this former work the operating regime was pulsed, and led to Ramsey spectroscopy of photons, whereas here it is CW microwave driven and employs overcoupled devices. However apart from this there is no novelty, neither conceptually nor from a device side.
This view can also be corroborated by the authors own appreciation of their work “Our current manuscript pushes the photonic molecule platform to a new regime of operation [...]. This has been accomplished by developing a new understanding of the system, and [...]. By precisely engineering coupling rates between these modes we were able to demonstrate high performance frequency domain mode shifting and beam splitting [...]. We also go a step further and generalize the proposed concept to a novel cascaded and efficient frequency shifter”.

**Our response:** We acknowledge that our two-resonator device has a similar design to that used in our previous work in Nature Photonics. Still, we feel that our result is important owing to significant technological advancement: demonstration of frequency shifts of tens of GHz with ~90% conversion efficiency. This efficiency is state of the art and is demonstrated with an integrated device using single-tone microwave signals. The device enables compact beam splitting and swap operations, which are also new functionalities compared to the Nature Photonics work, as mentioned by the reviewer below.

First, to this reviewer the new understanding is rather exaggerated. While the previous scheme on Ramsey spectroscopy was subtle and required both optical and microwave pulses (and lead to beautiful ‘classical’ Ramsey fringes), the current scheme is simple and follows straightforwardly. Also, there is literature on the topic (simply continuous RF excitation, between two optical modes as studied by the work of Matkso and Iltzenko on photonic receivers). As such there is not much novelty or insight to this reviewer associated with continuous RF driving – the Physics is expected. For example the conversion follows directly from [https://advances.sciencemag.org/content/4/8/eaar4994](https://advances.sciencemag.org/content/4/8/eaar4994) - but there are many other papers on this subject of two coupled optical resonances subject to a time periodic modulation.

**Our response:** We agree with the reviewer that, if one only considers two level systems, the new understanding is exaggerated. However, we would like to explain that this understanding is not limited to a two-level system. We generalize this concept to a multi-level system upon which the concept of the cascaded shifter is proposed, and which its novelty is also supported by the referee.

Second, the authors comment specifically on the novel concept of a cascaded and efficient frequency splitter. Given the large degree of overcoupling this schemes become realistic – but remains not shown.

**Our response:** We would like to thank the reviewer for acknowledging the novelty of our cascaded frequency shifter, and we hope that our experimental demonstration is satisfactory.

Third, the reviewer understands the reply to extend the novelty claim to “frequency beamsplitting”, which indeed is an interesting new twist, and which is novel. However, the application of frequency shifting remains weak in this reviewer’s opinion. What is demonstrated in this manuscript, conversion of music streams is to this reviewer rather a “contrived” application and in
stark contrast to the author’s prior work that demonstrated actual system laboratory demonstrations relevant to optical communication systems (e.g. PAM 4 and phase shift keying modulation formats). The frequency shifting with a low (kHz) bandwidth music data stream is not so convincing, and adds no real technological value to the manuscript. In contrast to the authors impressive and leading demonstrations in the past on this new platform.

**Our response:** We thank the reviewer for acknowledging the novelty of the frequency beam splitting. The original motivation of Fig. 3 (swap measurement) is to demonstrate the possibility of swapping two frequencies using a single device (i.e. bi-directionality of a frequency beam splitter). We modulate the device with kHz music signals only to distinguish the two different frequencies. That’s all. We did not intend to imply that our demonstration of transmission of low frequency audio signal has relevance to tele- and data-communication.

However, in response to the reviewer’s original comment we did perform pseudorandom bit frequency shifting and GHz-bandwidth swap operations, as shown in the Extended Data Figs. 3 and 5. In addition, using simulations we show that the optical bandwidth can be improved to \(~14\) GHz to accommodate some communication applications (Extended Data Fig. 4). Still, we do acknowledge that this device is not a perfect fit for current telecommunication systems due to its limited bandwidth.

