Design and Characterization of a Room Temperature All-Solid-State Electronic Source Tunable From 2.48 to 2.75 THz

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***Abstract*—We report on the design, fabrication and test of an all-solid-state, frequency agile source that produces over 1 μW (-30 dBm) across the 2.48–2.75 THz band at room temperature. This frequency-multiplied source is driven by a W-band synthesizer followed by a power amplifier that delivers 350–450 mW (25.5–26.5 dBm) and a cascade of three balanced frequency triplers. The first stage tripler is based on four power-combined six-anode GaAs Schottky diode devices, and the second stage tripler is based on two four-anode GaAs devices. The output tripler uses a single unbiased device featuring two anodes monolithically integrated onto a thin GaAs membrane. The source delivers a record 18 μW (-17.5 dBm) at 2.58 THz at room temperature. This frequency multiplied source is analyzed with a Fourier transform spectrometer (FTS) and the unwanted harmonics are found to be at least 29 dB below the desired signal. This source, when used as the local oscillator for a hot-electron bolometer mixer, will enable heterodyne instruments for future space missions to map the cosmologically-important 2.675 THz HD molecular line.**

***Index Terms*—Broadband terahertz (THz) source, frequency multiplier, frequency tripler, local oscillator, planar diode, power-combining, Schottky diode, THz, varactor.**

I. INTRODUCTION

THE 2–3 THz frequency range lies in the “terahertz gap,” namely, a frequency range that has been historically too high for electronic devices and too low for photonic devices. A major reason for the lack of instrumentation in this regime is the dearth of terahertz sources. Electronic sources for the Heterodyne Instrument for the Far Infrared (HIFI) onboard the Herschel Space Observatory (launched in 2009) [1], [2], work up to 1.9 THz using W-band power amplifiers driving planar Schottky diode frequency multipliers. Herschel, now stationed 1.5 million kilometers from Earth, provides valuable high-resolution spectroscopic observations of the cold Universe [3], [4]. Herschel provided a strong impetus towards the development of broadband terahertz sources. However, due to the immaturity of local oscillator (LO) technology, it does not include a 2.5–2.7 THz channel in its suite of receivers, which was highly desired to observe the $J = 1 - 0$ rotational spectral line of HD at 2.675 THz [5].

Electronic sources based on microwave oscillators followed by a combination of frequency multipliers and amplifiers are inherently phase-lockable and frequency agile, are robust, work both at room temperature and cryogenic temperatures and are sufficiently efficient to be the technology of choice for local oscillators of heterodyne instruments [6]. However, limitations including low output power and (until now) low technology readiness level have led to the development of a variety of alternate terahertz source technologies.

Introduced in 2002, terahertz quantum cascaded lasers (QCLs) are solid-state sources able to deliver several milliwatts of continuous wave (CW) power [7]. Though terahertz QCLs have already been employed in laboratories for pumping low-noise heterodyne receivers at a fixed frequency of 2.8 THz [8], QCLs only operate at cryogenic temperatures, frequency tuning is severely limited, and consequently, a QCL-based LO suitable for an airborne, balloon-borne or space-borne observatory has not been demonstrated. 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 [9]. A novel frequency-tunable photonic source, based on shining two lasers onto a non-linear crystal, was able to produce 2 mW at 1.9 THz at room temperature [10]. However, this source requires hundreds of watts of optical power, which makes it useful only for some ground-based applications.

We describe herein the first demonstration of a 2.48–2.75 THz solid-state source that produces power levels of several microwatts at room temperature. This source has already been extensively used in the laboratory for high resolution spectroscopy of molecular gases like CH_3OH, H_2O and HD at ultra-high resolution and frequency accuracy [11]. It enabled measurements

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with an unprecedented signal to noise ratio and was notable for its ease of use. This paper presents the design of this frequency multiplied source with an emphasis on the last stage frequency multiplier at 2.7 THz. Various test setups that were utilized to characterize the source power versus frequency and its spectral purity will also be discussed.

It is noteworthy that other teams are also developing terahertz frequency-multiplied sources. Of particular interest is a recent result reported shortly after [11] 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 3 μW at 2.56 THz and has been successfully flown onboard SOFIA [12].

