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125 GHz Frequency Doubler using a Waveguide Cavity Produced by Stereolithography

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***Abstract*—This letter reports on the first Schottky diode frequency doubler with a split-block waveguide structure fabricated by a high-precision stereolithography (SLA) printing process. The printed polymer waveguide parts were plated with copper and a thin protective layer of gold. The surface roughness of the printed waveguide parts has been characterized and the critical dimensions measured, revealing good printing quality as well as a dimensional accuracy that meets the tight tolerance requirements for sub-terahertz active devices. The 62.5 GHz to 125 GHz frequency doubler circuit comprises a 20 µm thick GaAs Schottky diode monolithic microwave integrated circuit (MMIC) in the waveguide. The measured doubler provides a maximum output power of 33 mW at 126 GHz for input power of 100 mW. The peak conversion efficiency was about 32% at input powers from 80 to 110 mW. This doubler performance is compared with and found to be nearly identical to the same MMIC housed in a CNC-machined metal package. This work demonstrates the capability of high-precision SLA techniques for producing sub-terahertz waveguide components.**

***Index Terms*—3D printing, frequency doubler, millimeter-wave, Schottky diode, MMIC, Stereolithography, waveguide.**

I. INTRODUCTION

TERAHERTZ frequency multipliers based on GaAs Schottky diodes have been extensively used as reliable sources for local oscillators (LO) in heterodyne receivers owing to their high efficiency, low cost and ability to work at room temperature[1]-[5]. Such multipliers have a wide range of practical applications including atmospheric remote sensing, object imaging and, potentially, high data rate communications. The waveguide packaging of these multipliers is conventionally fabricated using computer numeric control (CNC) machining, a technique that currently dominates the manufacturing industry. The process is well established and provides high-quality components with high accuracy, high precision, and good surface finish. It can meet the tight tolerance requirements in sub-terahertz frequency multipliers for electrical tuning purposes, and for accurate placement of the planar circuits within the waveguide structure.

This work demonstrates the potential of a 3D printing technology as a manufacturing route for the waveguide cavity of a sub-terahertz multiplier. In addition to its ability to fabricate complex geometries and monolithic structures, 3D printing technology has the competitive edge of being able to produce multiple parts at the same time and thus reducing production time. Over the past few years, 3D printing has been applied to many passive microwave components operating at various frequencies. Not many components have been demonstrated above 100 GHz due to the lack of high-precision printers with accuracies ≤10µm and adequate printing volumes. Examples include waveguide sections [6]-[7], feedhorn antennas [8] and filters [9]. In [10], authors demonstrated a 3-D-printed split-block assembly at 500 GHz that houses infrared laser diodes. However, no 3D-printed frequency multipliers have been reported before. This letter describes the first demonstration of a frequency doubler with a waveguide structure fabricated by 3D printing technology using a stereolithography (SLA) process with high resolution and accuracy. The printed polymer parts were coated with copper and gold. Its performance is compared to a doubler with the same type of MMIC but in a standard CNC-milled split metal block construction.

II. DESIGN AND FABRICATION

The frequency doubler is based on a single-chip Schottky diode monolithic microwave integrated circuit (MMIC) comprised of a four-anode anti-series configuration mounted on a 20 µm thick GaAs substrate. Examples of circuits using this technology are given in [11], together with some CNC machining accuracy analysis. The configuration of the doubler, following [12], is shown in Fig. 1(a) and a close-up picture of the Schottky diode MMIC is shown in Fig. 1(b). The drive power propagating through the WR-15 input waveguide is coupled to the MMIC using reduced height rectangular waveguide. The second harmonic output signal is transferred to the WR-8 output waveguide through an E-plane probe. The Schottky circuit is located in an E-plane split-block waveguide and mechanically supported by beamleads. The DC bias is applied via a low pass hammerhead filter and a chip capacitor. The waveguide cavity, with integrated UG387/m flanges, was printed using an SLA process [13] by a