Although the demonstrated swap operation is not sufficient for communication applications, it is useful for quantum photonics. For example, while we only use a single device to perform frequency beam splitting, this functionality would otherwise require the use of two phase modulators and one waveshaper in series [Lukens et al. *Optica* **4**, 8 (2016); Lu et al. *Phys. Rev. Lett.* **120**, 030502 (2018)]. In addition, our device could be useful for quantum networks. The current operating bandwidth (several GHz) is suitable for quantum defects [Aharonovich et al. *Nature Photonics* **10**, 631 (2016)] and could be used to overcome the inhomogeneous broadening of defects, or for interfering light in different frequency modes, which is important for creating long-range matter entanglement [Sinclair et al. *Phys. Rev. Lett.* **113**, 053603 (2014)].

Overall, despite the very long and detailed response, I regret to notice that the authors have not undertaken efforts to refute the key core criticism of this reviewer. While the authors have tried to strengthen the manuscripts core message by introducing the concept of a “beam splitter” (which is novel), the overall manuscript still suffers from the cascaded frequency shifting (an entire figure in the manuscript) being a concept. As such this reviewer is afraid that the manuscript will not lead to the same excitement and interest as prior work of the authors. The reviewer therefore regrets that the manuscript has not rise to the level of Nature - which new measurements would have allowed.

**Our response:** We thank the reviewer for reading our long and detailed response. We acknowledge that we should have undertaken efforts to refute the key core criticism of the reviewer - the cascaded frequency shifter. Therefore, we have taken several months to realize such a cascaded frequency shifter, including designing and testing the basic parameters of the triple-
resonator device with different shapes of rings and performing measurements on this complex system. To facilitate our result, we developed thermal heaters on our device, which allows precise and stable tuning ring resonances, to readily provide the conditions to achieve the cascaded shifting. We hope the reviewer agrees our work is now sufficient to be published in Nature.

Minor comments: the discussion of “on chip” insertion loss remains confusing, as the terms or not standard practice in the field. The coupling to resonators is mostly expressed as the degree of overcoupling, or “mirror input coupling efficiency” for Fabry Perot type cavities. The input insertion loss is very high with 5-10 dB per facet.

**Our response**: We appreciate the comments of the referee. However, in our personal opinion, the use of “insertion loss” for on-chip devices is not that uncommon. One example is the insertion loss of an on-chip optical ring filter. This insertion loss is defined as the ratio of the powers at the output drop-port waveguide and the input bus waveguide for a single ring resonator filter, which is in exactly the same spirit of our definition. Indeed, in our case, the two resonators are strongly coupled so that they can be treated as a single device. For example, in Feldmann et al. *Nature* **569**, 208 (2019), the authors fabricated on-chip wavelength division multiplexers that consisted of several ring filters, and they obtained an insertion loss of ~1.5 dB for those ring resonators. Other examples can be found in Xia et al. *Nature Photonics* **1**, 65 (2007) and Marchetti et al. *Appl. Sci.* **7**(2), 174 (2017).

As noted in the manuscript, it is possible to reduce the facet loss using spot size converters [Ying et al. *Optics Letters* **46**, 1478 (2021); He et al. *Optics Letters* **44**, 2314 (2019)] or adiabatic couplers [Khan et al. *APL Photonics* **5**, 056101 (2020)], to ~1-2 dB/facet. While extremely important for applications in general, minimizing the facet loss was not priority of this work. Waveguide couplers requires additional lithography and etching steps which further complicate the fabrication process, especially in an academic lab. We note that this approach (not worrying about the coupling loss) is consistent with the multitude of on-chip demonstrations that are published in the literature, including high profile journals. However, we do strongly agree that addressing fiber-chip coupling in a robust and scalable fashion is extremely important for the field of integrated photonics.
Reviewer Reports on the Second Revision:

Referee #3 (Remarks to the Author):

This reviewer would like to thank the authors for the detailed and careful reply to my previous comments. The main concern for the first and second submission was regarding the novelty of the data shown in the initial work. In their current version the authors introduce a very clever and ingenious way to achieve frequency shifting. In their figure 5 they demonstrate shifting over 119 GHz with a 29 GHz drive. The latter is a compelling demonstration and demonstrates a new capability.