II. Design and Fabrication

This section will discuss in detail the key new element of the 2.7 THz source: the last stage frequency tripler.

A. Balanced Design, Conversion Efficiency and Spectral Purity

The last stage frequency multiplier relies on the topology that has been successfully demonstrated up to 1.9 THz onboard the Herschel Space Observatory. The circuit is 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. This topology offers the advantage of a very small phase shift between the two anodes and the possibility to tune the matching at the second harmonic by adjusting the length of the beam-leads that ground the diodes and by adjusting the cross section of the channel where the chip is mounted. 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 the TE-mode at the second harmonic. A detailed description of this type of tripler has been presented previously [13]–[15]. The dimensions of the output waveguide are chosen to cut off any signal below 2 THz, which ensures that the third harmonic of the input signal emitted in the 2.48–2.75 THz band is not contaminated by any signal at the fundamental or second harmonic. Note that in practice, due to an imperfect balance, 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. Though imperfect, the balanced geometry of the circuit 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. Fortunately, 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.

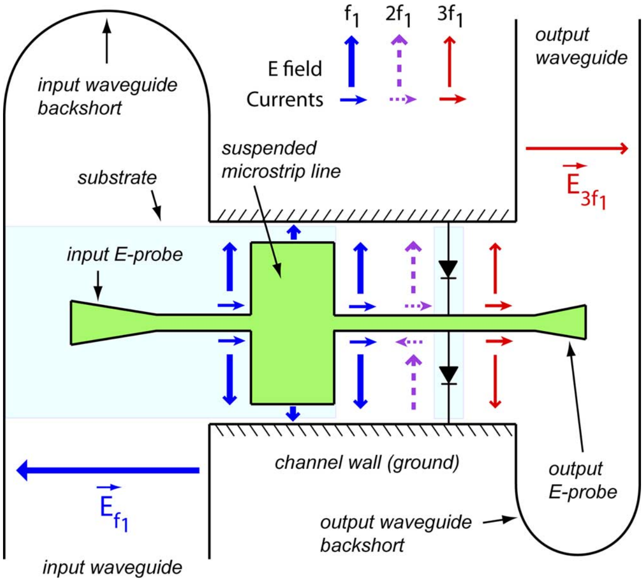

Fig. 1. Schematic of the 2.7 THz final stage balanced tripler. Assuming a perfect balance between the diodes, the electric fields and the current lines are represented for the fundamental frequency f_1 (thick plain lines), the frequency $2 \times f_1$ (dashed lines) and the output frequency $3 \times f_1$ (light plain lines.) The input signal at f_1 and the output signal at $3 \times f_1$ propagate on a quasi-TEM mode.

B. Device and Circuit Models

The design of Schottky diode based frequency multipliers beyond 2 THz becomes very challenging due to the size of the chip and the waveguide dimensions required for the proper impedance matching of the multiplier circuit. In addition, limited available input power necessitates precise modeling of both the Schottky diode and the matching circuit in order to drive the diodes into their nonlinear regimes [16]. Based on results obtained from the 900 GHz driver stage [17], the design of the 2.7 THz tripler was optimized for about 1 mW of input power. The general design method presented in [13] and [17] was applied. It is iterative and consists in decomposing the multiplier structure in several blocks that are analyzed separately with Ansys High Frequency Structure Simulator (HFSS)[1]. The S-parameters corresponding to the different blocks are included in a custom non-linear circuit model implemented in Agilent Advanced Design System (ADS)[2]. The harmonic balance simulator of ADS is then used to predict the performance of the frequency multiplier in terms of input matching, conversion efficiency, and output power. Fig. 2 shows the complete HFSS 3D model of the 2.7 THz frequency tripler.

The 2.7 THz frequency tripler features two Schottky planar varactor diodes with nominal anode area of around 0.15 $\mu\mathrm{m}^2$ deposited on an epilayer of GaAs doped enough (typically $> 2 \times 10^{17} \mathrm{cm}^{-3}$) to mitigate the effect of carrier velocity saturation at high frequencies. The epilayer lies on top of a $\sim \mathrm{micrometer} - \mathrm{thick}$ mesa of heavily doped GaAs ($> 1 \times 10^{18} \mathrm{cm}^{-3}$). The nonlinear response of the diodes is simulated using the standard model available in ADS adjusted for the junction capacitance, with other parameters estimated using the classic equations found in [18]. In addition, to account for fringe effects in the junction capacitance, a correction factor was included in the model [19]. An approximate value for the series resistance is calculated assuming that the epilayer of the diodes is fully depleted at the optimum operating condition and that the actual path of the current flow is equivalent to a

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[1] HFSS, Ansys Inc., Pittsburg, PA.