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S140 SHL machine at 20 μm layer height, 10 μm x/y optical resolution, 40 mW/cm^2 laser output power density and an average 0.85s light exposure time per image. The polymer used is BMF HTL Yellow20 that can withstand temperatures up to 114 ºC. The machine used projection micro stereolithography (PμSL) technology that allows micro-resolution as well as multi-exposure mode which utilizes the full platform printing area. The completed parts were washed in propan-2-ol and UV post cured for 30 minutes with a final thermal post cure at 60 C° for 30 minutes. Fig. 2 shows a picture of the as-fabricated E-plane split waveguide polymer parts. These incorporate dowels and pin holes to achieve accurate alignment of the two halves when assembled. The dowel radius is 0.75 mm and the hole radius is 0.8 mm. The width of the waveguide channel where the MMIC is placed is 630 μm and the width of the MMIC is 580 μm. The tight tolerance requirement of the channel width is critical to allow precise placement of the MMIC in the channel. 3D printers of a high accuracy (≤10 μm) are required for such sub-terahertz devices, but these are uncommon. Accurate alignment between the split blocks is another critical requirement and any misalignment larger than 25 μm could damage the MMIC circuit. The as-printed polymer parts were inspected using Alicona G4 InfiniteFocus optical system with no detected defects. It can be seen from the microscope image shown in Fig. 2 that the fine features are well defined. The channel width was measured to be 609 μm, which compares well with the design value of 630 μm. The accuracy may be further improved by in-situ calibration using scaling bars during the printing [14]. The on-chip backshort approach in [11] may be employed to make the doubler less prone to fabrication tolerances.

The polymer waveguide blocks were plated using electro-less copper (thickness around 4 μm) and a thin protective layer of gold (thickness around 0.1 μm). The surface roughness of the plated top block was measured at different locations using Alicona optical system, as shown in Fig. 3. The average surface roughness S_a is 1.4 μm. This roughness degrades the electrical conductivity of copper from 5.8 × 10^7 S/m to an effective value of 1.47 × 10^7 S/m at 120 GHz [15]. 3D electromagnetic simulation results show the effect of surface roughness on waveguide losses is negligible. The calculated extra insertion losses due to the surface roughness is 0.03 dB at 60 GHz in the input waveguide, and 0.04 dB at 120 GHz in the output waveguide section. It should be noted that the surface roughness of the as-printed polymer part prior to plating is around 0.4 μm. The increased surface roughness after plating was due to the pre-coating surface treatment necessary to give good adhesion of the copper layer.

The MMIC was placed in the channel and the DC bias connection was established via thermo compression bonding of gold ribbon. Fig. 4(a) shows a picture of the fabricated MMIC placed in the 3D-printed waveguide split-block. An external view of the assembled device is shown in Fig. 4(b). The overall dimensions are 30.4 mm × 25.5 mm × 19.1 mm.

III. Measurement Results

The measured results of the 3D-printed doubler are shown in Fig. 5 to Fig. 7 along with those from its conventionally, CNC-machined counterpart. At an input power of 100 mW, the achieved maximum output power was about 33 mW for the 3D-printed doubler and 35 mW for the CNC-machined doubler: Fig. 5. The two output power responses are within the measurement uncertainty and the usual component variations, indicating the competitive performance of the 3D printed device. Over the frequency range from 120 GHz to 130 GHz, the output power is above 16 mW for both doublers.

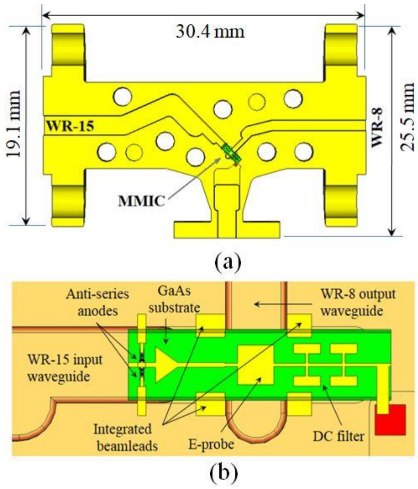


Fig. 1. Configuration of the 125 GHz frequency doubler: (a) layout of one split-block; (b) close-up picture of the Schottky diode MMIC.

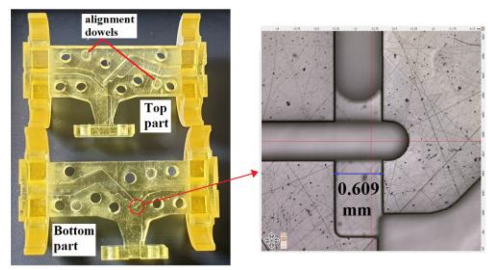


Fig. 2. Picture of the as-fabricated polymer waveguides made by SLA process (left) and an optical microscope image of the area where the MMIC sits (right).

