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Frequency tunable electronic sources working at room temperature in the 1 to 3 THz band

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ABSTRACT

Compact, room temperature terahertz sources are much needed in the 1 to 3 THz band for developing multi-pixel heterodyne receivers for astrophysics and planetary science or for building short-range high spatial resolution THz imaging systems able to see through low water content and non metallic materials, smoke or dust for a variety of applications ranging from the inspection of art artifacts to the detection of masked or concealed objects. All solid-sate electronic sources based on a W-band synthesizer followed by a high-power W-band amplifier and a cascade of Schottky diode based THz frequency multipliers are now capable of producing more than 1 mW at 0.9THz, 50 μW at 2 THz and 18 μW at 2.6 THz without the need of any cryogenic system. These sources are frequency agile and have a relative bandwidth of 10 to 15%, limited by the high power W-band amplifiers. The paper will present the latest developments of this technology and its perspective in terms of frequency range, bandwidth and power.

Keywords: Schottky diodes, frequency multipliers, local oscillators, heterodyne receivers

1. INTRODUCTION

Progress toward solid-state sources at 1 THz was reported in 1996 with a record 250 μW of power at 800 GHz produced by a ×2×3 frequency multiplier chain pumped by a Gunn oscillator [1]. This result was important, as it provided impetus to build the Heterodyne Instrument for the Far Infrared (HIFI) on board the Far InfraRed Space Telescope which was eventually launched as the Herschel Space Observatory in 2009 [2], [3]. Herschel is a corner stone mission of the European Space Agency in collaboration with the National Aeronautics and Space Administration and provides unprecedented insight into the cold Universe.

Herschel has been an important driver for the development of THz sources, but, technologies developed for EOS-MLS onboard AURA [4], a satellite launched by NASA in 2004 to study the Earth's atmosphere, proved decisive for the THz local oscillator (LO) of HIFI. The most important one was the GaAs monolithic membrane-diode process used to fabricate the single-ended room-temperature Schottky mixer tuned at the frequency of the OH^+ line at 2.5 THz [5] (the LO was a FIR laser [6]). This membrane technology was later employed in the frequency multipliers of HIFI working up to 1.9 THz.

A decade of research and development was however necessary before a fully solid-state electronic LO could go beyond 1.9 THz and reach 2.7 THz, where a number of molecular lines of astrophysical interest lie, in particular the J=1-0 line of HD at 2675 GHz [7]. In the meantime, many other solutions to the generation of coherent waves in the 2-3 THz range have emerged, none of these, however, have led to the construction of a practical LO for heterodyne receivers in the 2.4-2.7 THz band.

A recent and extensive review of technology, capabilities, and performance of terahertz sources is given by G. Chattopadhyay in [8]. A large part of the paper is dedicated to electronic sources based on microwave oscillators followed by a combination of frequency multipliers and amplifiers. These solid-state sources are indeed inherently phase-lockable and frequency agile, are robust, work both at room temperature and cryogenic temperatures and use sufficiently low dc power to be the technology of choice for space-borne heterodyne instrument like HIFI.

Introduced in 2002, THz quantum cascaded lasers (QCLs) working at cryogenic temperatures are solid-state sources able to deliver several mW of continuous power [[9]] [[10]]. Though some THz QCLs have already been employed in the laboratory for pumping low-noise heterodyne receivers at a fixed frequency of 2.8 THz [[11]], a QCL-based LO suited for an airborne, balloon-borne or space-borne observatory is still to be demonstrated.

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Photo-mixers have also been developed for the purpose of building an LO in this frequency range. They have the advantage of being tunable over a large bandwidth, but are still limited to sub-microwatt levels at 2.5 THz and require cryogenic cooling [12]. A novel type of frequency-tunable photonic source was able to produce a power of 2 mW of at 1.9 THz and at room temperature [13]. However, this source requires hundreds of watts of optical power, which makes it useful only for some ground-based applications.