I had asked the authors to provide this in my initial review – and I am pleased to see the results that are in my view adding substantial novelty to the manuscript. To this reviewer, the data transmission of the music stream is much less interesting than the impressive demonstration of frequency shifting in their revised version. The scheme is beautifully and very cleverly implemented and I congratulate the authors.

As such I recommend publication of this work in Nature.

That said, the authors should and need to change two points in the manuscript, which are misleading, and can readily lead to a misinterpretation what the state of the art in the field is. The authors have made impressive advances and there is no reason to oversell the results.

First, The authors should remove the notion of: "on-chip insertion loss of 0.45 dB" in the abstract. The group is a leading group in integrated photonics and the current description is confusing to many, and misleading. The insertion loss is widely and broadly accepted to be the loss into and out of the device, i.e. the chip. What is meant here is the degree of over coupling to the resonators. The latter is well established in the community of microresonators based research, and thus the authors can simply state the amount of overcoupling. Indeed there exists already a metric for this in literature: the ideality. 

https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.91.043902

The actual insertion loss of their device is another point of concern. It is regrettably and not understandable to this reviewer, why the authors are not more careful and avoid giving the impression to mislead the readership, which they run the risk of doing. My second point of concern is the "device insertion loss" definition.

What is consistent is the representation of the IQ modulator work – which is quoted to have an insertion loss of 4.7 dB. Quoting: "In-phase and quadrature (IQ) modulators ...the expense of a large fundamental device insertion loss of 4.7 dB. "

Next they write: "Here we overcome these limitations and demonstrate on-chip EO frequency shifters that have up to ~ 99% shift efficiency and low device insertion loss. "

The last statement "low device insertion loss" is simply not true and false. Their definition of insert loss is not including the chip to fiber coupling. This is mentioned later by the authors: "Note that our definition of \( dIL \) does not include fiber-to-chip coupling loss, which is currently \( \approx 5 \times 10 \) dB/facet. "

Hence the authors take competing work as face value insertion loss (4.7dB) and compare this to their own metric of on-chip insertion loss? This total insertion loss is similar if not lower than the loss of this work. It is strange to see this quoted and misleading, as it suggests this work has improved insertion loss (which it has not with 5-10 dB).

Intentional or not, this is misleading at best.

In addition, the authors also they do not quote this manuscript, which appears highly relevant: https://www.nature.com/articles/s41467-020-17806-0.pdf. It demonstrates LNOI IQ modulators. It appears highly relevant and should be cited.

Despite quite an improvement in the presented data, I still have some comments on explanations and data presentation.
Last, the notion of a "shift efficiency" that is calculated as 
"(output power in desired mode) / (total output power)"
 does not account for intracavity loss. The authors write that the insertion loss is 6 dB for the cascaded frequency shifter (1.54 dB per mode), while quoting a "shift efficiency" of 80 
%. That is confusing. The true power conversion efficiency on chip, i.e. (output power in desired mode in waveguide) / (input power in waveguide) is thus 20 
%. I would like to add that 20% efficiency on chip is still quite an impressive result for integrated high-frequency microwave-optical mixing in my opinion. For this reason the authors have no reason to oversell – the results are impressive as they are. But they risk to confuse literature by suggestion that the LNOI platform is ultra efficient in all metrics including input losses. Which is not the case, and an enduring challenge.

