Hybrid quantum nanophotonic devices for coupling to rare-earth ions

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ABSTRACT

With an assortment of narrow line-width transitions spanning the visible and IR spectrum and long spin coherence times, rare-earth doped crystals are the leading material system for solid-state quantum memories. Integrating these materials in an on-chip optical platform would create opportunities for highly integrated light-matter interfaces for quantum communication and quantum computing. Nano-photonic resonators with high quality factors and small mode volumes are required for efficient on-chip coupling to the small dipole moment of rare-earth ion transitions. However, direct fabrication of optical cavities in these crystals with current nanofabrication techniques is difficult and unparallelized, as either exotic etch chemistries or physical milling processes are required. We fabricated hybrid devices by mechanically transferring a nanoscale membrane of gallium arsenide (GaAs) onto a neodymium-doped yttrium silicon oxide (Y_2SiO_5) crystal and then using electron beam lithography and standard III-V dry etching to pattern nanobeam photonic crystal cavities and ring resonator cavities, a technique that is easily adapted to other frequency ranges for arbitrary dopants in any rare earth host system. Single crystalline GaAs was chosen for its low loss and high refractive index at the transition wavelength. We demonstrated the potential to evanescently couple between the cavity field and the 883 nm $^4I_{9/2}$-$^4F_{3/2}$ transition of nearby neodymium impurities in the host crystal by examining transmission spectra through a waveguide coupled to the resonator with a custom-built confocal microscope. The prospects and requirements for using this system for scalable quantum networks are discussed.

Keywords: Quantum optics, Optical devices, Quantum electrodynamics, Rare-earth-doped materials, Coherent optical effects, Optical memories

1. COUPLING TO RARE EARTH IONS

Rare-earth ions (REIs), which were an integral part of driving the technologies of the telecommunications revolution due to the long lifetimes of their excited electron states, are being revisited for applications in optical quantum memories due to these same unparalleled properties amongst solid-state materials[1]. Long coherence times have also been shown in trapped atom and trapped ion systems in vacuum; however, scalability of quantum optical systems mandates a solid state approach to maintain commercial viability. These long lifetimes result from small dipole moments, which necessitate weak interactions with the environment, which in turn result in low coupling strength. Coupling REIs to an optical cavity increases the strength of the interaction between the optical field and the ion via the Purcell effect, proportional to the ratio of quality factor to cavity mode volume[3]. Upon reaching a mode volume of a few cubic wavelengths, and a quality factor on the order of $Q=10^5$, we can reach a regime where a single ion in the cavity strongly affects the cavity field. In Figure 1 we show a representation of a possible coupling scheme and the effect that the ion has on the cavity field using parameters that are commonly achieved in modern fabricated optical nanocavities.

While progress has been made coupling these REIs to macroscopic optical cavities[2], the use of microcavities to enhance interaction with these ions has yet to be accomplished in a scalable fabrication scheme. Other schemes involve serial processing like focused ion beam milling[4], and do not achieve the scalability of parallelized processing. We use a hybrid method, which allows us to perform fabrication in more common materials using more common tools, while still leveraging the benefits of uncommon materials for their coherence properties. In our hybrid approach, we use high refractive index dielectric materials, like amorphous silicon or single crystal gallium arsenide, for which there are standard fabrication procedures, but are low loss at the frequencies relevant to optical REI transitions of Nd and Er ions in a yttrium othosilicate (YSO) substrate.

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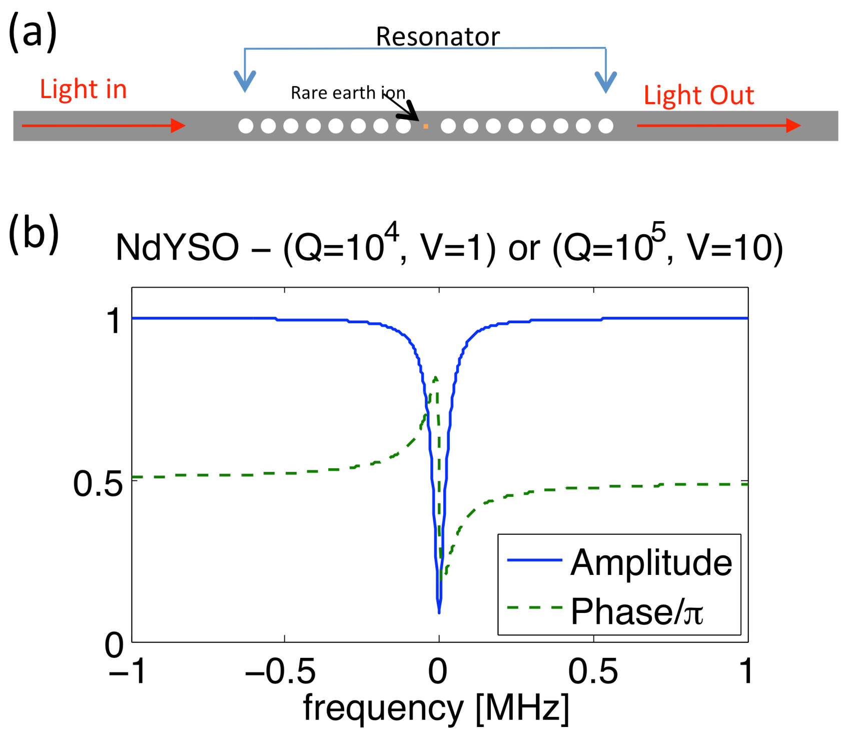