[2] ADS, Agilent Technologies, Palo Alto, CA.

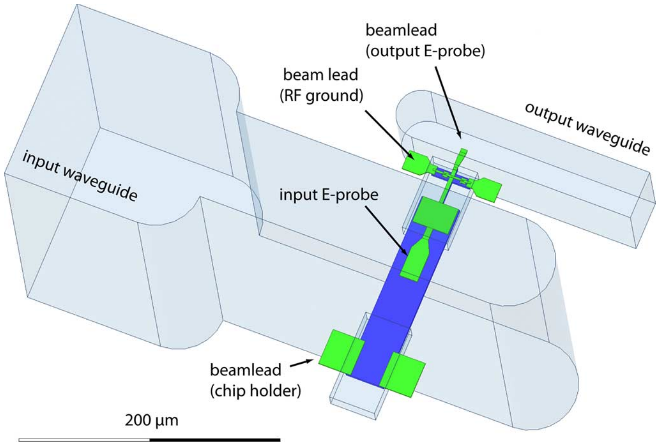

Fig. 2. Ansys HFSS 3D model of the 2.7 THz balanced frequency tripler.

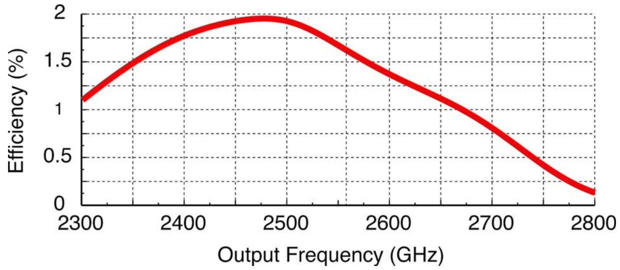

Fig. 3. Predicted performance of the 2.7 THz Schottky diode tripler for a flat input power of 1 mW across the band.

vertical path through the thin n$^+$-layer (the ohmic contact resistance was considered small enough to not have any significant impact). This yields a series resistance of around 50 Ω using the mobility-field characteristics of n-doped GaAs [18] and the analytical equations in [20]. This value gives a good estimate of the achievable peak efficiency.

The simulated performance of the 2.7 THz tripler is shown in Fig. 3. Realistic metal losses have been accounted for in the simulations by including high-frequency gold conductivities as indicated in [21] ($\sigma \sim 1 \cdot 10^7$ S/m for evaporated gold and $\sigma \sim 2 \cdot 10^7$ S/m for electroplated gold). An efficiency of 1.6% over a 15% 3-dB bandwidth was predicted for a flat input power of 1 mW.

C. Fabrication

The 2.7 THz tripler chip is mounted in a split-block waveguide, which includes an integral 2.7 THz output diagonal feedhorn. The multiplier chip circuit is located between the input waveguide and the output waveguide, inside a channel with approximately 40 × 15 μm^2 cross-section. 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. The input waveguide features a single waveguide matching section to optimize the bandwidth. A detailed SEM image of the completed chip mounted inside the waveguide half-block is shown in Fig. 4.

III. MEASUREMENTS

Two 2.7 THz tripler blocks were machined and assembled. Both were tested with a 900 GHz driver chain described in [17]. The driver chain consists of a W-band synthesizer followed by a power-combined W-band amplifier module, followed by a power-combined quad-chip 300 GHz frequency tripler based on [22], followed by a power-combined dual-chip 900 GHz frequency tripler. When pumped with 330–500 mW (25–27 dBm) at W-band, the pair of frequency triplers delivers more than 1 mW in the 840–900 GHz band at room temperature. However, for most of the data presented in this paper the input power at W was limited at a flat 350 mW (25.5 dBm) and the power delivered by the driver chain was in the range 0.25–1 mW (−6 dBm to 0 dBm).