Last, I do think the authors need to improve their explanation on uni-directionality quite a bit both in text and figures. Combining figure 4 (cascaded shifting process) of the main text with figure 5 (experimental demonstration of the proposed device) would help a reader to better understand the concept. In this case the details on simulations are not really needed in the main text and could be moved to Methods. In my opinion, all the conversion plots should be presented in logarithmic scale in the main text, at least as an inset. The reason is that it is hard to estimate the efficiencies presented in linear scale.

In summary I recommend the manuscript to Nature and the results are impressive. Yet the authors should discuss their results not in terms of "device insertion loss" but simply "chip insertion loss", "carrier extinction" and "shift conversion efficiency" (power in the sideband vs. power in the waveguide that is subject to the resonators). This convention is also used in soliton microcombs (where conversion efficiency is with respect to the waveguide power before and after the resonator).

Author Rebuttals to Second Revision:

Referees' comments:

Referee #3 (Remarks to the Author):

This reviewer would like to thank the authors for the detailed and careful reply to my previous comments. The main concern for the first and second submission was regarding the novelty of the data shown in the initial work. In their current version the authors introduce a very clever and ingenious way to achieve frequency shifting. In their figure 5 they demonstrate shifting over 119 GHz with a 29 GHz drive. The latter is a compelling demonstration and demonstrates a new capability.

I had asked the authors to provide this in my initial review – and I am pleased to see the results that are in my view adding substantial novelty to the manuscript. To this reviewer, the data transmission of the music stream is much less interesting than the impressive demonstration of frequency shifting in their revised version. The scheme is beautifully and very cleverly implement and I congratulate the authors.

As such I recommend publication of this work in Nature.

Our response: We thank the referee for their positive comments about our results and their support of publication in Nature.
That said, the authors should and need to change two points in the manuscript, which are misleading, and can readily lead to a misinterpretation what the state of the art in the field is. The authors have made impressive advances and there is no reason to oversell the results.

**Our response:** We have changed the two points in the manuscript that was mentioned by the referee (see below).

First, The authors should remove the notion of: “on-chip insertion loss of 0.45 dB” in the abstract. The group is a leading group in integrated photonics and the current description is confusing to many, and misleading. The insertion loss is widely and broadly accepted to be the loss into and out of the device, i.e. the chip.

What is meant here is the degree of over coupling to the resonators. The latter is well established in the community of microresonators based research, and thus the authors can simply state the amount of overcoupling. Indeed there exists already a metric for this in literature: the ideality.

https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.91.043902

**Our response:** Thank you for your comments. While we think that on-chip insertion loss is commonly used figure of merit in the nanophotonic community, we understand the Referee’s concern. For this reason, we have removed “on-chip insertion loss of 0.45 dB” from the abstract.

The actual insertion loss of their device is another point of concern. It is regrettably and not understandable to this reviewer, why the authors are not more careful and avoid giving the impression to mislead the readership, which they run the risk of doing. My second point of concern is the “device insertion loss” definition.

What is consistent is the representation of the IQ modulator work – which is quoted to have an insertion loss of 4.7 dB. Quoting: “In-phase and quadrature (IQ) modulators …the expense of a large fundamental device insertion loss of 4.7 dB. “

Next they write: “Here we overcome these limitations and demonstrate on-chip EO frequency shifters that have up to ~ 99% shift efficiency and low device insertion loss. “

The last statement “low device insertion loss” is simply not true and false. Their definition of insert loss is not including the chip to fiber coupling. This is mentioned later by the authors: “Note that our definition of DIL does not include fiber-to-chip coupling loss, which is currently ~5 – 10 dB/facet. “

Hence the authors take competing work as face value insertion loss (4.7dB) and compare this to their own metric of on-chip insertion loss? This total insertion loss is similar if not lower
than the loss of this work. It is strange to see this quoted and misleading, as it suggests this work has improved insertion loss (which it has not with 5-10 dB).

Intentional or not, this is misleading at best.

