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SLA 3D printer, RECILS enables low-cost and low-loss waveguide bandpass filters for electromagnetic waves at 200-400GHz band

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Abstract

We have successfully fabricated hollow waveguides designed for electromagnetic waves at 200-400 GHz band. These waveguides, with a cross-section of 0.86 × 0.43mm^2 and a length of 25.4-mm long formed by our SLA (Stereo-Lithography-Type)-3D printer, RECILS which is featured by its ability to produce palm-sized objects with a high resolution of 20-30 µm at high speed (100 cm^3/hour). The surfaces of the hollow structures made of UV-cured resin are copper-plated to confine electromagnetic waves. Experimental evidence confirms that our 25.4mm RECILS-produced, copper-plated waveguides exhibit an insertion loss of just 0.5–1.0 dB within the 200–400GHz band, an efficiency that competes with commercially available metal waveguides. Bandpass filter characteristics of the waveguides in which sub-mm-scale coupled resonator structures are formed by RECILS are in good agreement with the simulation results adopting corresponding models of bulk copper-metal bandpass filter waveguides. These results indicate that the combination of RECILS and metal plating could offer efficient solutions for producing multifunctional sub-THz waveguide devices of any shape at low cost and in a short time.

Keywords: Sub-THz; Electromagnetic Wave; Waveguide; Bandpass Filter Waveguide; SLA 3D Printing; Metal Plating

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1. Introduction

The use of electromagnetic (EM) waves within the sub-terahertz (sub-THz) band (0.1 THz to 1 THz) is growing in significance, especially for future wireless communications, sensinng, radio astronomy, and other related fields. Research and development focused on elemental technologies and system demonstrations in the sub-THz band are rapidly progressing, paving the way beyond 5G and 6G. To address the difficulties associated with high-frequency signal transmission through cables, we employ wireless signals propagating in compact, cross-sectional metallic waveguides. Within these waveguides, EM waves are successfully confined and allowed to propagate. As the frequency increases, the cross-sectional size of the waveguide decreases.

For instance, the standardized cross-sectional size for the 220-330 GHz band (J-band) is 0.86 × 0.43 mm^2. However, creating sub-millimeter scale hollow structures with high aspect ratios (smsHS) in bulk metal using traditional machining methods has become increasingly challenging, largely due to the limited freedom to shape these structures and the inability to integrate 3D structures.

Conversely, 3D printers provide a unique advantage, as they can easily fabricate hollow structures, even those with high aspect ratios, through their layering process. Additionally, they enable the creation of three-dimensional free-form hollow structures. Many studies have reported the successful production of waveguides in the microwave and millimeter-wave regions using 3D printers. Recently, even the creation of waveguide devices in the sub-THz region has been accomplished using metal 3D printers (T. Skaik et al. 2022, 2023). However, issues such as surface roughness and cooling-induced cracks can cause significant losses, which can be minimized through plating techniques.

In contrast, SLA-3D printers are recognized for their high resolution, outstanding modeling accuracy, and smooth surface finish. However, the objects they fabricate are typically made from resin cured by UV laser light, which doesn't facilitate the confinement of EM waves. To address this, we suggest modifying the surface of SLA printed objects with metal to allow for EM wave confinement. In this study, we introduce a novel method for fabricating waveguides and bandpass filter waveguides in the 200 GHz to 400 GHz frequency range. Our approach marries a plating technique with RECILS (K. Soeda et al., 2021), a high-performing UV curable resin-based 3D printer. We will discuss the fabrication process and evaluation results of these waveguides in detail.