Figure 1. (a) Illustration of an example configuration for coupling an optical resonator to a small emitter, in this case, a one-dimensional photonic crystal cavity and a rare earth ion. The nanobeam can be fabricated using standard III-V fabrication procedures for a GaAs beam.

2. SIMULATION AND FABRICATION OF OPTICAL RESONATORS

Designs of one-dimensional photonic crystal nanobeam cavities were optimized using the finite-difference time-domain (FDTD) method, using the freely available MIT Electromagnetic Equation Propagation software (MEEP)[5]. Specifically, we found the resonant mode frequencies using a built in function implementing the filter diagonalization method for determining decay rates[6]. To form the cavity region, parabolic variation of the hole spacing was used to create a defect in the center, while spacing at the ends of the cavity provided a distributed Bragg reflective mirror. For the photonic crystal nanobeams, the height and width of the beam, as well as the hole diameter and parabolic spacing parameters were optimized. The number of holes was varied to achieve strong coupling to the waveguide, whereby the losses to free-space modes equaled losses to the waveguide mode. Similarly, the diameters, heights, and widths of rings and disks were optimized to maximize quality factor. Then, distance to the waveguide was determined by simulation to critically couple the resonator to the waveguide, yielding a loaded quality factor of 144,000 and a mode volume of 0.58 cubic wavelengths.

After mode volumes and quality factors were determined, the quantum optics toolbox was used to determine the predicted strength of the interaction between the atom and cavity. The results of this simulation for a radiation limited quality factor and mode volume of the optimized photonic crystal cavity are shown in Figure 1 (b).

2.1 Gallium arsenide devices

To fabricate these GaAs resonators, we developed two separate techniques. For the nanobeam resonators, we started with a gallium arsenide wafer that, using molecular beam epitaxy, had an epitaxially grown $Al_{0.8}Ga_{0.2}As$ sacrificial layer grown on it, and an epitaxial GaAs membrane grown on top of that. Electron beam lithography was then used to pattern the one-dimensional photonic crystal in a positive electron beam resist, and a chlorine/argon chemistry was used to transfer the pattern into the top GaAs layer using ICP etching. These beams are then undercut and tested before being fully undercut and transferred in solution to the YSO substrate. An example of a nanobeam during the partial undercut step is shown in Figure 2 (d).