**Our response:** Thank you for your comments. We would like to point out that 4.7 dB insertion loss in IQ modulator based shifter also does not include fiber-coupling loss. Therefore, we believe it was appropriate to compare intrinsic 4.7 dB loss of that approach (excluding fiber coupling) with our “on chip insertion loss”.

However, to avoid any further confusion, we have removed all mentioning of the “device insertion loss” from the manuscript based on reviewer’s suggestion. See also our responses below regarding definitions of insertion loss and efficiency.

In addition, the authors also do not quote this manuscript, which appears highly relevant: https://www.nature.com/articles/s41467-020-17806-0.pdf. It demonstrates LNOI IQ modulators. It appears highly relevant and should be cited.

**Our response:** We thank the referee for mentioning this work. We have added this paper in the reference list.

Despite quite an improvement in the presented data, I still have some comments on explanations and data presentation.

Last, the notion of a "shift efficiency" that is calculated as ")(output power in desired mode) / (total output power)" does not account for intracavity loss. The authors write that the insertion loss is 6 dB for the cascaded frequency shifter (1.54 dB per mode), while quoting a "shift efficiency" of 80 %. That is confusing. The true power conversion efficiency on chip, i.e. (output power in desired mode in waveguide) / (input power in waveguide) is thus 20 %.

I would like to add that 20% efficiency on chip is still quite an impressive result for integrated high-frequency microwave-optical mixing in my opinion. For this reason the authors have no reason to oversell – the results are impressive as they are.

But they risk to confuse literature by suggestion that the LNOI platform is ultra efficient in all metrics including input losses. Which is not the case, and an enduring challenge.

**Our response:** We are happy to quote 20% on chip conversion efficiency, as referee requested. We do agree that this is impressive result. Our goal was not to oversell, but to inform the reader where this number comes from: 80% from conversion itself, and 25% from the loss of the device. The multiplication of the two number gives 20%.

However, we decided to remove the term “shift efficiency”. The only “efficiency” that is mentioned in the manuscript now is called the “conversion efficiency”. This conversion efficiency is defined according to what the referee mentioned: (output power in desired mode in waveguide) / (input power in waveguide) and it is 20%.
Last, I do think the authors need to improve their explanation on uni-directionality quite a bit both in text and figures. Combining figure 4 (cascaded shifting process) of the main text with figure 5 (experimental demonstration of the proposed device) would help a reader to better understand the concept. In this case the details on simulations are not really needed in the main text and could be moved to Methods.

**Our response:** We thank the referee for helping us improve the manuscript. We have made changes regarding the explanation of uni-directionality (see the main text of the manuscript). Specifically, we removed the word “unidirectional” from our manuscript. In addition, we have combined Fig. 4 and Fig. 5. Simulations of cascaded shifter are moved to the Methods.

In my opinion, all the conversion plots should be presented in logarithmic scale in the main text, at least as an inset. The reason is that it is hard to estimate the efficiencies presented in linear scale.

**Our response:** We thank the referee for helping us improve the manuscript. We have included logarithmic scale plots as insets in all of the plots that are related to conversion.

In summary I recommend the manuscript to Nature and the results are impressive. Yet the authors should discuss their results not in terms of “device insertion loss” but simply “chip insertion loss”, “carrier extinction” and “shift conversion efficiency” (power in the sideband vs. power in the waveguide that is subject to the resonators). This convention is also used in soliton microcombs (where conversion efficiency is with respect to the waveguide power before and after the resonator).

**Our response:** We thank the referee for the recommendation of publication in Nature. We now use the three figures of merit that the referee mentioned: “conversion efficiency”, “carrier suppression ratio”, and “chip facet loss”. Furthermore, we use two additional figures of merits “shift ratio” and “on-chip loss” to qualify the effect of parasitic sidebands and the effect of loss on chip, which we believe offers additional insight into the shift process, and additional information that are not covered by the three figures of merits that referee mentioned. We believe these five figures of merit together provide the most complete information to the readers.