Design, Fabrication, and Measurement of Terahertz Mode Converter

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***Abstract* — In this report, two mode converters are designed and fabricated to extract TE_{41} and TE_{01} modes for the generations of 0.4 THz and 1 THz signal by high-harmonic interaction with gyrating electron beam, respectively. The purities of the desired modes in these two converters are both higher than 90% with remarkably broad bandwidth (380 GHz to 420 GHz for TE_{41} mode and 910GHz to 995 GHz for TE_{01} mode). Since the geometrical aspect ratios of the designed mode converters are both larger than 5, it is too difficult to realize them by the traditional machining processes and UV lithography. We therefore employed X-ray lithography to fabricate these designs, which will be characterized by THz time-domain spectroscopy.**

I. INTRODUCTION

TERAHERTZ (THz) research has fast growth in the past few years, facilitating numerous applications in communication [1], medical image [2], and security [3]. Creation of a terahertz source with high power and broadband tunability therefor becomes an important issue. Gyrotron implemented on cusp gun [4], capable of generating sufficient power, is an ideal tunable radiation source by precisely controlling the harmonic interaction between gyrating electrons and specific waveguide modes, such as TE_{41} mode (for 0.4 THz) and TE_{01} mode (for 1.0 THz).

Mode converter is able to efficiently extract the power of specific waveguide mode generated by gyrotron. .. A typical Y-type mode converter is composed of two-stage Y-shape power dividers made of branched rectangular waveguides, followed by a mode-converting section made of cylindrical waveguide [5]. The input end of the rectangular waveguide is operated in the fundamental TE_{10} mode, which will be subsequently divided into four sub-signals with equal amplitude and phase by the Y-shape power dividers. These sub-signals will be simultaneously injected into a cylindrical waveguide (mode-converting section) through side-wall coupling, together to excite the desired TE_{41} mode (for 400 GHz) or TE_{01} mode (for 1000 GHz). In order to enhance the coupling efficiency and the purity of the desired mode, the radius of the cylindrical waveguide, the tapered slope of the branched waveguides and the divided angles of the Y-shape power dividers were optimized.

However, to this end, there is still severe lack of these devices due to the limitation in machining capabilities. The line widths of these converters at sub-THz/THz regions are too small (about hundred micrometers) to realize through the conventional machining technique that exhibits the highest accuracy only about 10 μm. Micro-fabrication through LIGA (a German acronym for X-ray lithography, electroplating, and molding) and DRIE (deep reactive ion etching) therefore play a novel and important role to fabricate these practical components. [6]

II. DESIGN AND FABRICATION RESULTS

Figure 1 (2) shows the field pattern and the transmission power of the designed TE_{41} mode converter (TE_{01} mode converter). The TE_{41} and TE_{01} mode converters work for 400 GHz and 1000 GHz with -1dB bandwidths achieve 40 GHz and 85 GHz (10% bandwidth), respectively. Because the aspect ratios of input-end rectangular waveguides for both designs reach 2, all higher-order modes other than the fundamental TE_{41} and TE_{10} modes are below cutoffs, facilitating the single-mode operations in the branched tunnels. Furthermore, the radius of the cylindrical waveguide is selected as 705 μm (202 μm), corresponding to a cutoff of TE_{41} mode (TE_{01} mode) at 360 GHz (905 GHz) close to the operating frequency around 400 GHz (1000 GHz). This ensures the maximum coupling efficiency and the highest mode purity of the desired mode, as all of the higher-order modes in each converter are evanescent.

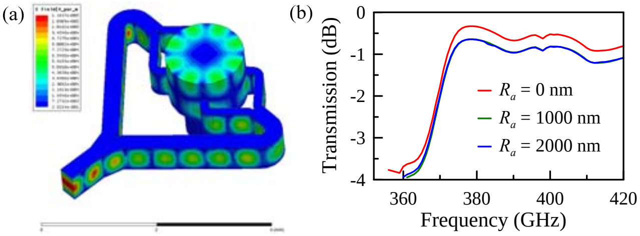


Fig.1 (a) The field pattern of the electric field in TE_{41} mode converter. (b) The simulated transmission magnitudes of TE_{41} mode in the converter.

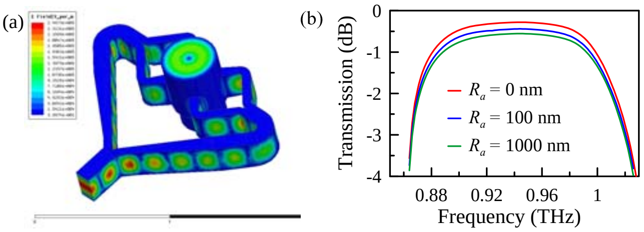


Fig.2 (a) The field pattern of the electric field in TE_{01} mode converter. (b) The simulated transmission magnitudes of TE_{01} mode in the converter.