This paper will present post-Herschel 1.8-2.0 THz and 2.5-2.7 THz solid-state LO chains able to achieve power levels up to 60 μW at 1.94 THz and up to 18 μW at 2.58 THz at room temperature. These breakthrough results were first announced in [14]-[17]. The 2.5-2.7 THz source has also been employed for the spectroscopy of molecular gases like CH_3OH, H_2O and HD at ultra-high resolution and frequency accuracy [15]. It enabled measurements with an unprecedented signal to noise ratio and was notable for its ease of use. This source was also used as a local oscillator of a 2.7 THz Hot Electron Bolometer (HEB) mixer [[18]]. This article will present the design of theses frequency multiplied sources with an emphasis on the last stage frequency multipliers at 2.06 THz and 2.7 THz. It is noteworthy that other teams are also developing terahertz frequency-multiplied sources. Of particular interest is a recent result reported shortly after [14] was published of a source used as a local oscillator in a terahertz heterodyne receiver developed for radio astronomy. This source produced a peak power of 3μW at 2.56 THz and has been successfully flown onboard SOFIA [[19]].

2. DESIGN AND FABRICATION OF THE 2.06THZ AND 2.7 THZ FREQUENCY TRIPLERS

2.1 Design

The new 2.06 THz and 2.7 THz frequency triplers rely on the topology that has been successfully demonstrated onboard the Herschel Space Observatory. A detailed description of the design methodology of this type of frequency multipliers can be found in [20]-[22].

Both circuits are balanced, with two Schottky diodes in series at dc (see Fig. 1) that form a virtual loop to trap the second harmonic of the input signal and maximize the transfer of energy to the third harmonic, i.e. the output signal. An E-plane probe located in the input waveguide couples the input signal to a suspended microstrip line. This line is connected to a one-cell low-pass filter to prevent the third harmonic from leaking into the input waveguide. The third harmonic produced by the diodes is coupled to the output waveguide by a second E-plane probe. In order to balance the circuit, the dimensions of both the channel and the circuit are chosen to cut off all modes but the quasi-TEM mode at the second harmonic.

In practice, the balance of the circuits is imperfect and some parasitic power at the second harmonic might propagate outside the diode loop toward the circuit inside the channel in a quasi-TEM mode, like the third harmonic of the input signal. The dimensions of the output waveguides are therefore chosen to have a cutoff frequency below twice the highest frequency of the input signal, which ensures that the third harmonic of the input signal emitted respectively in the 1.8-2.0 THz band and the 2.5-2.7 THz band is not contaminated by any signal at the second harmonic. Though imperfect, the balanced geometry of the circuits ensures that power at the even harmonics of the input are efficiently suppressed, leaving the fifth harmonic as the dominant unwanted harmonic at the output. However, given the high order of multiplication and the high frequency, very little power is expected to be produced by the diodes at the fifth harmonic.

The input waveguides feature an impedance step, i.e. a reduction of the height, as part of the input-matching network. This is used to increase the bandwidth of the frequency multipliers without increasing the size of the micro-electronic circuits. The output waveguide of these new frequency multipliers, however, does not feature any such additional matching element and is directly connected to a diagonal feed horn.

2.2 Fabrication

The circuits were fabricated on a few-micron thin GaAs membrane. The 2.06 THz and 2.7 THz frequency triplers feature two sub-micron Schottky planar varactor diodes deposited on an epilayer of GaAs doped enough to mitigate the effect of carrier velocity saturation at high frequencies. The epilayer lies on top of a ~micrometer-thick mesa of heavily doped GaAs. The 2.06 THz and 2.7 THz tripler chips are mounted in a split-block waveguide, which includes an integral output diagonal feed-horn. The multiplier chip circuits are located between the input waveguide and the output waveguide, inside a channel. Four gold beam-leads located at the membrane corners suspend the chip in the channel. Two of these provide the required dc and RF connections for the diodes. Fig. 2 shows side-by-side photographs of Herschel-HIFI 1.9 THz frequency tripler and the new 2.06 THz frequency tripler at approximately the same scale. Fig.3 shows a schematic and a SEM picture of the 2.7 THz tripler.