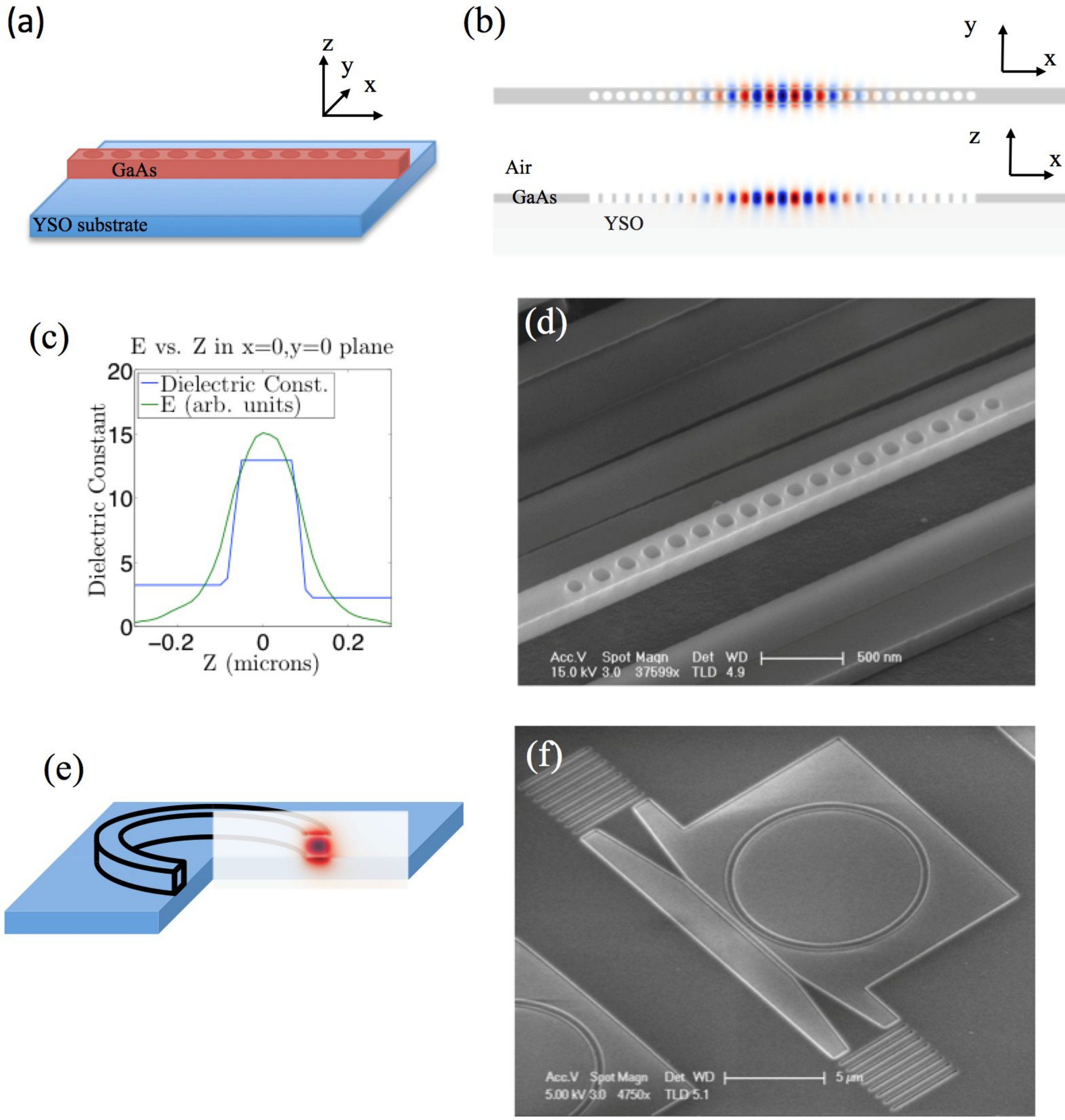

Figure 2. (a) Diagram of the gallium arsenide nanobeam cavity on a YSO substrate. (b) The cavity mode as viewed from the top and the side for the nanobeam cavity, as well as (c) a plot of the field along the z direction showing the evanescent tail, which couples the cavity to the REIs. (d) An undercut nanobeam that is suspended during testing before transfer. (e) The mode of the ring resonator shown in (f), which is amorphous silicon on silicon dioxide.

