In-Phase Power-Combined Frequency Triplers at 300 GHz

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***Abstract*—We report on the design, fabrication and characterization of a 300 GHz Schottky-diode frequency tripler made of two mirror-image integrated circuits that are power-combined in-phase in a single waveguide block using compact Y-junctions at the input and output waveguides. Each chip features six anodes on a 5 μm thick GaAs membrane. The tripler has 5–15% conversion efficiency measured across the 265–330 GHz band when driven with 50–250 mW of input power at room temperature. At 318 GHz it delivers a peak power of 26 mW with 11% conversion efficiency. The power-combined frequency multiplier is compared with a single-chip tripler designed for the same band using the same integrated circuit.**

***Index Terms*—Frequency multiplier, frequency tripler, local oscillator, planar diode, power-combining, Schottky diode, submillimeter wavelengths, varactor.**

I. INTRODUCTION

DUE to the lack of practical fundamental sources at submillimeter wavelengths, the use of a microwave oscillator followed by frequency multipliers is the most viable solution for numerous applications requiring submillimeter-wave sources. Such applications range from submillimeter-wavelength or terahertz-frequency local oscillators for heterodyne receivers used for atmospheric measurements, planetary science, and astrophysics [1], [2], to the building of active imaging systems for biomedical and security applications [3].

The practical limit of the output power of a frequency multiplier is typically either the power beyond which conversion efficiency drops off due to saturation effects or the power beyond which the device lifetime becomes unacceptably short due to thermal or reverse-breakdown effects [4]. Our previous 300 GHz frequency tripler features six Schottky anodes to maximize the power handling of a single chip [5]. Since numerous constraints make it difficult to design frequency triplers at this short wavelength with more than six anodes and still achieve efficient conversion and broad bandwidth [6], an additional approach to increasing power handling was needed. A proven way to increase the power of a given source is to power-combine two or more parallel stages. However, for efficient power combining this approach requires increasing care at short wavelengths to keep the parallel paths well-matched despite fabrication and assembly tolerances and to minimize losses in the additional circuits required for dividing and recombining the signal. We present the design, fabrication and test results of a 300 GHz frequency tripler that uses two mirror-image circuits power-combined in-phase with a total of twelve Schottky anodes to produce 26 mW at 318 GHz when pumped with 250 mW input power at 106 GHz.

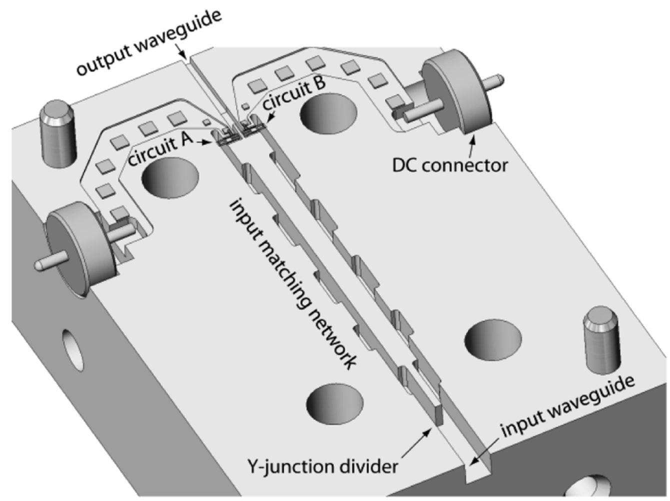

Fig. 1. 3-D schematic view of the bottom half of the power-combined 260–340 GHz frequency tripler based on two mirror-image integrated circuits.

II. DESIGN AND FABRICATION

The power-combined 300 GHz tripler is based on an integrated circuit designed originally for a single chip 260–340 GHz balanced tripler [5]. The power-combined version is based on two mirror-image tripler chips that are power-combined in-phase in a single waveguide block using a compact Y-junction divider at the input waveguide and a Y-junction combiner at the output waveguide. The complete power-combined tripler was designed using the methodology presented in detail in [2].

Fig. 1 shows an overall schematic view of the tripler including the input matching circuit. Fig. 2 shows a photograph of the circuit area with the output waveguide combiner. The tripler uses a split-block waveguide design with two independent DC bias lines. The input waveguide is split in two by a Y-junction to evenly feed two circuits each featuring six Schottky planar varactor diodes of about 16 fF each. The chips are mounted

