Tunable Broadband Frequency-Multiplied Terahertz Sources

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***Abstract*—Continued advances in Schottky diode frequency multiplier technology enable solid-state submillimeter-wave and terahertz sources with higher output power tunable over broader bandwidths than have been previously demonstrated. For example, 630 µW of continuous-wave power were measured at 900 GHz at room temperature and 1.4 mW at 920 GHz from the same frequency multiplier chain when cooled to 77 K. The 3 dB bandwidth of this chain is about 100 GHz. Simulations predict that an additional tripler driven by this new 900 GHz tripler chip could produce 1 to 2 µW at 2.7 THz when operated at 77 K, which is sufficient to pump a superconducting heterodyne mixer. We present these recent results as well as summarize the current state-of-the-art of JPL frequency multiplied sources. Finally, we review the limitations of our current generation of frequency multipliers to predict that future advances in amplifier and diode technology should enable at least a ten-fold increase in available tunable output power from solid state frequency-multiplied sources.**

I. Introduction And Background

Submillimeter-wave sources based on chains of planar GaAs Schottky diode frequency multipliers were developed over the past decade for use as the local oscillators of heterodyne detectors for astrophysics instruments [1-3]. These sources use microwave oscillators followed by cascaded amplifiers and frequency multipliers to provide moderate continuous-wave (CW) power ranging from tens of milliwatts at 200 GHz to tens of microwatts at 1.9 THz, with electronically-tunable bandwidths typically in the 10% to 15% range. These sources are a fundamental building-block for terahertz electronics, and can be expected to be used in a wide range of applications as the terahertz gap is finally closed.

II. Results

A new generation of electronically-tunable frequency multipliers developed at JPL for the 200 GHz to 1 THz band was optimized to better take advantage of the high power available from driver amplifiers, i.e., up to 500 mW in the 70 to 113 GHz band [4]. These designs feature increased total Schottky anode areas to offer substantially increased maximum output power compared to previous generations of devices, and simultaneously employ improved architectures to offer large bandwidths (up to 25%) and improved conversion efficiencies. In addition to these incremental improvements, the maximum power at 300 GHz was further doubled by combining two GaAs chips in a single tripler block using a pair of integrated waveguide Y junctions [5]. This power-combined tripler achieves both state-of-the-art conversion efficiency and high power over a bandwidth of at least 20%.

Results for a variety of JPL multiplier chains measured at room temperature are shown in Figure 1. Figure 2 shows measured output power for cooled multiplier chains. Figure 3 shows a frequency tripler that uses four anodes in a balanced configuration that, when driven with the dual-chip 300 GHz tripler discussed above, produces 630 µW of CW power at 900 GHz at room temperature, and 1.4 mW at 920 GHz when operated at 77 K.

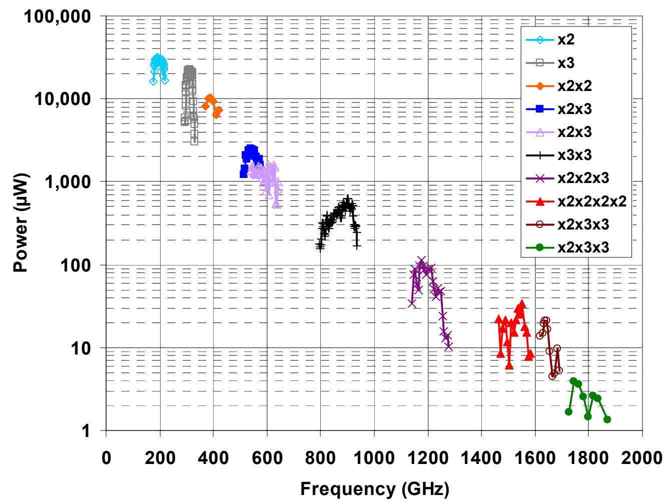

Figure 1. Output power of a variety of Schottky diode frequency multiplier chains measured at room temperature.