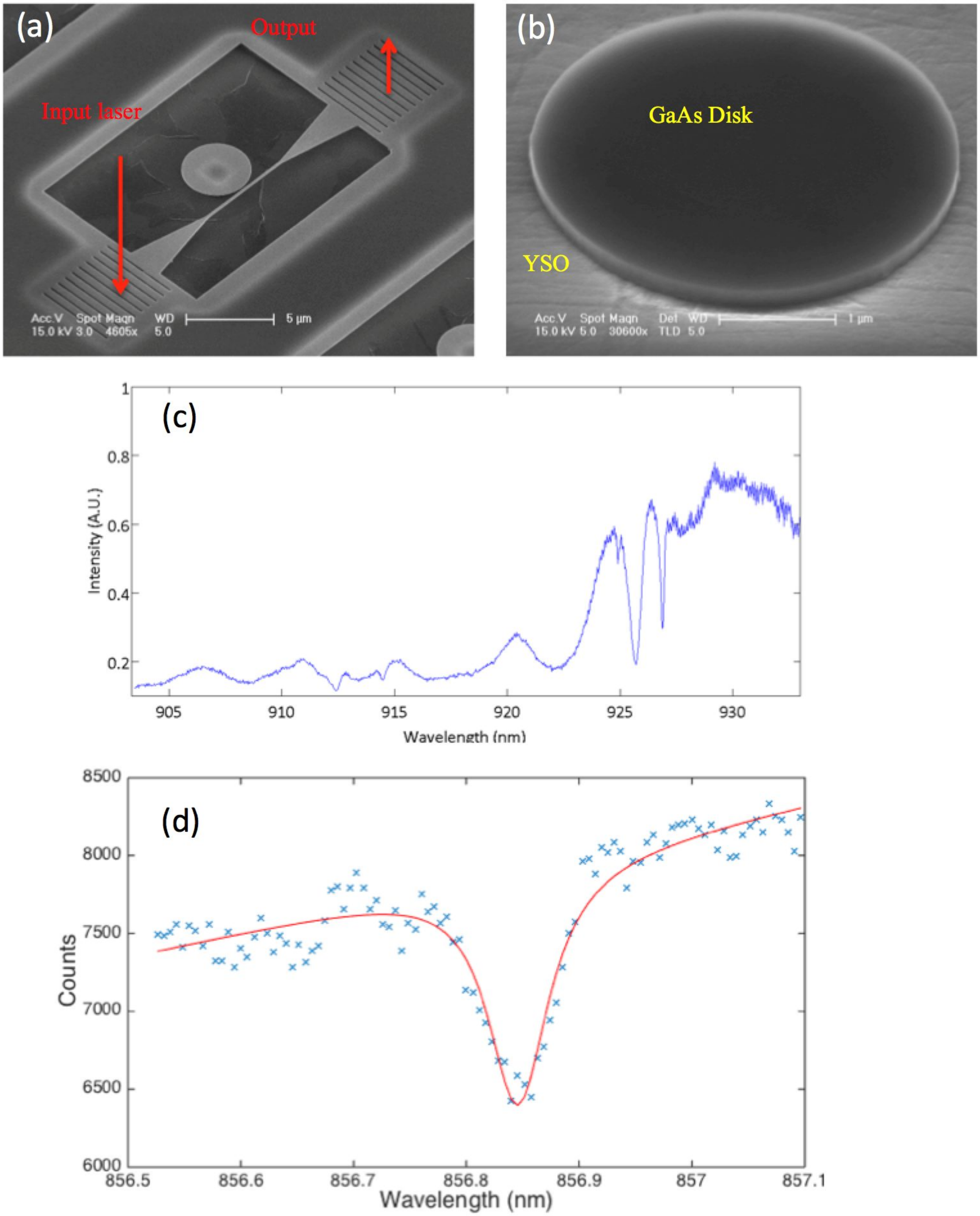

Figure 3. (a) Diagram showing input and output coupling gratings on an undercut GaAs disk, evanescently coupled to a waveguide. (b) A transferred GaAs disk, which has been transferred to a YSO substrate. (c) The resonant transmission dip from the device shown in (a), demonstrating a quality factor of approximately 5500. (d) The resonant transmission dip from the device shown in Figure 2(f), demonstrating a quality factor of approximately 15000.

The GaAs disk resonators are fabricated by first covering the same epitaxial GaAs/AlGaAs/GaAs wafer material with a layer of S1813 photoresist, and then etching the sacrificial layer in a diluted HF bath. Once the membrane has been fully released, we transfer it from solution onto the YSO chip. After surface tension bonds the two as the sample dries, we remove the photoresist, and pattern the disks with electron beam lithography and dry etching using standard III-V processing techniques on the top membrane. The previous method of transfer in solution is highly impractical for waveguide-coupled disks, since the distance between the disk and waveguide is a critical parameter, and cannot be maintained in solution.

2.2 Amorphous silicon devices

Lastly we also developed an alternative material system for resonances in the near infrared. Amorphous silicon (a-Si) is deposited using plasma enhanced chemical vapor deposition with silane. The a-Si can be deposited directly on the YSO substrate, with devices patterned using electron beam lithography and etched with sulfur hexafluoride and octofluorobutane dry etch. The results of some of these fabricated devices are shown in Figure 2.

3. MEASUREMENT AND CHARACTERIZATION

3.1 Characterization setup

The devices are measured using a confocal microscope built for this purpose, where light from a supercontinuum source is coupled into an input port using a grating coupler, and transmission is measured via an output port. The input beam couples to the resonator, evanescently in the case of the disk and ring, and the light that does not couple is scattered out of an output grating at the other end of the waveguide. The coupling results in spectral feature in the transmission; fitting a Lorentzian distribution to this feature can be used to determine the quality factor. To increase the signal to noise ratio, a simple beam expander is used with a pinhole aperture at the focal plane to spatially filter the collected light, exclusively transmitting the transmitted light from the output grating; the geometry of this measurement as it pertains to the device is shown in Figure 3 (a).

3.2 Device characterization

Figure 3 (b) shows a transferred GaAs disk, while the undercut GaAs disk shown in Figure 3 (a) was measured to have the transmission spectrum shown in Figure 3 (c). The transmission dip at 927 nm is shown corresponds to a resonance with a quality factor of approximately 5500, which would be large enough to show interactions with the atoms were it on a YSO substrate.

The deposited a-Si was found to have transmission in the near infrared, supporting a ring resonator mode demonstrating a quality factor of 15000 at a wavelength of 856 nm. This surprisingly large band edge is believed to be the result of hydrogen incorporation during growth. This resonator is shown in Figure 2 (f), its mode is shown in Figure 2 (e), and the optical characterization of its resonance is shown in Figure 3 (d).

4. CONCLUSION

In conclusion, we have demonstrated the potential held by hybrid material systems for developing scalable optical platforms for coupling to rare earth ions in host materials. Improving quality factors marginally will allow the demonstration of coherent manipulation of the quantum state of the ion ensembles by the cavity field, and straightforward implementation of optical memory protocols.

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