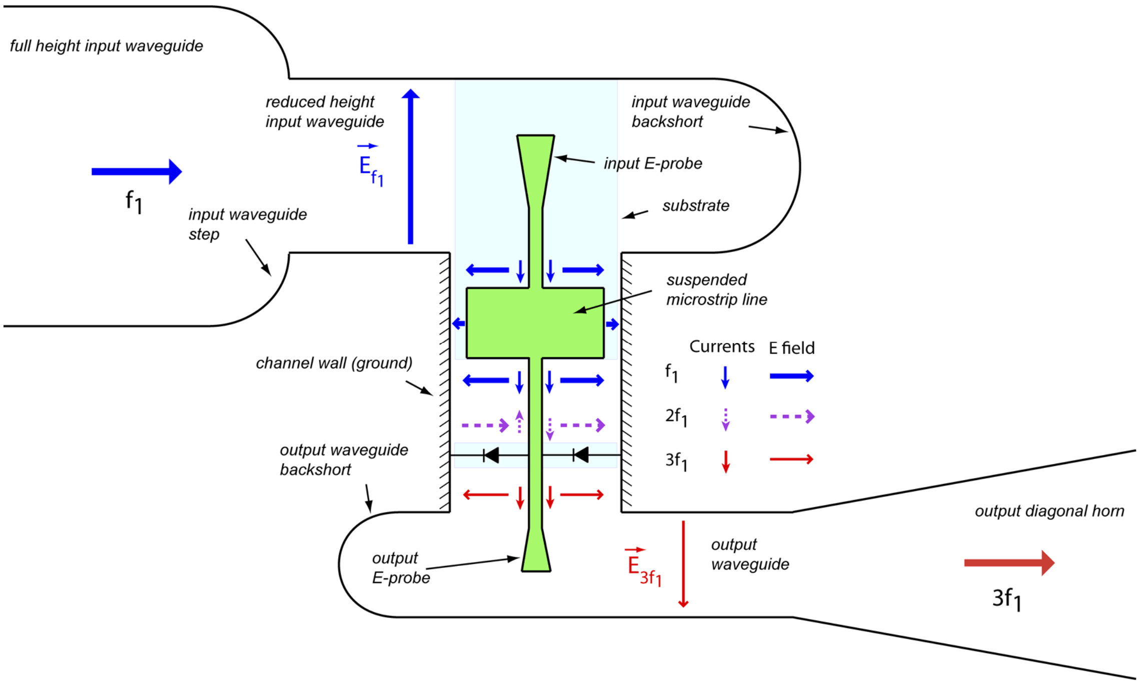

Figure1: Schematic of the 1.9 THz or 2.7 THz balanced tripler. Assuming a perfect balance between the diodes, the electric fields and the current lines are represented for the fundamental frequency f_1 (thick plain lines), the frequency $2\times f_1$ (dashed lines) and the output frequency $3\times f_1$ (light plain lines.) The input signal at f_1 and the output signal at $3\times f_1$ propagate on a quasi-TEM mode.

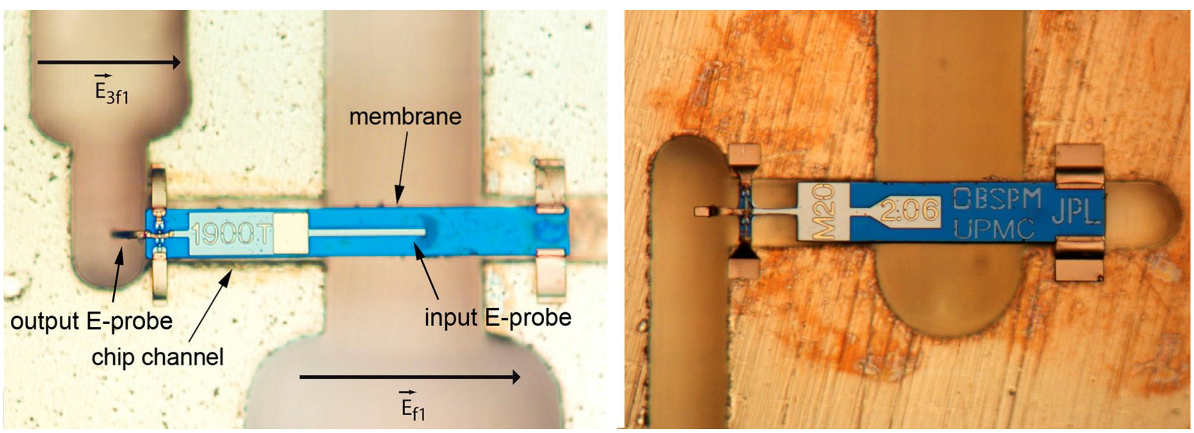

Figure 2: Photograph of HIFI-Herschel 1.9 THz frequency tripler (left) and JPL new 2.06 THz frequency tripler.