2. Fabrication of 200-400GHz Waveguides using RECIS.

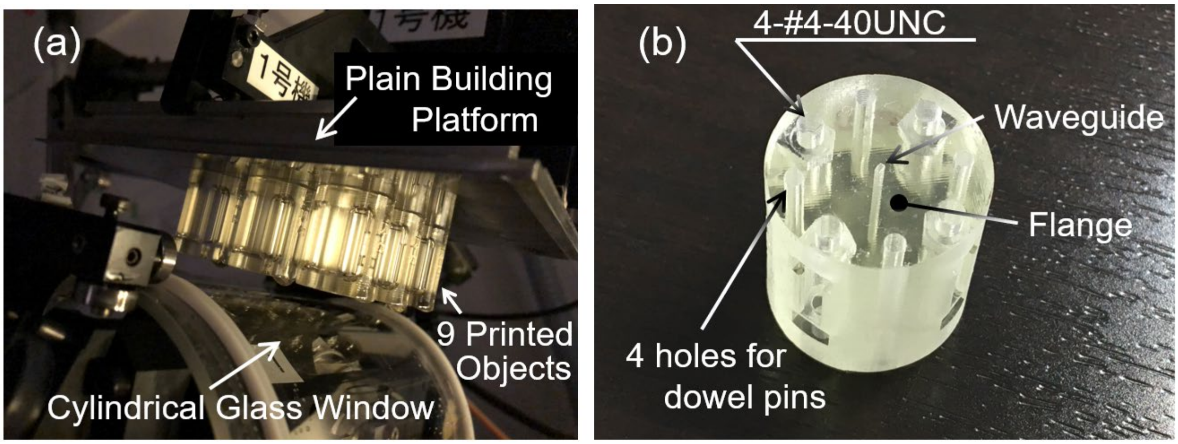

Fig. 1. (a) 9 pieces of waveguide objects are 3D-printed simultaneously, positioned underneath the plain building platform. (b) A RECILS-printed object for a waveguide has a hollow structure with a cross section of 0.86 x 0.43 mm^2 and a length of 25.4mm. The design includes four #4-40UNC screws and four holes for dowel pins, facilitating connection with another waveguide.

2.1. Fabrication of smsHWs using RECILS

The fabrication of microscale structures, like smsHS, showcases the potential of 3D printers. However, conventional SLA-type 3D printers often struggle to achieve both palm-sized object fabrication and a resolution of 20–30 μm. A game-changer is RECILS, an advanced SLA-type 3D printer that features a flat building platform and a cylindrical glass window. This setup allows for the creation of palm-sized objects while maintaining the resolution of 20–30 µm.

RECILS exhibits the ability to fabricate objects measuring up to 100 x 100 x 80 mm³ in size while maintaining a resolution of 20 to 30 µm. Additionally, it boasts a remarkable fabrication speed of up to 100 mL per hour. Fig. 1 (a) shows the fabrication of nine 1-inch-long waveguides using RECILS. These waveguides were constructed to be suspended on the flat building platform, with a total build time of 5 hours (equivalent to approximately 35 minutes per object).

In Fig. 1(b), an object produced using RECILS is depicted, highlighting a hollow structure in the center with a cross-sectional area of 0.86 x 0.43 mm² and a length of 25.4 mm. Both side of the object are flanges having four screws and four holes for the insertion of dowel pins to connect with other waveguides.

2.2. Plating

To confine the EM waves within the hollow structure and facilitate coupling with other waveguides, we applied a plating process to both the smsHS's surface and the flanges at each end. This process involved the creation of a Ni buffer layer, followed by Cu plating. However, using the traditional immersion method proved challenging when reaching the smsHS. To address this, we employed a peristaltic pump to guarantee the plating solution effectively covered the desired areas. We used RECILS to fabricate adapters and a joint, which were then attached to the tubes that pumped the plating solution into the smsHS and its flanges, as depicted in Fig. 2(a). To optimize the process, two waveguides, the adapters, and the joint were inserted into the holder simultaneously, as shown in Fig. 2(b). This streamlined approach negates the need for screws and significantly