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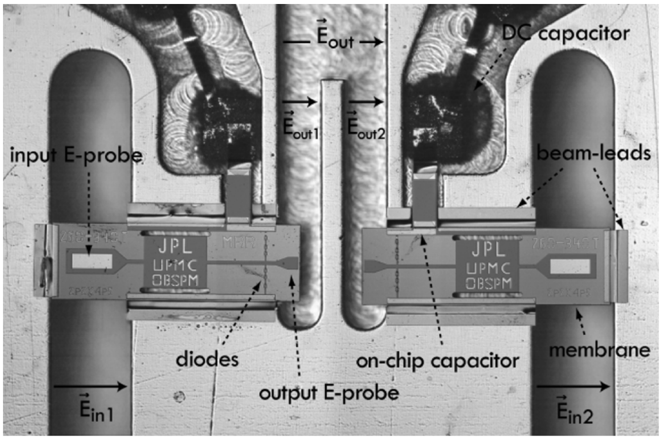

Fig. 2. Close-up view of the power-combined 260–340 GHz frequency tripler showing the two mirror-image GaAs integrated circuits. The E-field vectors in the input and output waveguides are indicated by plain arrows. The E-fields generated by the two sub-circuits are combined in-phase in the output waveguide.

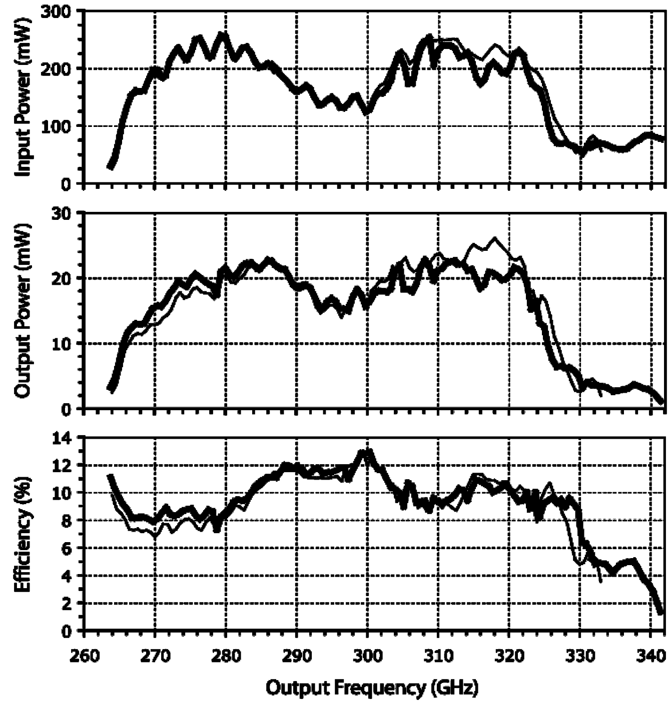

Fig. 3. Input power (top), output power (middle) and corresponding conversion efficiency (bottom) across the 265–340 GHz band of two (SN1 and SN2) power-combined frequency triplers. Note that the conversion efficiency is still quite high at the lowest frequency tested. For each graph, the thick curve refers to the SN1 unit while the light curve refers to the SN2 unit. The bias voltages were optimized at each frequency point. The measurements were made using three different power amplifiers to cover 88–114 GHz due to the large fractional bandwidth of the frequency triplers.

in two independent channels that run between their respective input and the output waveguides. The two reduced-height output waveguides are combined by a Y-junction that is seen by each branch of the circuit as a simple waveguide step.

On each chip, an E-plane probe located in the input waveguide couples the signal at the input frequency to a suspended microstrip line. This line has several sections of low and high impedance used to match the diodes at the input and output frequencies and 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 (idler) frequency. The dimensions of the output waveguide ensure that the second harmonic is cut off at all frequencies measured, and the balanced geometry of the chips ensures that power at the fourth harmonic of the input is strongly suppressed.

III. Measurements

We assembled and tested two tripler blocks. Assembly was simple and repeatable, and it was not difficult to reasonably align the chips in the block. The output power and the conversion efficiency of two different 300 GHz power-combined frequency triplers were measured at room temperature.

A. Test Setup

For output frequencies below or equal to 331 GHz, the source used to test the triplers was composed of a synthesizer tuned in the 14.66–18.39 GHz band followed by an active sextupler, a WR10 isolator, one of two different power-combined amplifiers to cover either the 88–100 GHz or the 100–110 GHz band, and a WR10 isolator. For output frequencies between 331 GHz and 340 GHz, the test source was composed of a Gunn oscillator followed by an isolator, a harmonic mixer, an amplifier working in the 110–120 GHz band, and a waveguide isolator. The frequency of the Gunn oscillator was measured by mixing the Gunn output with a synthesized CW signal in a harmonic mixer and measuring the beat signal on a spectrum analyzer.

The input power of the triplers was adjusted by varying the drain voltage of the power amplifiers and was monitored using a 15 dB WR10 directional coupler, an Agilent WR10 W8486A power sensor and an Agilent E4419B power meter[1]. The calibration of the input power was made separately using an Erickson Instruments PM2 power meter[2]. The output power of the triplers was measured using the same Erickson PM2 power meter and a one-inch long WR10 to WR3 waveguide transition. The results presented here were not corrected for the transition loss.

