Schottky Diode Based Frequency Sources to 360 GHz

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***Abstract*— Signal sources at 100s of GHz rely on technology which is not used in mass production and has traditionally been subject to significant variation in manufacturing accuracy and therefore performance. Although the relatively recent emergence of MMIC amplifier circuit technologies has demonstrated circuits to a few 100 GHz, the highest power and frequency outputs use Schottky diode based circuits. In this paper examples of European state-of-the-art frequency multipliers are reported (for example, 100mW Pout at 180GHz) which demonstrate how MMIC-type approaches are employed to improve the performance and 'useability' of planar Schottky diode technology beyond 300 GHz..**

***Keywords*—Schottky diode, frequency multiplier, power-combined.**

I. INTRODUCTION

Research into millimeter-wave local oscillator (LO) sources for space-borne applications has seen tremendous progress in the past few years [1-2]. This growth has largely been driven by the advances in planar GaAs Schottky diode technology which has established itself as the preferred device for most room temperature operated frequency multiplied LOs. Their ability to up-convert signals from MMIC amplifiers (typically available to W-band) make them highly desirable in future applications for high frequency communication, radars, non-destructive testing (NDT) and scientific experimentation.

Design of active circuits to 100's of GHz requires a combination of 3D EM simulation with non-linear harmonic balance – not commonplace in conventional microwave circuit design. These techniques are now well established and yield close correlations with measurement.

As would be expected, the physical size of the circuits decreases with wavelength. And as a result, component dimensional tolerance and alignment accuracy becomes increasingly important. Integration of the diodes with filters and capacitors into a MMIC structure reduce assembly complexity and lead to improved circuit yield.

This work highlights the results obtained from GaAs Schottky diode-based frequency multipliers. Examples are included for 90/180 GHz and 180/360 GHz frequency doublers. Results for 90/180 GHz doublers are shown for single and combined circuits. Frequency triplers 62/187 GHz are also discussed.

II. CIRCUIT DESIGN

The Schottky varactor diodes used consist of an air-bridged mesa structure to minimize parasitics. Diodes are ordinarily configured in a series connected or antiparallel manner, dependent on the electromagnetic environment of the input and output signals, and the requirements for circuit balance etc. Varactor anode areas can be adjusted, and diodes can be 'stacked' according to the input power requirements.

The integrated MMIC process at Teratech extends the GaAs substrates used to form the diodes to contain thin film filtering circuit sections (typically contained on Quartz for hybrid circuits). Metal-Insulator-Metal capacitors can also be formed using a 2-layer metal processing and have 96 pF/mm^2 specific capacitance. The GaAs MMIC substrates can be thinned to 15um thickness. Beam-leads (suspended gold strips) can be formed extending from the GaAs edges. The DC reverse breakdown voltages measured for each anode are >12V.

Examples of frequency doubler and tripler circuits are shown in Figs. 1 and 2 which employ anti-parallel and series connected diodes respectively. To operate with optimum efficiency the diodes require a DC bias. In the balanced doubler configuration (Fig. 1) bias can be applied along the central conductor via lowpass on-chip bias filtering and off-chip bypass capacitors. For balanced triplers, Fig. 2, bias is applied at one end of the varactor stack, requiring a DC blocking capacitor to maintain the RF bypass grounding at that point.

Matching is achieved using stepped impedance sections on the MMIC, and also through the use of reduced height waveguide sections. Optimum circuit operation requires designs using a co-simulation of the physical structure in, for example HFSS, and a harmonic balance analysis. Diodes are 'embedded' with the 3D model using internal port structures.

Thermal design of the circuits becomes increasingly important, as the output power and circuit reliability are influenced by input power levels and block temperatures [3].

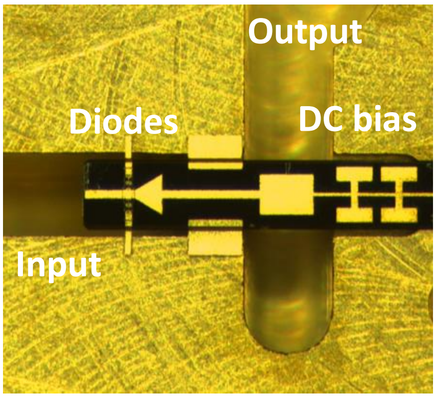

Fig. 1. Photograph 90/180 GHz doubler circuit. MMIC area [1690x320x20 um^3]