The measured output power and conversion efficiency as functions of input power are shown in Fig. 6 at 125 GHz output frequency. The maximum output power is 37 mW and 38 mW for the two devices, respectively, both obtained at an input power of 120 mW. In this case, the maximum doubler input power was limited by the 60 GHz source capability. The peak conversion efficiency of the 3D-printed doubler was about 32% at input powers from 80 mW to 110 mW. The CNC-machined doubler exhibited higher peak conversion efficiency, of about 41%, at input powers from 30 mW to 60 mW. The drop in efficiency can be attributed in part to the misalignment of the MMIC in the waveguide cavity due to rough waveguide edges. The efficiency differs more at lower power. The reason could be a combination of poorer matching at the lower input power and chip variation. It should be noted that variations of up to 10% in conversion efficiency are usually expected between nominally identical devices with the same anode size. The measured input reflectivity, S_{11}, of both doublers at an input power of 100 mW is shown in Fig. 7. Both doublers have similar results with a return loss better than 6 dB from 61 GHz to 65 GHz have been achieved.

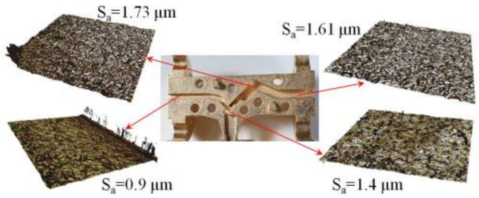
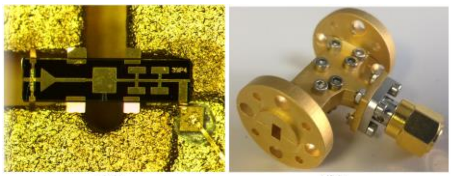


Fig. 3. Surface roughness characterization of the metalized top block.



(a) (b)

Fig. 4. Pictures of the fabricated frequency doubler: (a) the fabricated MMIC placed in the 3D-printed waveguide split-block; (b) the assembled doubler.

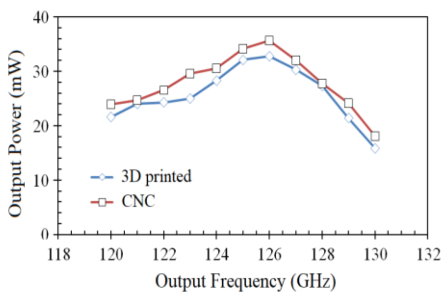


Fig. 5. Measured output power versus output frequency for 100 mW input power for the 3D-printed and the CNC-machined doublers.

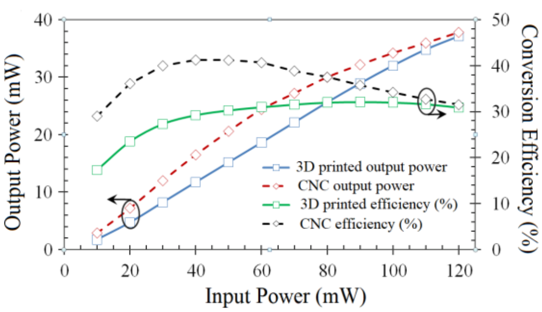


Fig. 6. Measured output power and conversion efficiency versus input power at 125 GHz output frequency.

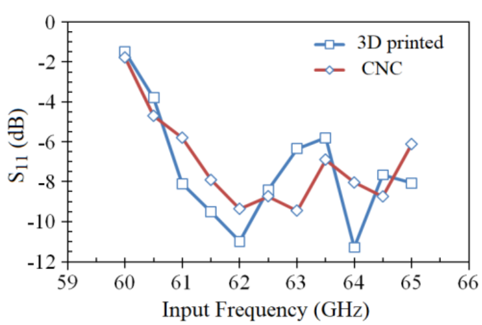


Fig. 7. Measured input S_{11} of the two doublers at input power of 100 mW

IV. Conclusion

An end-to-end process of utilizing 3D printing technology to manufacture the waveguide enclosure of a 62.5/125 GHz Schottky diode frequency doubler is reported. Both CNC-machining and high-precision SLA printing process have been used and compared. As a first-time demonstration of a 3D-printed frequency doubler, the measured results between the two processes agree very well, considering chip-to-chip variability and assembly misalignments. The doubler provides a maximum output power of 33 mW at 126 GHz and the measured peak conversion efficiency was about 32% at input powers from 80 mW to 110 mW. Compared to the CNC-machined counterpart, the 3D-printed doubler exhibited similar performance with similar output power and conversion efficiency. This work demonstrated the successful application of 3D printing technology in producing waveguide structures with sufficient dimensional accuracy suitable for sub-terahertz active devices. The printer also has a very stable printing process with repeatability figure much lower than its resolution. Scalability to higher frequencies is feasible by using the same printer with reduced layer thickness to 10 or even 5 μm instead of the 20 μm standard used in this work. Alternatively, higher accuracy and higher resolution printer is available but usually with more restricted printing volume which limits the part size.

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