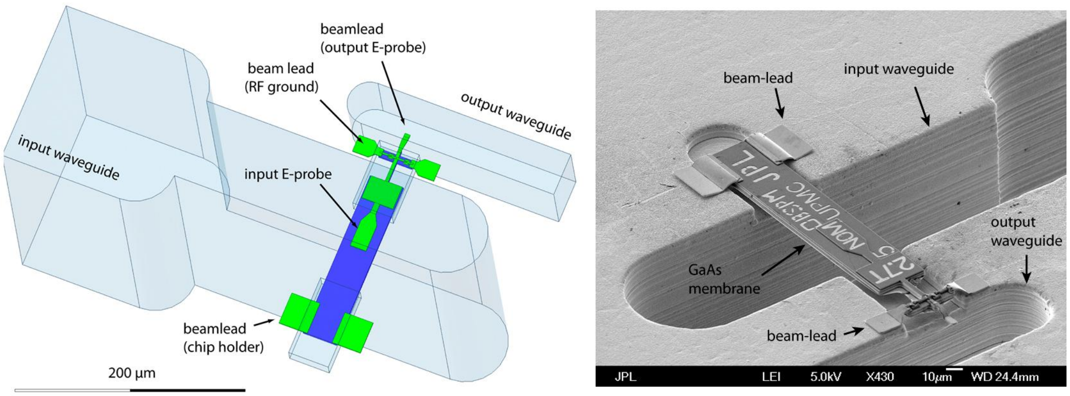

Figure 3: Schematic (left) and SEM picture (right) of the 2.7 THz frequency tripler

3. EXPERIMENTAL RESULTS

3.1 Driver stages

Two different driver chains were specifically designed to test the 2.06 THz and the 2.7 THz triplers. These chains were described in detail in [[17]] and [[16]] respectively. The first driver chain uses a ×2×3 multiplication scheme from F-band and delivers 0.9-1.8 mW in the 617-680 GHz band, while the second driver chain uses a ×3×3 multiplication scheme from W-band and delivers 0.25-1.0 mW in the 830-915 GHz band. The output frequency was set using an Agilent E8257C signal generator followed by either an active sextupler to W-band or a Ka-band amplifier followed by a F-band Schottky-diode based frequency tripler from Virginia Diode Inc. F-band and W-band GaAs-based power amplifiers with respectively 100-200 mW and 110-350 mW of output power, were used to pump the frequency multiplier driver chains.

3.2 Output power measurement

The output power was recorded using an Ericson-VDI PM4 power meter and a 25 mm-long WR10 rectangular to circular waveguide transition connected to the diagonal horn of the 2.06 THz and 2.7 THz frequency triplers. Part of the experiments were made in pure nitrogen atmosphere. For the most sensitive experiments in the 2.5-2.7 THz band, the power delivered by the Agilent E8257C signal generator was modulated at a slow frequency and the signal detected by the Erickson-VDI PM4 power meter was measured using a lock-in amplifier. The dynamic range of the PM4 power meter was extended by more than 10 dB and power levels lower than 100 nW could be measured (details can be found in [[16]].)

Fig.4 shows the output power versus frequency of the new 2.06 THz frequency tripler at room temperature and in air. To explore the low-end of the band, a different driver chain was built using parts of the Herschel-HIFI 1.9 THz LO chain. This multiplier produced an unprecedented 60 µW of output power at 1.95 THz and at room temperature. Power levels in excess of 20 µW were recorded in most of the 1.80-2.04 THz band. As these measurements were made in air, some absorptions lines may have affected the measurements. Fig. 5 shows the output power and the conversion efficiency versus input power of the 2.06 THz frequency tripler at 1.890 THz output frequency and at room temperature. The conversion efficiency reached almost 3% and peaked at about 0.6 mW of input power.