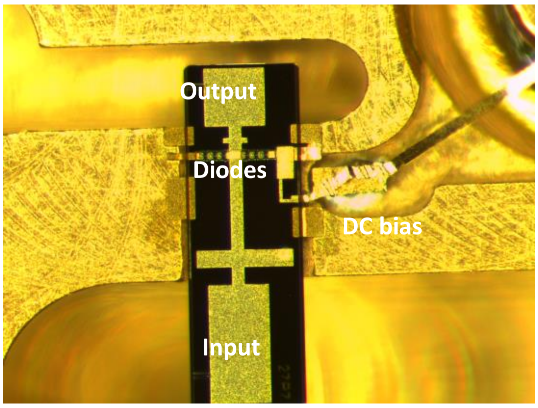

Fig. 2. Photograph of the 62/187 GHz band tripler circuit. MMIC area [1417x465x15 um^3]

III. CIRCUIT TEST RESULTS

An HP 83711A frequency synthesizer was used at the input of test source multiplier chains. For W-band inputs an RPG sextupler and a narrowband Quinstar 90 GHz power amplifier were used. At 62 GHz input a Sage quadrupler was used. Keysight and Erickson PM4 power meters were used for incident and output power measurements. Isolators and couplers were used at the circuit inputs.

A. Frequency Doublers

The measured frequency response of the 90/180 GHz doubler is shown in Fig. 3 for 100 mW input power. Fig. 4 shows an input power sweep at 180 GHz. For an input power of 420 mW, the frequency doubler generated an output of 84 mW with a conversion efficiency of 20%. For these tests the bias voltage was optimized at each point.

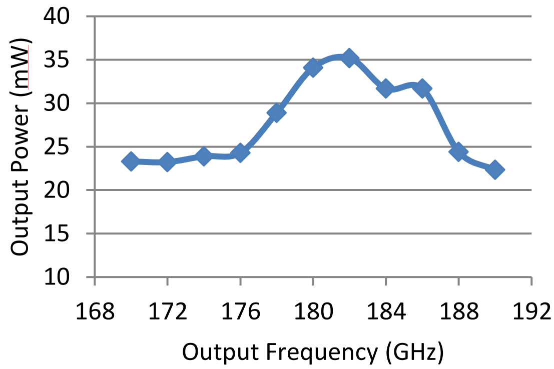

Fig. 3. Measured output power for constant 100 mW input power across the frequency bandwidth for a single 90/180GHz frequency doubler.

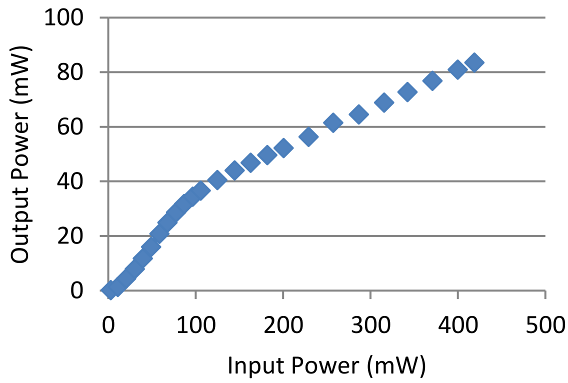

Fig. 4. Measured output power for the single 90/180 GHz frequency doubler.

The single doubler circuit described in this section was used to form a power combined pair of doubler circuits, contained in the same 20mm^3 block form factor. The split block is shown in Fig. 5.Measured results for two blocks are shown in Fig. 6. The combined circuit efficiency peaks at 36 % at 130 mW input power, and yields 26% efficiency at 130 mW peak output power. Reproducibility in results block-to-block as shown in Fig.6 are typical for the assembly using MMIC structures.

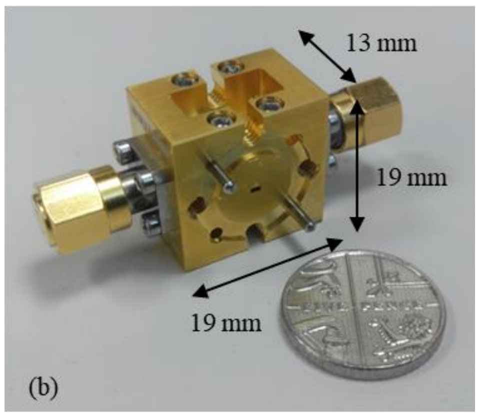

Fig. 5. Photograph of the split block power combined 90/180 GHz doubler

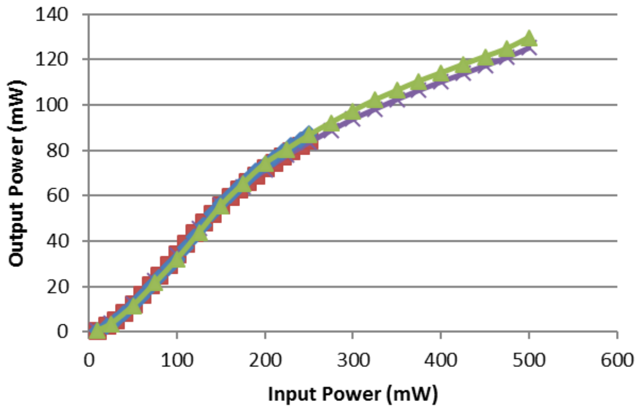

Fig. 6. Measured results for power combined 90/180 GHz frequency doubler at 180 GHz output frequency

To complete the results for frequency doublers, Fig. 7 shows the output power for a 360 GHz frequency doubler. This circuit was pumped with the combined 90/180 GHz doubler discussed previously. The 180/360GHz circuit is configured as a MMIC in a split block - similar to the 90/180 GHz circuits.