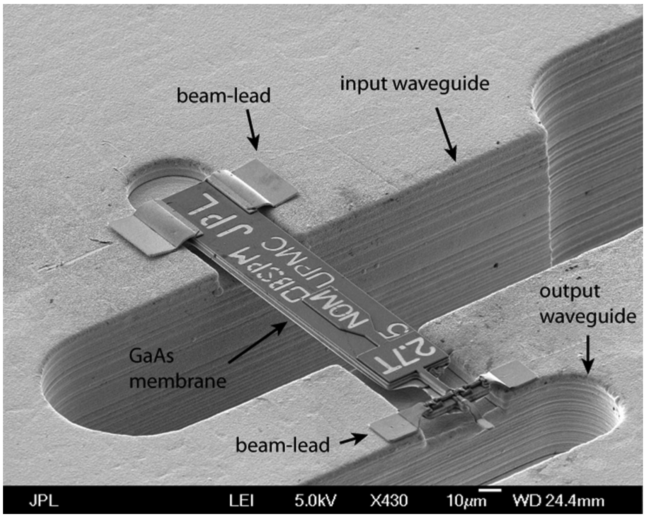

Fig. 4. SEM image of the 2.7 THz balanced frequency tripler chip mounted on the bottom half of the waveguide block.

A. Power Measurement Test Setup

The output power was measured with a VDI-Erickson PM4 power meter. A 25 mm-long circular to WR-10 rectangular waveguide transition was used to couple power to the meter. This power meter has the advantage of waveguide coupling that shields the measurement from any radiation leaked at lower frequencies. The WR-10 input waveguide is oversized for terahertz frequencies, so a small terahertz horn radiates into it and the beam couples to the sensor with minimal interaction with the waveguide walls. This type of sensor can be easily calibrated at W-band, and a cross-comparison with Thomas Keating power meters showed good agreement (within 1 dB or less) at 1 THz.

To minimize attenuation by water vapor, the frequency multiplier chain and the VDI-Erickson power meter were placed in a vacuum chamber that was purged and then filled with pure nitrogen gas at a pressure of 80 kPa. The output power was first recorded by the PM4 power meter set on the 2 mW scale with a calibration factor of 100%, and later corrected by a factor of 1.15 (0.6 dB) to take into account the RF losses of the 25-mm-long internal WR10 waveguide and of the circular to rectangular waveguide transition [23].

The output power of the multiplier chain was electronically modulated to cancel the effects of drift of the Erickson PM4 power meter. A lock-in amplifier was used to record the voltage at the analog output of the power meter. A calibration of the output voltage versus RF power was performed at various power

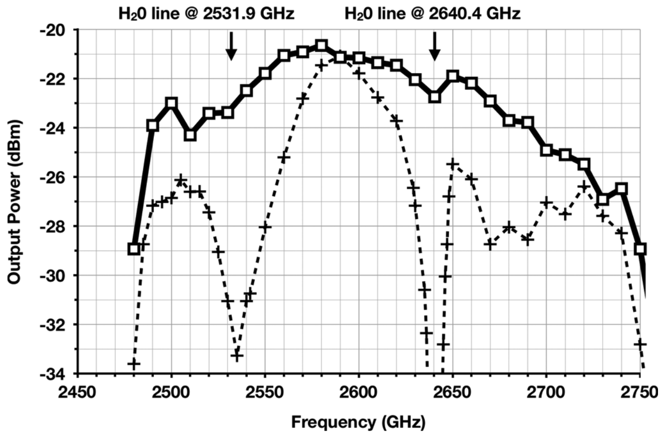

Fig. 5. Output power versus frequency at room temperature of JPL 2.7 THz source SN4 in a pure nitrogen atmosphere (top thick curve with square markers), and in a laboratory atmosphere (bottom dashed curve with cross markers).