Two 2.5-2.7 THz LO chain were fabricated and tested. For both chains, two sets of power measurements were recorded, one in a pure nitrogen atmosphere and one in an atmosphere including water vapor. This way, the H_2O absorption lines at 2.5319 THz and at 2.6404 THz provide independent confirmation of the output frequency. Fig. 6 shows that both chains achieved unprecedented output power levels and bandwidth for an electronic source working in this frequency range at room temperature. Both chains delivered powers in excess of 1 µW across the full band. The multiplier chain identified as SN4 delivered a peak of 8 µW at 2.59 THz and delivered 4 µW or more in the 2.49-2.69 THz band. The source labeled SN6 delivered a peak of 14 µW at 2.58 THz and 4 µW or more in the 2.49-2.67 THz band. It can be seen that power in this frequency range should be measured in a dry atmosphere or in vacuum, as strong absorptions were observed for a path of only about 5 cm in air.

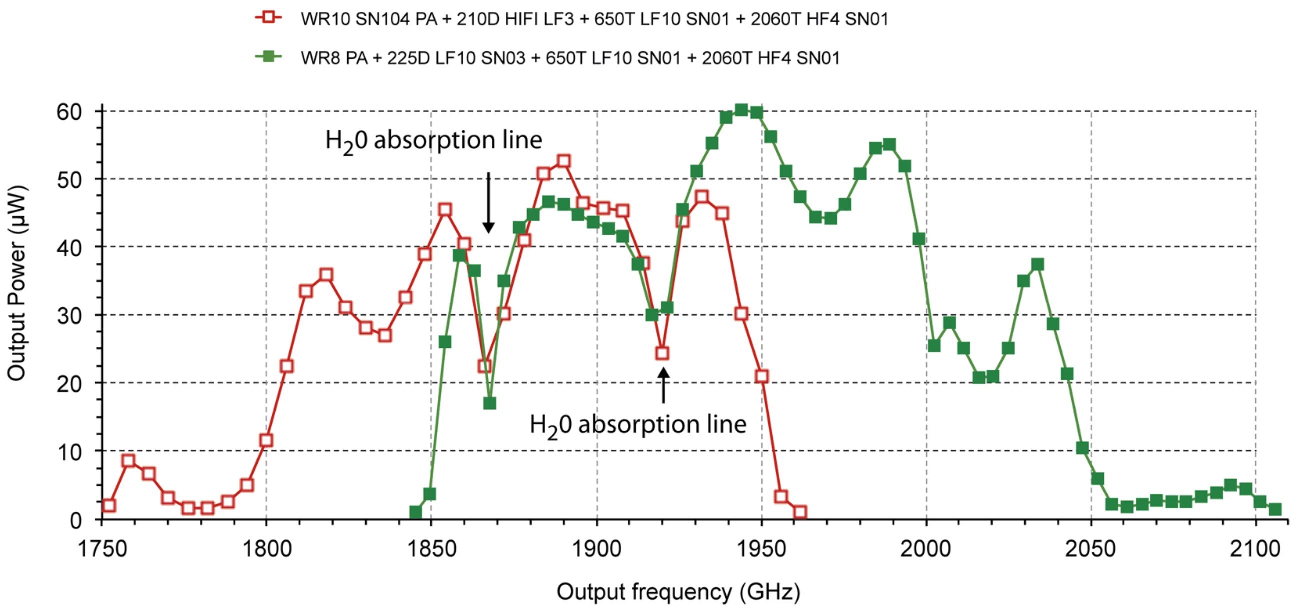

Figure 4: Output power versus frequency of the new JPL 1.8-2.0 THz LO chain at room temperature and in air. Two different driver stages are used to explore the full bandwidth of the 2.06 THz tripler.

