Micromachined 3D Millimeter-Wave and Terahertz Devices

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***Abstract* — Micromachining is a very promising technology to manufacture miniature three-dimensional (3D) devices at millimeter-wave (mm-wave) and terahertz (THz) frequencies. After a decade's development, this technology has begun to demonstrate its viability and capability. It has delivered devices with competitive performance to traditional metal machining or electroforming, for coaxial and waveguide structures with sub-millimeter dimensions. This paper will discuss three strands of work that tackle three main challenges - fabrications, designs and measurements – in this technology. Several passive devices will be presented to illustrate the progress made on the multilayered SU8 techniques. These include guided transmission structures and devices based on rectangular coaxial lines, waveguides and free-space frequency selective surfaces. The concerned frequency covers from 30 GHz to 1 THz.**

***Index Terms* — Micromachining, millimeter-wave devices, waveguides, frequency selective surfaces.**

I. INTRODUCTION

As the frequency enters the millimeter-wave (mm-wave) and terahertz (THz) region, the width of planar transmission lines gets so small that the power density becomes increasingly prohibitive to deliver decent transmission efficiency. To cope with this, three-dimensional (3D) transmission structures such as rectangular coaxial lines and waveguides are often resorted to. However, as their critical dimensions are down to the sub-millimeter regime at these frequencies, fabrication of such 3D structures becomes a significant challenge. For instance, the standard WR-03 waveguide (220 - 325 GHz) has a cross-sectional aperture of 0.864 mm × 0.432 mm. A fabrication tolerance less than 10 μm and a surface roughness better than 100 nm are most desired. Although the high-precision metal machining or electroforming could meet the required fabrication accuracy, they tend to be very time-consuming and expensive. Their cost-effectiveness is poor. As the frequency increases and/or the internal structures get complicated, metal machining becomes impossible. The emergence of larger-scale applications of mm-wave and THz devices has stimulated the research into alternative fabrication techniques for 3D devices on the wafer level.

Various techniques have been investigated. Among them, UV-LIGA [1], PolyStrata^{TM} [2], Silicon-DRIE [3] and thick-resist photolithography [4], [5] are the most promising in providing the desired fabrication accuracy for up to 1 THz. LIGA is able to produce all-metal solid structures. PolyStrata demonstrated a high level of integration on the wafer. Compared with these, silicon-DRIE is a more accessible technique. As a competing technique with DRIE, the thick-resist technology offers better cost-effectiveness for its lower facility requirement while producing the best surface smoothness on the vertical walls. Interestingly, some of these developments coincide with the rapid adaption of the concept of additive manufacturing. This paper focuses on the multilayer fabrication technique using the thick photoresist – SU8.

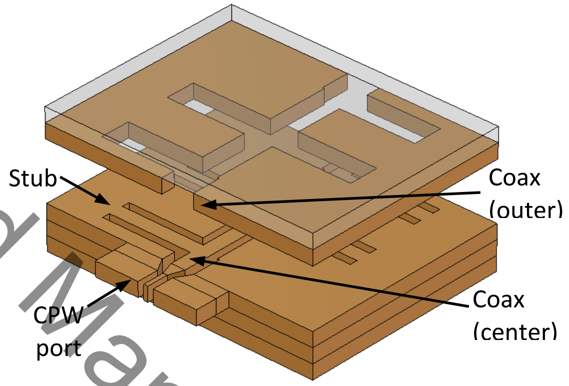


Fig.1. A rectangular coaxial line filter formed of five equal-thickness layers (for viewing the top two layers are separated and the top layer is made transparent).

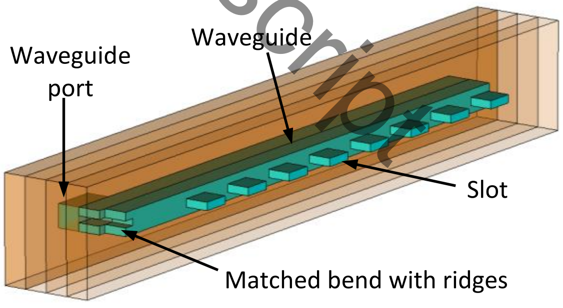


Fig. 2. A rectangular-waveguide antenna formed of four equal-thickness layers. (The outstanding structure in blue in the middle represents the air-filled channel and slots, surrounded by conductors set to be transparent in the graph.)