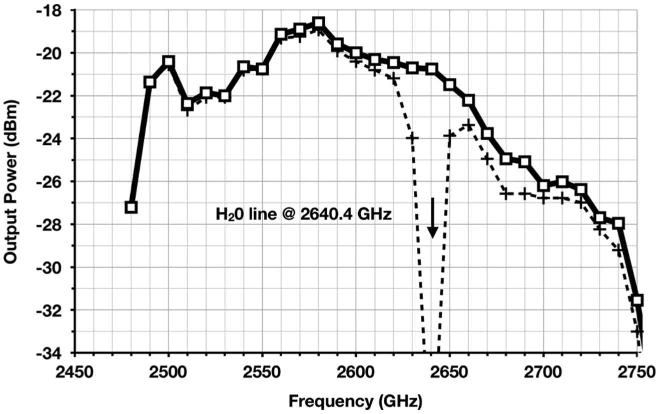

Fig. 6. Output power versus frequency at room temperature of JPL 2.7 THz source SN6 in a pure nitrogen atmosphere (top thick curve with square markers), and in a nitrogen atmosphere with a slight amount of water vapor (bottom dashed curve with cross markers).

levels in the range 5–200 μW (-23 dBm to -7 dBm) using a reference source at W-band and a precision attenuator. The calibration consisted in comparing the reading of the PM4 meter with no modulation to the output voltage of the lock-in amplifier when the modulation to the RF signal was applied. The linearity of the measurement system was checked down to power levels as low as 100 nW (-40 dBm) by attenuating the W-band source. Integration times of several minutes were necessary to record such low power levels.

The ratio between the detected RF power and output voltage of the lock-in amplifier does not depend on the RF frequency, it depends only on the time constant of the detector/power meter, modulation frequency, and settings on the lock-in amplifier itself. This method was double-checked at 2.7 THz when power levels exceeding 5 μW (-23 dBm) were directly recorded on the PM4 power-meter with no modulation applied.

B. Frequency Sweep

Two different frequency multiplier chains were tested across the 2.48–2.75 THz band. The bias voltage applied to the 300 GHz stage was fixed at -12 V in all the measurements presented in this paper, and the voltage applied to the 900 GHz stage was set at -2 V for frequencies above 2.54 THz and optimized in the -1 V to -0.2 V range for frequencies in the 2.48–2.54 THz band. The input power at W-band was held constant at 350 mW (25.5 dBm) for frequencies above 2.53 THz and rolled off below 2.53 THz to 155 mW at 2.48 THz. The frequency was set on an Agilent E8257D synthesizer connected to an Agilent 83558A W-band source module (a sextupler). The total frequency multiplication factor was 162.

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. Figs. 5 and 6 show 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 (-30 dBm) across the full band.

The multiplier chain identified as SN4 (Fig. 5) delivered a peak of 8 μW (-21 dBm) at 2.59 THz and delivered 4 μW (-24 dBm) or more in the 2.49-2.69 THz band. The source labeled SN6 (Fig. 6) delivered a peak of 14 μW (-18.5 dBm) at 2.58 THz and 4 μW (-24dBm) 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.

C. Power Sweep

The input power at W-band of the source SN6 was swept from 110–450 mW (20.5–26.5 dBm) at the fixed frequency of 2.58 THz (see Fig. 7). A record output power of 18 μW (-17.5 dBm) was measured. From Fig. 7 it can be seen that the maximum conversion efficiency of this chain peaks at 4×10^{-5} (-44 dB) for 350–400 mW (25.5–26 dBm) of input power. The saturation of the conversion gain is due to the saturation of the two first stages of the chain, especially the first stage. In particular, the conversion gain of the first tripler (to 300 GHz) is expected to be maximized around 110 mW (20.5 dBm) of input power based on the data presented in [21]. From 110 to 350 mW (20.5–5 dBm) of input power at W-band, the decrease of the conversion gain of the first stage multiplier is compensated by an increase of the conversion gain of the subsequent stages.

D. Wide-Band FTS Scans

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. 8 shows the measured response at two frequencies of interest, i.e., at 2.580 THz (with peak output power) and near the astrophysically-significant HD line at 2.675 THz. The multiplied source spectral purity is remarkably good with all high frequency spurious signals and undesired harmonics below -29 dB with respect to the main signal.