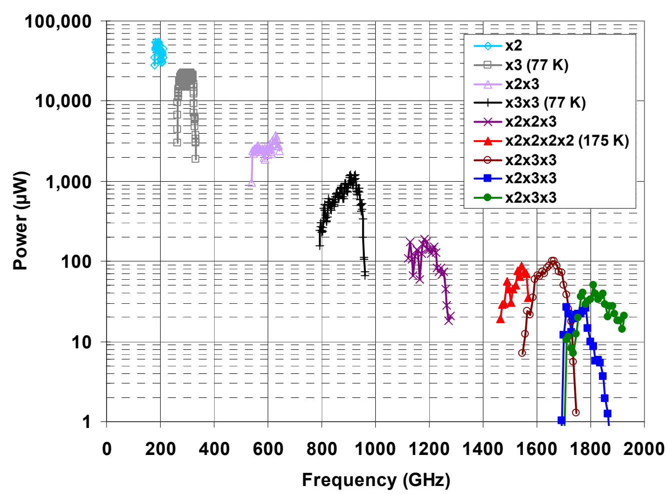

Figure 2. Frequency-multiplier chain output power measured at 120 K unless noted otherwise.

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III. Future Directions

Millimeter-wave power amplifier technology is advancing rapidly, and it is expected that MMIC amplifiers based on GaN transistors will soon be available that produce several watts of continuous-wave power at frequencies above 100 GHz [6]. Even before these next-generation chips become available, power combining is already a proven method to increase amplifier power. For example, Figure 4 shows the measured power from an amplifier that produces 0.8 W at 92.5 GHz. This amplifier was realized by combining four MMICs in parallel in a balanced configuration using branchline hybrid couplers. Indeed, rising amplifier power is driving a paradigm shift in frequency multiplier technology. Whereas in the past, frequency multipliers were designed assuming limited available millimeter-wave input power from Gunn oscillators and therefore emphasized conversion efficiency as the key performance parameter driving designs, future frequency multipliers will increasingly emphasize power handling as the dominant characteristic so long as multiplier output power is maximized.

Given the expected imminent increase in available amplifier output power when millimeter-wave GaN amplifiers become available, a number of approaches are being investigated to improve frequency multiplier power handling. The dominant limitation to frequency multiplier power-handling occurs when the input signal to the multiplier becomes large enough to drive the diodes into reverse breakdown. Moving the lower-frequency multipliers (up to a few hundred gigahertz) from GaAs (which was chosen to maximize efficiency) to a wider-bandgap material such as GaN will enable very large increases in power per anode before reaching the breakdown regime [7]. Increasing anode area, increasing the number of anodes per chip, reoptimising doping levels, and moving to a high thermal conductivity substrate will allow additional improvements in single-chip power handling. Once these possibilities have been fully exploited, if limits for single-chip power handling are reached, then power combining can further increase output power by a factor of a few. For example, Figure 5 shows a frequency multiplier designed to power-combine four current-generation GaAs tripler chips. In addition to using four chips with twenty-four Schottky anodes total to increase the maximum safe input power, this design also uses branchline quadrature hybrid couplers and internal loads to provide good return loss and isolation at both the input and output. We expect this block to produce at least 40 mW at 300 GHz.

It is evident that current-generation frequency multiplied sources are still very far from reaching any hard physical limits on output power. The anticipated advances discussed above are expected to eventually increase output power by at least an order of magnitude over the current state-of-the-art as long as solutions for thermal management can be found that don't compromise RF performance. Higher available power levels will in turn enable increasing the output frequency to at least 3 THz.