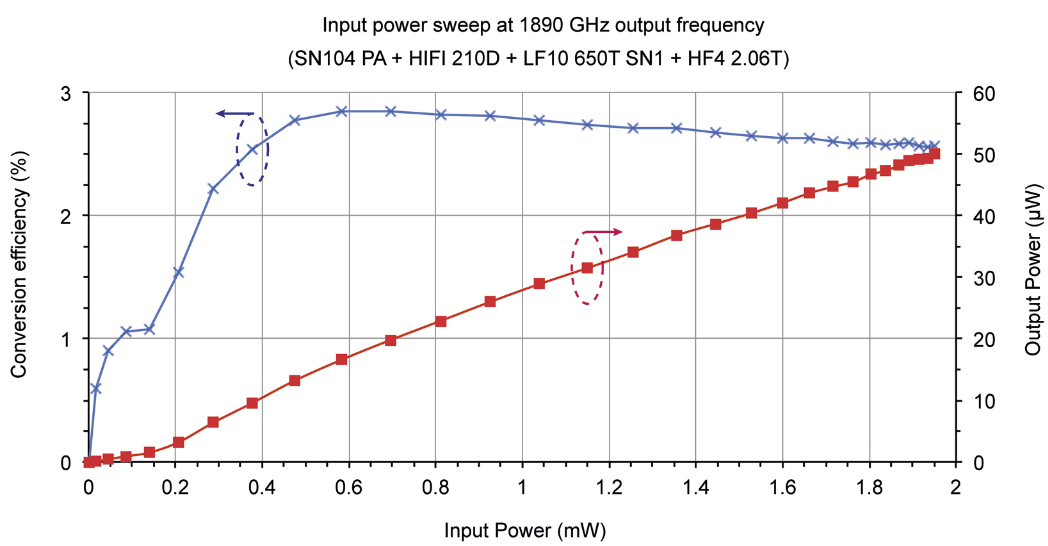

Figure 5: Output power versus input power at 1.890 THz output frequency of the new JPL 1.8-2.0 THz LO chain at room temperature and in air.

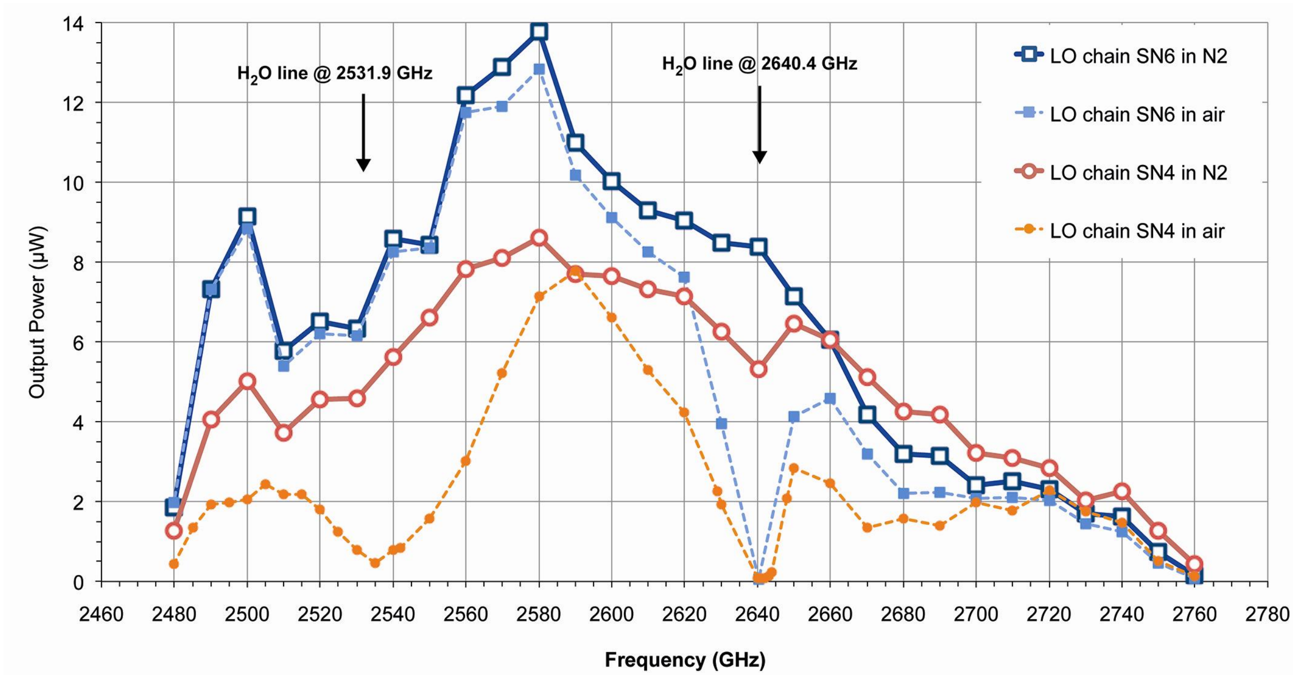

Figure 6: Output power versus frequency at room temperature of JPL 2.7 THz source SN6 in a pure nitrogen atmosphere (top thick curve with open square markers), and in a nitrogen atmosphere with a slight amount of water vapor (top dashed curve with filled square markers.) Output power versus frequency at room temperature of JPL 2.7 THz source SN4 in a pure nitrogen atmosphere (middle thick curve with open circle markers), and in a laboratory atmosphere (bottom dashed curve with filled circle markers.)