E. Spectral Analysis Near Carrier Frequency

The spectrum of the output signal was analyzed with an Anritsu MS2724B spectrum analyzer and an external bias-able 900 GHz Schottky fundamental balanced mixer [24] used as

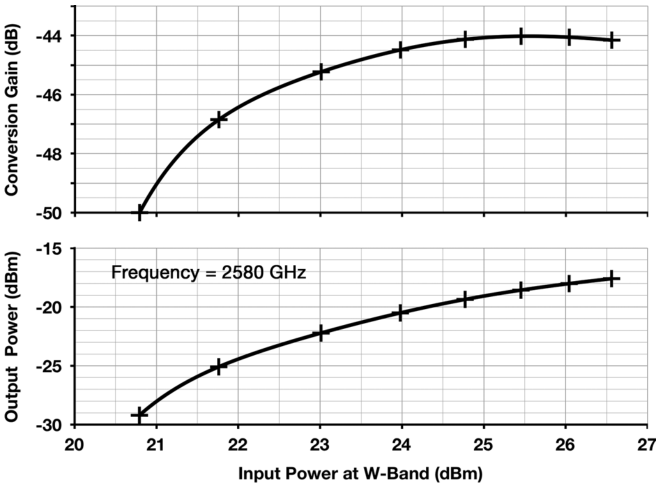

Fig. 7. Conversion gain (top) and output power (bottom) versus input power at W-band at room temperature of the SN6 2.7 THz source in a pure nitrogen atmosphere.

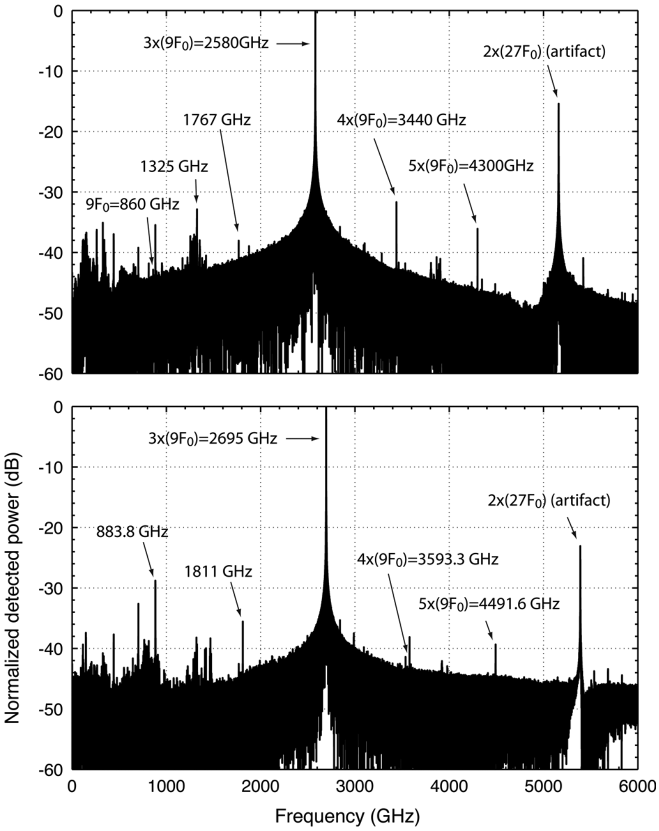

Fig. 8. FTS scans with 100 MHz resolution of the 2.7 THz source SN6 at 2.58 THz (top) and 2.695 THz (bottom). For each scan the graph is normalized to the peak power that corresponds to the 27th harmonic of the input frequency f_0 at W-band. It can be seen that the chain has excellent spectral purity 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 some scans.

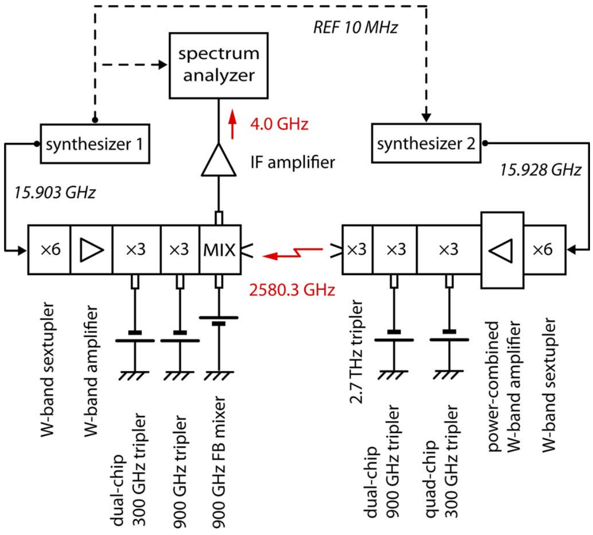

Fig. 9. Diagram of the 2.7 THz coherent transceiver showing the 900 GHz fundamental balanced mixer and its local oscillator (left) and the 2.7 THz source (right).