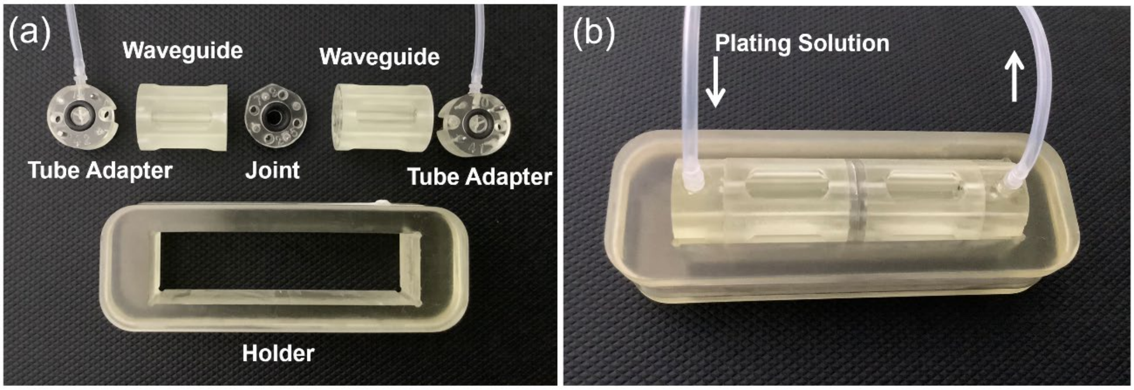

Fig. 2. (a) Adapters and holders for plating printed by RECILS. (b) Two waveguides with adapters are effortlessly inserted into a holder, eliminating the need for screws and subsequently reducing the setup time.

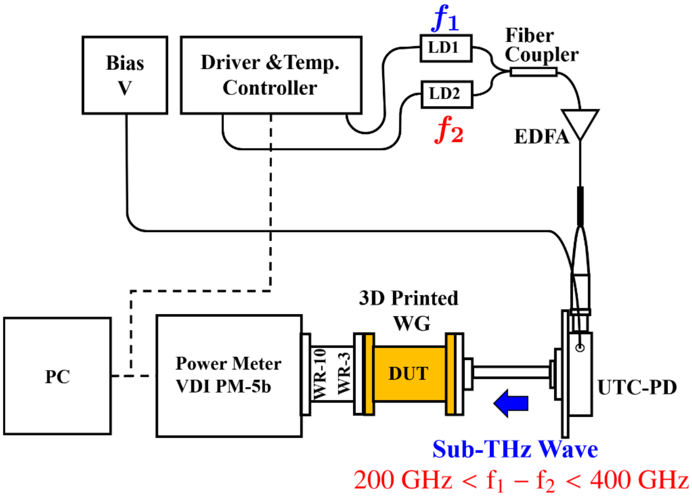

Fig. 3 Schematic of the insertion loss measurement setup. The outputs from each laser diode (LD1 and LD2) are coupled to a high-speed photodiode (UTC-PD), which emits electromagnetic waves at a frequency of f1 - f2.

reduces the overall process time. The holder, containing the two waveguides, adapters, and a joint, was placed in a temperature-controlled water bath, with the plating time adjusted to achieve the desired Ni and Cu thicknesses of 1 µm and 4–5 µm, respectively.

3. Measurements of Insertion Loss

The insertion loss measurement system, represented in Fig. 3, uses semiconductor lasers LD1 and LD2 to generate continuous-wave laser lights. These lights are coupled into Uni-Traveling-Carrier Photodiodes (UTC-PD) via a fiber coupler. Each semiconductor laser emits light at frequencies f1 and f2, respectively. The UTC-PD then generates a continuous wave at a frequency of f1-f2, which is coupled to the waveguide (DTU). In the experiment, we kept the frequency f1 constant, while adjusting f2 by altering the temperature of LD2. This process allows the generation of sub-THz waves ranging from 200 GHz to 400 GHz.

We measured the output intensity from the waveguide using a THz power meter and computed the insertion loss by comparing the transmitted intensity with and without the sample.

4. Performance of RECILS-printed waveguides

The straight waveguide, measuring 25.4 mm in length, exhibited an insertion loss of 0.5–1.0 dB, displaying similar traits to commercially available metal waveguides. The bandpass filter comprises five internal resonators interconnected by an iris, as shown in Fig. 4(a), which is an X-ray Computed Tomography (CT) image. The white areas represent the plated metal parts. Each resonator has a length (L) of 410, 440, and 490 µm, and the iris thickness is 120 µm.