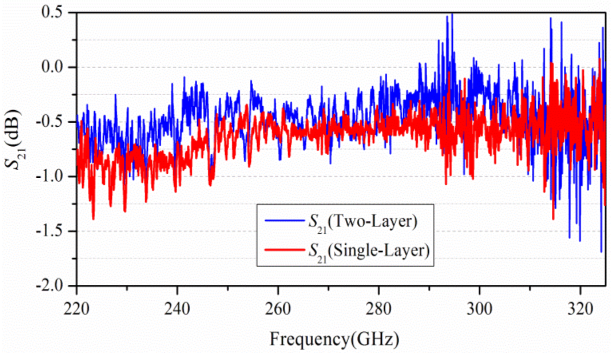


Fig. 3. Measured S_{21} responses of two 14.97 mm long WR-3 waveguides (From [10]). One was fabricated using single SU8 deposition process labelled as 'Single-layer' and the other using double deposition process labelled as 'Two-layer'.

II. DEVICES

SU8 has been primarily used in MEMS [6]. In the application described in this paper, this photo-imageable resist is used as the structural material for building 3D coaxial and waveguide devices in a multilayered fashion, as illustrated in Fig. 1 and Fig. 2. The thickness of each layer ranges from 0.1 mm to about 1 mm. Rectangular coaxial lines have been demonstrated up to the W-band with a cross section of 0.456 mm by 0.6 mm [7], [8]. Full-height standard waveguides have been demonstrated up to WR-1.5 band (500-750 GHz) with a cross section of 0.191 mm by 0.381 mm [9]-[11]. For the WR-3 waveguides, an attenuation of 0.01-0.05 dB/mm across the band has been achieved using the SU8 process as shown in Fig. 3. This is comparable to one of the best machined metal waveguides with an average attenuation of 0.02 dB/mm over the same band [10].

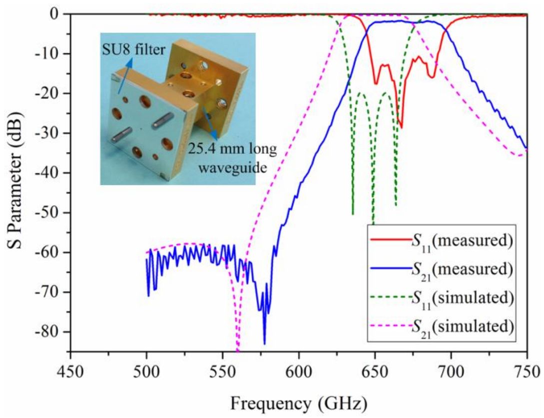
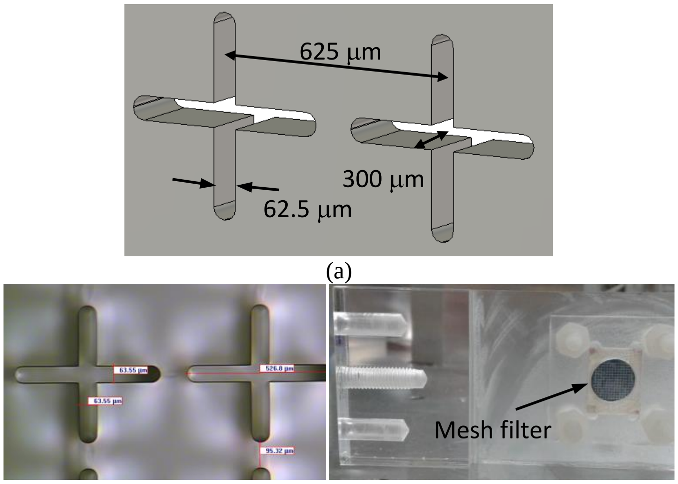


Fig. 4. Performance of the SU8 WR-1.5 waveguide filter. The measurement taken includes the contribution from a 25.4 mm long metal waveguide which is attached to the SU8 device (inset).