According to the simulation results from HFSS (Figs. 1b and 2b), as the surface roughness of the metallic walls (denoted by R_a) increases to 1 μm, the transmission powers of desired modes would be dramatically reduced below -0.4 dB. It indicates the importance of surface roughness in the real fabrication. Therefore, we select X-ray LIGA and DRIE to fabricate our designs, which exhibit excellent performance in not only the surface roughness (few nanometers), but also the maximum achievable aspect ratio (~5). These features are superior to UV lithography and RIE (reactive ion etching).

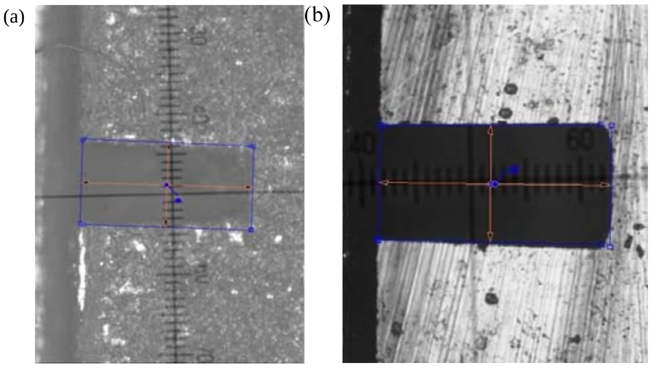
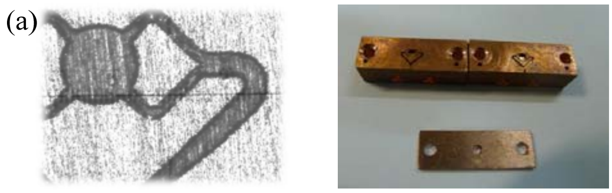
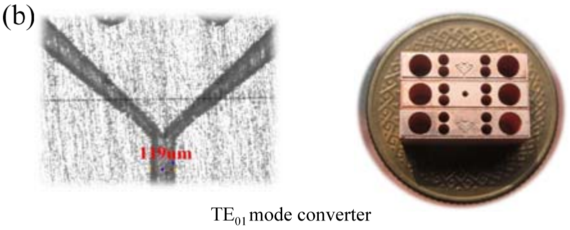


Fig.3 (a) The photo from optical microscopy (OM) of the WR-2.2 rectangular waveguide fabricated by X-Ray LIGA. (b) The OM photo of the WR2.2 waveguide fabricated by DRIE

To examine the feasibility of X-ray LIGA and DRIE for our designs, we first employed them to fabricate a simple WR-2.2 rectangular waveguide (has a width of 560 μm and a height of 280 μm, with an aspect ratio of 2), which is just the input end of TE$_{41}$ mode converter. Figures 3a and 3b show the side-view OM photos of the rectangular waveguides fabricated by X-ray LIGA and DRIE, respectively. As shown, the waveguide boundary fabricated by DIRE has slight distortion compared to that fabricated by X-ray LIGA. This result suggests that X-ray LIGA exhibits greater accuracy and higher achievable aspect ratio than DRIE. Consequently, X-ray LIGA is more suitable to fabricate our mode converters.



TE$_{41}$ mode converter



TE$_{01}$ mode converter

Fig.4 (a) The TE$_{41}$ mode converter was fabricated by X-ray micro fabrication. (b) The TE$_{01}$ mode converter was fabricated by X-ray micro fabrication.

Since the tunnel depths (corresponding to the widths of rectangular waveguides) reach several hundred micrometers, we thus chose SU8-2100 as our photo-resist, which was coated on a copper substrate with proper thickness for each design. Meanwhile, the X-ray gold masks for defining the cross-sectional patterns of TE$_{41}$ and TE$_{01}$ mode converters were respectively made by traditional UV lithography. The aforementioned SU8-2100-coated substrate integrated with the corresponding gold mask was then processed by X-ray lithography in National Synchrotron Radiation Research Center, Taiwan (NSRRC, Taiwan). After that, copper was electroplated on the walls of semi-finished device, forming the metallic boundaries of waveguides. Finally, the residue photo-resist was removed by ion etching such that the air tunnels of the converter were carved out. The structure photo (from OM) of the TE$_{41}$ (TE$_{01}$) mode converter made by the aforementioned process is shown in Fig. 4a (Fig. 4b). Both of devices show good agreement with the original designs.

III. CONCLUSIONS

The broadband TE$_{41}$ and TE$_{01}$ mode converters with -1dB bandwidth respectively achieving 40 GHz at 400GHz and 95 GHz at 1THz (about 10%) are well designed by HFSS and fabricate by X-ray LIGA and DRIE process. These two novel technologies show the significant merit for fabricating THz devices beyond the traditional machining process. And we also compare the behavior of two novel technologies, X-ray LIGA and DIRE, when the structure of desired device is high aspect ratio. Next, we are characterizing the developed sub-THz and THz mode converters through time-domain spectroscopy and really apply those devices in the cusp gun gyrotron system for high-power radiation source. Besides, we can employ the way to design and fabrication converters of any desired mode.

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