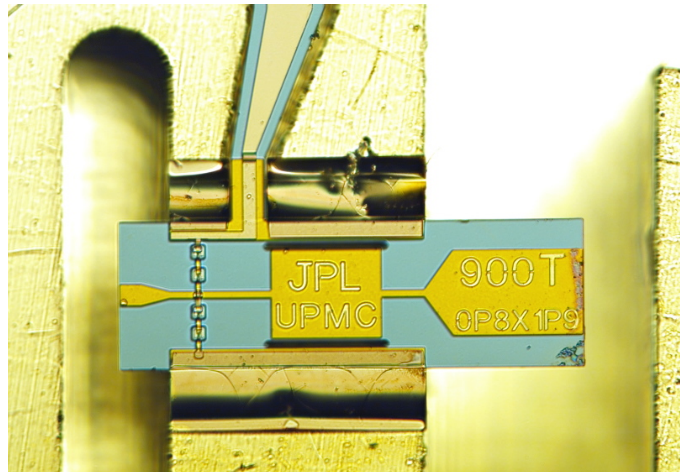

Figure 3. A 900 GHz frequency tripler. Four Schottky anodes provide sufficient power handling to produce 1.4 mW at 920 GHz when operated at 77 K.

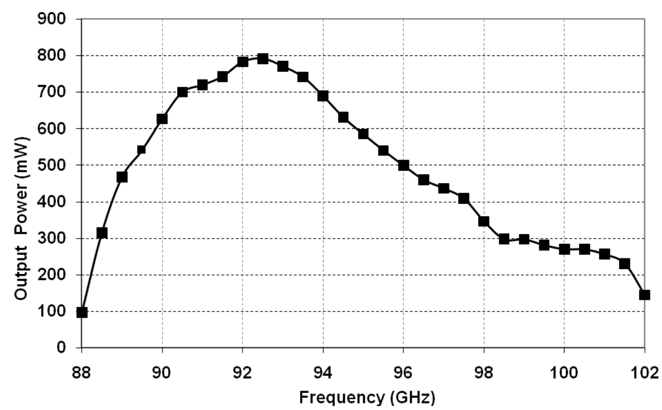

Figure 4. Measured CW power from an amplifier featuring four MMIC chips operated in parallel.

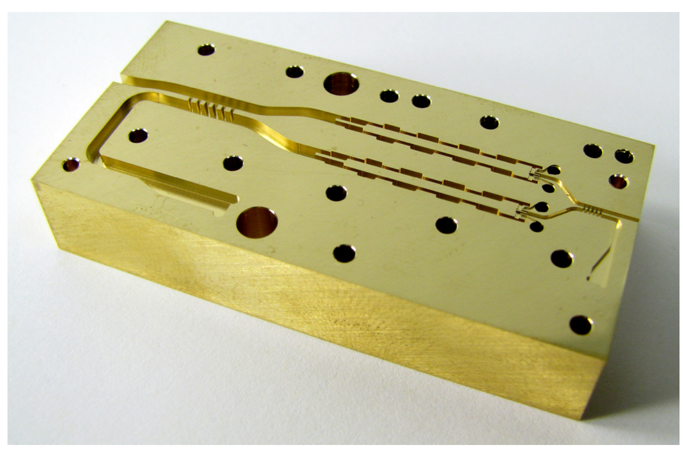

Figure 5. A four-chip 260-340 GHz frequency tripler. Branchline quadrature hybrid couplers split and recombine the signal to provide good return loss and isolation at the input and output.

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IV. Conclusions

Electronically-tunable room-temperature broadband solid-state frequency-multiplied sources available today can produce CW power ranging from over 0.6 mW at 900 GHz to a few microwatts at 1.9 THz. It is likely that the available power from room-temperature frequency multiplied sources in this band can be increased by at least a factor of ten through the combination of expected advances in millimeter-wave power amplifier technology, implementing driver-stage multipliers with a high-bandgap semiconductor, power combining, and a variety of evolutionary design improvements. We believe that improving frequency multiplier technology will enable HEB receivers to be pumped with tunable solid state local oscillators up to at least 3 THz. Other applications enabled by improving frequency multiplier technologies include arrays of terahertz heterodyne mixers pumped by a single tunable local oscillator, tunable room-temperature solid-state terahertz heterodyne receivers, and improved submillimeter-wave active imagers.

Acknowledgment

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