Fig. 4(b) illustrates the characteristics of three bandpass filters (BPFs) with resonator lengths of 410, 440, and 490 µm. The insertion loss (IL) in the transmission region was around 1 dB, and the extinction ratio was 30 dB. Moreover, when we measured it with a vector network analyzer, the extinction ratio exceeded 60 dB. These results are on par with those of bulk metal BPF waveguides.

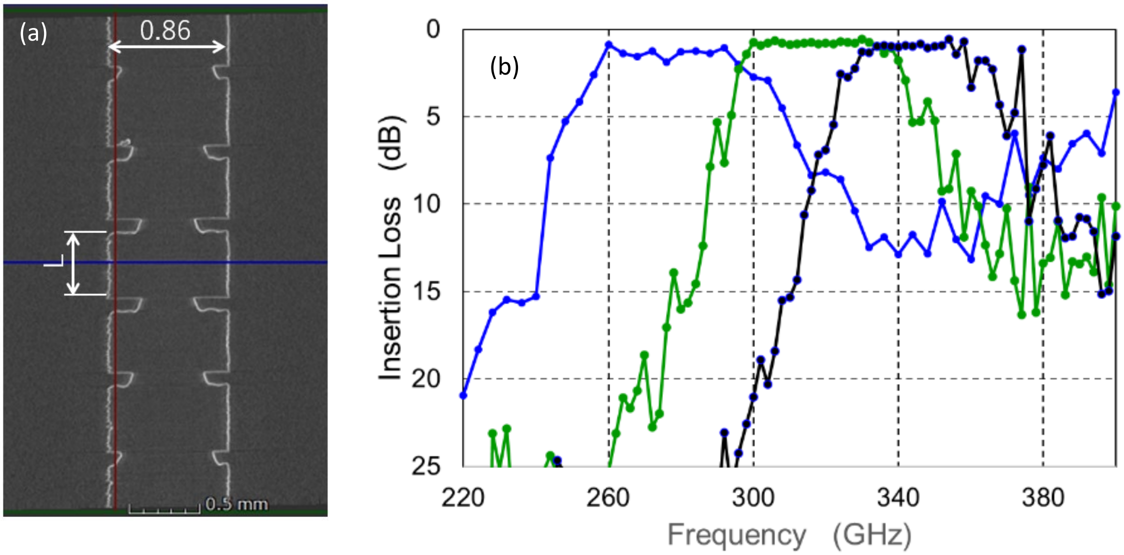

Fig. 4 (a) X-ray CT image of the band-pass filter waveguide. (b) Graph illustrating the insertion loss of three BPF waveguides with resonator lengths L of 490 µm (blue), 440 µm (green), and 410 µm (black).

5. Conclusion and Outlook

We utilized RECIS, a 3D printer capable of creating palm-sized structures with a resolution of 20–30 µm, to fabricate smsHSs with a cross-section of 0.86 × 0.43 mm^2 and a length of 25.4 mm. By combining this technology with metal plating on the inner surface and both ends of smsHSs, we successfully created a waveguide operating in the frequency range of 200 to 400 GHz. Furthermore, we also fabricated bandpass filter (BPF) waveguides by incorporating a coupled resonator structure. These RECILS-printed waveguides exhibited characteristics comparable to those of traditional metal waveguides and metal BPF waveguides. The results obtained in this study highlight the significant potential of combining RECILS with plating as a fabrication technology for waveguides in the sub-THz band. As wireless communications evolve and the usage of higher frequencies increases, there is an escalating demand for waveguides with smaller cross-sections, making conventional machining methods less feasible. Additionally, the integration of multiple waveguide components is crucial for the development of advanced wireless systems, but this often results in increased size and weight. By leveraging RECILS to construct sub-THz waveguide components, it is projected that the weight and cost of future systems can be reduced, providing a more efficient solution.

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