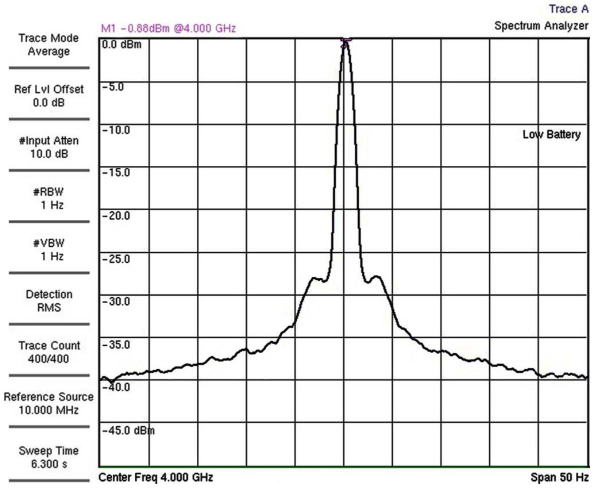

Fig. 10. Spectrum of the beat signal of the RF signal at 2.5803 THz for an IF of 4.0 GHz, a span of 50 Hz, and a 1 Hz resolution bandwidth.

a third-order subharmonic mixer at 2.7 THz. The frequency multiplier chain output beam was directly coupled to the 900 GHz mixer input horn with an air gap of about 0.5 mm between the horn apertures. Fig. 9 shows the test configuration. The two synthesizers and the spectrum analyzer were all locked to a single 10 MHz quartz oscillator.

The mixer LO chain consisted of an Agilent E8257C synthesizer featuring the ultra-low phase-noise UNR option, an Agilent 83558A W-band source module followed by a W-band power amplifier, a dual-chip 300 GHz frequency tripler and a single-chip 900 GHz frequency tripler. The IF was set at 4.0 GHz and a low-noise preamplifier was used between the mixer and the spectrum analyzer.

Figs. 10 and 11 show the recorded spectrum of the IF signal at 4.0 GHz for an RF of 2.5803 THz with a resolution bandwidth of 1 Hz and spans of 50 and 200 Hz, respectively. At an offset of 10 Hz, the measured phase noise was -35 dBc, and at an offset of 100 Hz the measured phase noise was -40 dBc.

With a common reference signal at 10 MHz, the recorded spectrum at the IF was affected by a partial cancellation of the phase noise, so the real spectrum of the 2.7 THz source could

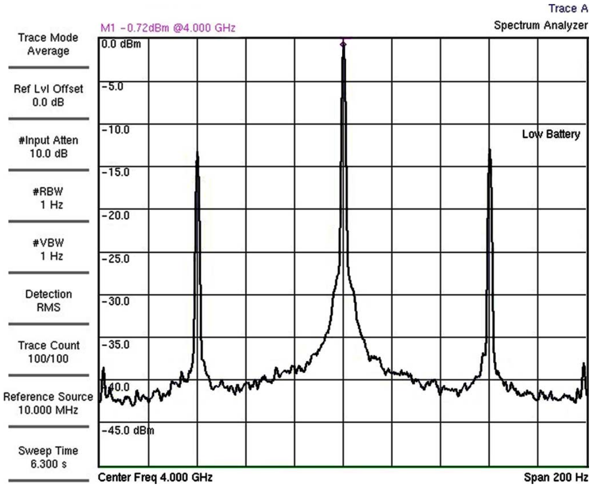

Fig. 11. Spectrum of the beat signal of the RF signal at 2.5803 THz for an IF of 4.0 GHz, a span of 200 Hz, and a 1 Hz resolution bandwidth. The spectrum shows a modulation at 60 Hz.