3.3 Spectral purity

The spectral purity of the 2.7 THz source SN6 was measured from about 10 GHz to 6 THz using a Fourier Transform Spectrometer with 100 MHz resolution. Scans at different frequencies across the band at room temperature have been performed. Fig. 7 (left) shows the measured response at 2.695 THz, near the astrophysically-significant HD line at 2.675 THz. The graph is normalized to the peak power that corresponds to the 27^{th} harmonic of the input frequency f_0 at W-band. It can be seen that the chain has excellent spectral purity with spurious and undesired harmonics below -29 dB with respect to the main signal. Note that the strong signal at exactly twice the frequency of the main signal is an artifact due to aliasing in the FTS. Other signals with unexplained origins were also detected in the scans.

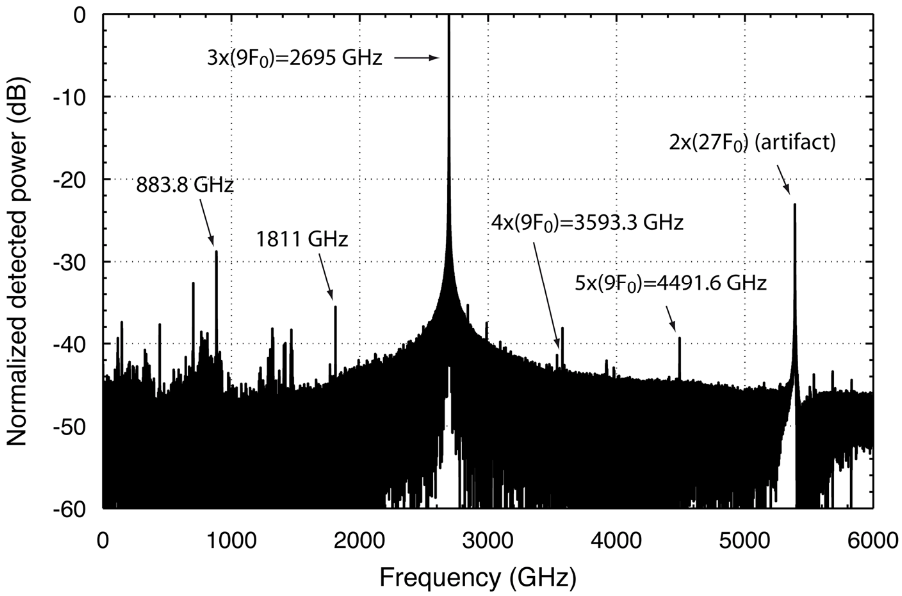

Figure 7: FTS spectrum of the 2.5-2.7 THz source tuned at 2695 GHz.

4. CONCLUSION

The results presented in this work for the 2.5-2.7 THz chain indicate that this frequency range can easily be covered with the HIFI style versatile and broadband multiplier sources. Given the tremendous progress of high power GaN amplifiers [23], THz HEMT transistors [24],[25] or even CMOS amplifiers below 1 THz [26], it is predictable that the first and then the second stage of the present LO chain will be replaced in the coming years by transistor-based high-power drivers, much like the W-band Gunn oscillator was progressively replaced during the past decade by W-band synthesizers followed by W-band amplifiers. THz Schottky diode-based frequency multipliers will then reveal their full potential, being driven by power levels in the 3-10 mW range, where non-linearities can be better exploited for higher conversion efficiencies. Moreover, advanced power-combined techniques [27], [28] coupled with advanced micro-machining of waveguide blocks [29] could dramatically improve the power handling capabilities of THz frequency multipliers and subsequently their output power.

Based on the present results, and the potential offered by amplifiers, a fully solid-state electronic source working up to 4.7 THz at room temperature is now feasible. It would use both three-terminal and two-terminal THz devices in three-dimensional waveguide structures made out of silicon. While such an electronic source will never deliver power levels comparable to those produced by QCLs, it would offer, incomparable frequency agility and versatility and provide at least enough power to sufficiently pump a single HEB mixer.

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