For all the measurements, the input power of the triplers was kept below 250 mW. The reverse voltage of each circuit was kept above -14 V (for 6 anodes in series) and the rectified direct current was kept below 3 mA. The two bias voltages were optimized independently at each frequency to maximize the output power. Performance gains by independently optimizing the two bias voltages were small; for most applications, the two bias lines could be tied to a single bias voltage for simplified operation.

B. Frequency Sweep

The two different power-combined frequency triplers have similar measured performance across the 265–330 GHz band. Their efficiencies range from 5% to 13% across the frequency band for 50 mW to 250 mW of input pump power (see Fig. 3). One of the triplers produced a record 26 mW at 318 GHz with

[1]Agilent Technologies, Inc., 5301 Stevens Creek Blvd., Santa Clara, CA 95051.

[2]Erickson Instruments, LLC, 316 Pine Street, Amherst, MA 01002.

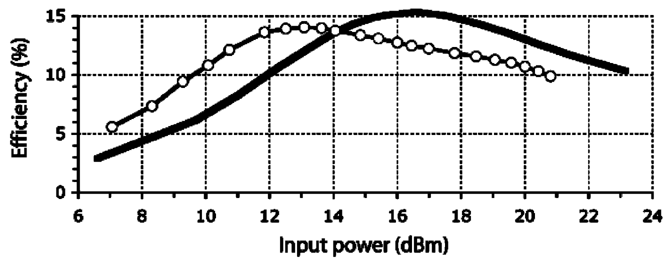

Fig. 4. Power sweep of the single-chip tripler at 292.2 GHz (light curve with open markers) and of the power-combined tripler SN1 at 286.2 GHz (heavy curve with no markers). It can be seen that the power-combined tripler begins to compress at an input power which is 3 dB above that of the single-circuit tripler, as expected.

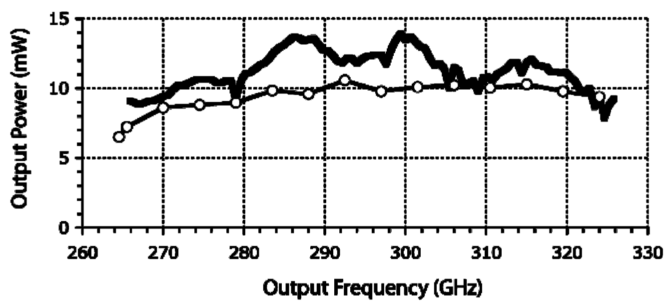

Fig. 5. Comparison of the available output power of the power-combined 300 GHz tripler SN1 (top thick curve with no markers) with that of the single-chip 300 GHz tripler when pumped with the same 100 mW input power (bottom curve with open markers).

11% conversion efficiency. At the same frequency, the other tripler has 10% conversion efficiency and produced 20.5 mW of output power (the input power at 106 GHz was slightly less in this case compared to the other tripler). Although the triplers have not yet been measured below 264 GHz, the efficiency is still quite high at 264 GHz. At frequencies above 331 GHz we tested only one tripler which has an efficiency of 5% up to 338 GHz and 3% at 340 GHz.

C. Comparison With a Single-Circuit 300 GHz Tripler

Fig. 4 shows the conversion efficiency versus input power of the power-combined 300 GHz tripler and of a single-chip 300 GHz tripler. Each tripler was tuned to a frequency where the conversion efficiency was near the maximum and where at least 200 mW and 100 mW of drive power were available for the power-combined tripler and the single-chip tripler, respectively. Fig. 5 shows the output power versus frequency of these same two triplers when driven with a flat input power of 100 mW.

Figs. 4 and 5 clearly indicate that despite the high frequencies involved and large fractional bandwidth, the power combining is nearly ideal, with the power-combined version performing with almost identical bandwidth and conversion efficiency as the single-circuit version except with twice the power handling. The conversion efficiency of the power-combined tripler exceeds 10% for input powers ranging from 1.4 mW to 17 mW per anode or 17 mW to 206 mW of total power. The peak efficiency reaches a record 15.3% at 286.2 GHz and is obtained with an input power of 3.5 mW per anode or 41.5 mW of total power. This large dynamic range makes the power-combined tripler very versatile.

IV. Conclusion

Two submillimeter-wave tripler chips have been successfully power combined in a single waveguide block. The power combined tripler produces approximately twice as much power without sacrificing efficiency or bandwidth compared with a single chip implementation. This approach represents an important step towards building more powerful sources in the submillimeter-wave range which can then successfully drive sources beyond 1 THz.

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