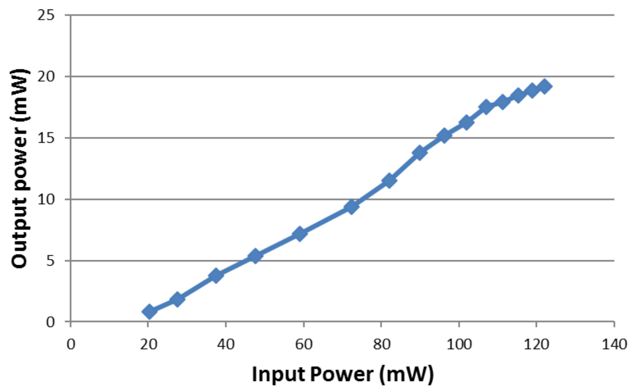

Fig. 7. Measured results for 180/360GHz doubler at 360 GHz output frequency

B. *Frequency Triplers*

Results for the 62/187 GHz frequency tripler are shown in Fig. 8 and Fig. 9 for swept frequency and input power respectively. At each point the bias voltage was optimised.

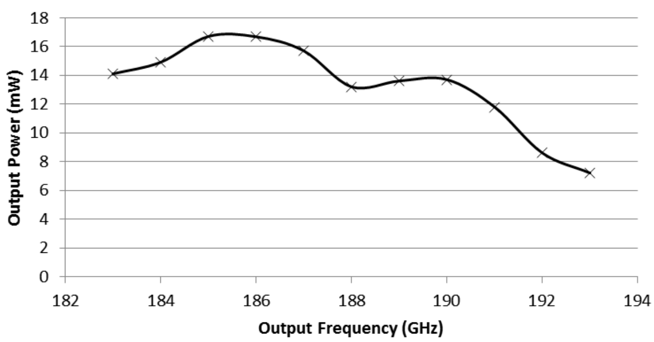

Fig. 8. Measured results for 62/187 GHz frequency tripler at 100 mW input power

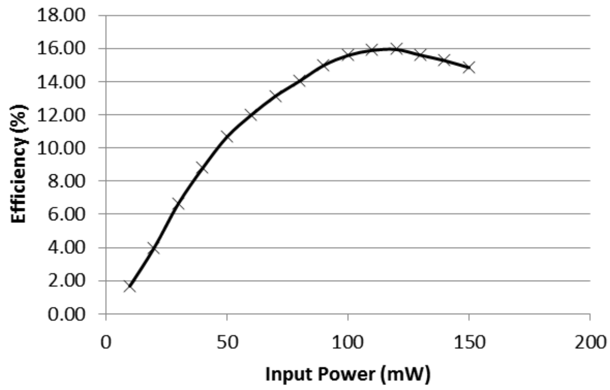

Fig. 9. Measured results for 62/187 GHz frequency tripler at 187 GHz

IV. Performance Summary

Results presented here represent equivalence with world state-of-the-art. This is summarized in Table I [5]. There are few groups making diodes capable of operation at 100s of GHz. And fewer groups able to integrate further structures in a MMIC process. Working closely with circuit design groups offers a large advantage in technology development.

TABLE I
STATE OF ART SCHOTTKY MUTILPIERS

Group	Performance	Brief performance
ACST GmbH Germany	161/332 GHz doubler	30% at 332 GHz (14mW)
Observatory de Paris	147/295 GHz doubler	27% at 295 GHz (10.5mW)
This Paper	180/360 GHz doubler	15% at 360 GHz (19 mW)
VDI	80/160 GHz doubler	25% at 160 GHz (125 mW)
JPL	90/180 GHz doubler	25% at 180 GHz (120 mW)
This Paper	90/180 GHz doubler (power comb)	26% at 180 GHz (128 mW)
VDI	72/216 GHz tripler	16% at 220 GHz (24 mW)
JPL	36/110 GHz tripler (power comb)	25% at 110 GHz (138 mW)
This Paper	62/187 GHz tripler	15% at 187 GHz (22.5 mW)

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