A range of passive devices from 30 GHz to just under 1 THz have been demonstrated. Various types of wideband or narrow-band filters have been implemented using either rectangular coaxial (up to 110 GHz) or waveguide (up to 700 GHz) structures. These include stub filters [7], interdigital filters, waveguide filters [11] and cavity filters [12]. Fig. 1 shows a W-band stub filter and Fig. 4 shows the response of a WR-1.5 waveguide filter, representing one of the highest operation frequencies demonstrated by a micromachined filter [11]. Directional couplers [5] and Butler matrices [13] have been designed to feed 38 GHz and 63 GHz air-filled patch arrays [14]. Slotted waveguide antennas with various feeding configurations have been fabricated at 300 GHz for gain enhancements and beam scanning [15]. Fig. 2 shows one of these. A common feature of all above-mentioned devices is the air-dielectric (or air-filled) 3D structure which essentially eliminates any dielectric losses.



(a)

(b) (c)

Fig. 5. Micromachined thick mesh filters. (a) Diagram of the unit cell; (b) Microscopic view of the bare SU8 piece before metallization; (c) Fabricated mesh filter in the sample holder for free-space measurements.

Most recently, the SU8 based lithography process has been adopted to produce freestanding thick mesh filters [16], also knowns as frequency selective surfaces (FSSs), at 300 GHz. As shown in Fig. 5, the thickness of the mesh structure is five times of the width of the cross-shaped slots. This large thickness not only increases the mechanical strength but also enhances the resonant quality factor. This is an extra degree of freedom in controlling the transmission characteristics of the FSS. Further shaping of the passband characteristics have been demonstrated using a stacked structure of multiple micromachined mesh filters. This unique low-cost fabrication process is favorably suited for THz devices for free-space sensing and material characterizations.

III. FABRICATION AND MEASUREMENTS

The SU8 fabrication process is based on photolithography with multiple steps of critically controlled baking in order to form stable cross-linked structures. This has been detailed in [17], [18]. The rectangular coaxial and waveguide structures are mostly formed of four or five layers of equal thickness. The simplest process involves a single deposition of SU8 and one step UV exposure forming a single layer. An advanced double-deposition process with two exposures has also been successfully demonstrated to produce a single block of double-layered structures in order to reduce the number of contact interfaces when the multiple SU8 layers are stacked together to form the 3D structure.

Measuring theses micromachined devices is a significant challenge due to the non-standard port structures. For the rectangular coaxial devices, as shown in Fig. 1 a transition from the rectangular coax to a suspended thick CPW line is devised to facilitate interconnections with mm-wave on-wafer probes. For the THz waveguide devices, without a reliable and secure interconnection between the micromachined waveguide and the standard metal flange, the connection loss may well dominate the measured transmission and reflection responses. Therefore, a lot of effort has been made to ensure the reliability and repeatability of the measurements. Extra transition structures [9] or external testing fixtures [19] have been used. The antenna in Fig. 2 contains a matched right-angle bend, designed to realise secure and accurate contact with standard metal waveguide flanges.

IV. CONCLUSIONS

There have been significant advancements of various micromachining technologies to manufacture 3D mm-wave and THz devices with sub-millimeter dimensions. The SU8 based multilayer fabrication technique has demonstrated its potential to be one of the most cost-effective and simple with low facility investment but good capability. This technique has delivered a range of passive devices such as filters, couplers, antennas and arrays. It can be adapted to devices operating over a wide frequency range from 30 GHz up to 1 THz. The fabrication process has been advanced from single deposition to multiple deposition of SU8, resulting in much improved device performance. Different interconnection methods have been experimented and much improved reliability and accuracy in the measurement have been achieved. Although the current fabrication process has achieved competitive performance compared with other micromachining, as well as metal machining techniques, a further reduction of the fabrication tolerance and assembly error is most desirable. One future research direction is to explore the integration of micromachined passives with active components for sensors and communication systems.

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