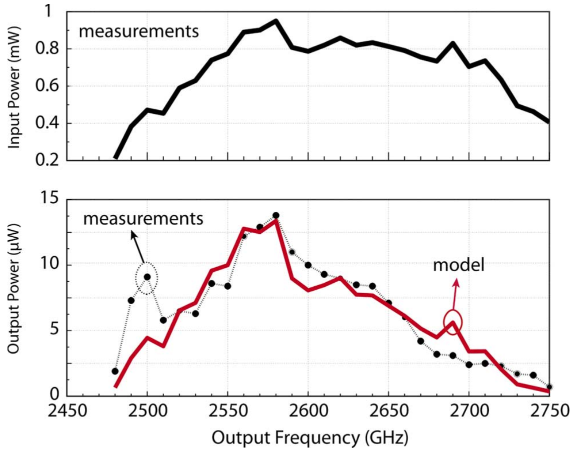

Fig. 12. Measured performance of the 2.7 THz source SN6 (bottom) compared to simulations of the final frequency tripler (bottom) accounting for the measured available input power in the 823–917 GHz band (top).

not be directly derived from this experiment. However, the documentation for the better of the two synthesizers specifies phase noise of -70 dBc at 10 Hz from the carrier and -87 dBc at 100 Hz for an output signal at 10 GHz [25]. Given a multiplication factor of 270 between 10 GHz and 2.7 THz, these values are expected to be degraded by 48 dB to become -22 dBc at 10 Hz from the carrier and -39 dBc at 100 Hz from the carrier. In other words, according to our measurements, the multiplier chain does not introduce more phase noise in the 1–100 Hz band than the natural degradation of $20 \times \log_{10}(N)$, where N is the order of multiplication. At 10 Hz we actually measured less noise due to the correlation between the two LO sources. This is an indication that when using an ultra-low noise commercial synthesizer, the line at 2.7 THz should not collapse and should stay coherent [26]. We note spurious signals at 60 Hz offsets at -12 dBc. Although no detailed investigations were carried out to determine their exact origin, they are likely to be from power line pick up.

IV. COMPARISON OF SIMULATIONS AND MEASUREMENTS

The predicted performance shown in Fig. 3 assumed a constant input power of 1 mW to the last stage tripler across the band. However, the actual power provided to this tripler is between 0.2–0.95 mW in the 815–915 GHz band (see Fig. 12, top graph). This leads to a decrease in the efficiency and bandwidth compared to the predicted performance since the multiplier is under-pumped. Fig. 12 shows a comparison between the measurement of the JPL 2.7 THz source SN6 (black dots) and simulation (heavy line) that take into account the actual measured input power of the 2.7 THz frequency tripler. The agreement between simulations and measurements is excellent except around 2.5 THz, where a resonance is observed, possibly the result of an interaction between the driver stage and the final tripler.

V. CONCLUSION AND PERSPECTIVE

We have demonstrated the first ever electronically tunable solid-state source in the 2.4 to 2.7 THz range. This source, based on power amplifiers and power-combined frequency multiplier chips, is compact and spectrally clean, making it suitable to use for high resolution spectroscopy, among other applications. Furthermore, extensive use in the JPL spectroscopy lab has confirmed that this source is both robust and easy to use. Given the tremendous progress of high power GaN amplifiers [27], terahertz HEMT transistors [28], [29] or even CMOS amplifiers below 1 THz [30], it is predicted that the first and then the second stage of the present source will be augmented in coming years by transistor-based high-power drivers, much like the W-band Gunn oscillator was replaced during the past decade by W-band synthesizers followed by W-band amplifiers. Terahertz Schottky-diode-based frequency multipliers will then reveal their full potential, being driven by power levels in the 3–10 mW range, where nonlinearities of the semiconductor devices can be better exploited for higher conversion efficiencies. Moreover, advanced power-combined techniques [31], [32] coupled with advanced micro-machining of waveguide blocks [33] could dramatically improve the power handling capabilities of high frequency multipliers and consequently their output power. Based on these considerations, the authors believe that a fully solid-state electronic source working up to 4.7 THz at room temperature is feasible. While such an electronic source will not deliver power levels comparable to those produced by QCLs, it would offer incomparable frequency agility and versatility as well as the potential to pump hot-electron bolometer mixers to enable the heterodyne detection of the astrophysically-important OI line at this frequency.

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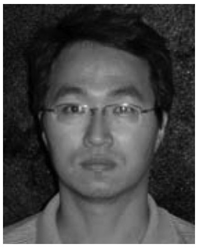

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