Fabrication of a 0.346 THz BWO for Plasma Diagnostics

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***Abstract*—Nuclear fusion energy is perhaps one of the most demanding challenges the scientific community is facing. Unfortunately, the plasma is affected by micro-turbulence, which is still not fully understood, but which can degrade plasma confinement. The 0.346 THz backward wave oscillator is the enabling device for a high-k plasma collective scattering diagnostic that will provide unprecedented insight on turbulence thereby contributing to the realization of fully operational fusion reactors. This paper describes the final fabrication phase of the 0.346 THz backward wave oscillator for the collective scattering diagnostic jointly performed in an international project, involving three leading institutions in vacuum electronics. The advancements in technology will open the route to new families of THz vacuum electron devices to enable new THz applications and provide industry with new advanced processes.**

***Index Terms*—Backward wave oscillator, Double corrugated waveguide, Nano-CNC milling, Nuclear fusion, Vacuum electronics**

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I. INTRODUCTION

PLASMA micro-turbulence on the electron gyro-scale is a significant obstacle for the success of nuclear fusion energy and extensive efforts are devoted to the modeling and measurement of the plasma behavior [1-3]. Collective Thompson scattering has proven to be a suitable diagnostic technique to perform the requisite measurements in a nonperturbative manner. The actual equipment is still not adequate to properly map the plasma. The availability of an affordable and compact THz source [4, 5] will permit one to extend the dimensions of the plasma region to probe and replace bulky FIR laser so far used.

A backward wave oscillator (BWO) at 0.346 THz has been identified as a key device to provide adequate local oscillator power to enable a large matrix of heterodyne detectors, to extend the region of plasma diagnostic [6]. The BWO design phase was extensive due to the formidable fabrication challenges and resulted in a number of different solutions and advancements in the field. The final design was then chosen on the basis of performance and feasibility. The fabrication phase is in progress.

The BWO consists of several components: an electron gun producing a high current density electron beam; a magnetic system maintaining a single, slim linear electron beam; a slow wave circuit transferring the electron's energy into electromagnetic wave energy; a collector recovering the residual energy of the spent electron beam; an RF window maintaining the tube's internal vacuum and coupling the output wave out of the device with minimum losses.

In this paper, we present design and fabrication issues related to two candidate slow wave structures (SWS), the double corrugated waveguide (DCW) circuit and the grooved single grating (GSG) circuit, for the 0.346THz BWO. The circuit simulation results are presented in Section II. The fabrication of the double corrugated waveguide (DCW) circuit and the grooved single grating (GSG) circuit are presented in Section III. The electron gun and magnetic field are described in Section IV. The RF window is described in Section V. Section VI is the conclusion of this paper.

II. Circuit Simulations

Novel effective solutions of BWO realizations have been presented based on the double corrugated waveguide (DCW) [7] slow-wave structure. The DCW was conceived to support a cylindrical electron beam flowing along two parallel rows of pillars in a rectangular waveguide. The schematic view of the DCW SWS is shown in Fig. 1.

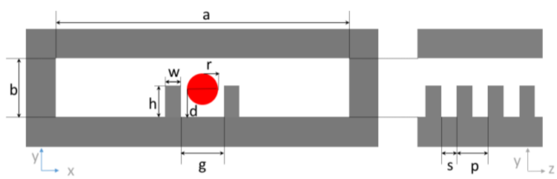

Fig. 1. Schematic view of the double corrugated waveguide from transverse and axial cross-sectional views.

The typical design of the DCW is based on setting the distance between the two rows of pillars, that forms the beam channel, as narrow as possible, to have a high interaction impedance and assure a suitable distance of the beam from the metal surfaces of the pillars. The interaction impedance is an inverse function of the beam channel width [4]. The beam cross section is constrained by the beam channel width and the performance are limited by the maximum current that the beam can support, in terms of current density, gun compression factor and value of the magnetic focusing system.

An existing electron beam optic system (described in Section IV) has been adopted with 22 kV beam voltage, 50 mA beam current. In this paper, it is demonstrated that the use of a wider beam channel, 220 microns vs. 120 microns, to host an electron beam with wider diameter, 160 microns vs. 80 microns, higher beam voltage, 22kV vs. 12.8 kV, and higher current, 50 mA vs. 10 mA, can provide a substantial increase of performance, even if the width of the beam channel exceeds the theoretical optimum value [1].

The diameter of the electron beam is substantially wider than the electron beam designed in previous versions of the DCW BWO [6]. As above mentioned, the distance between the two rows of pillars should be kept as small as possible to increase the interaction impedance. In the present design, a different approach was adopted. The wide and high energy electron beam was located in the wide channel between the two rows of pillars, interacting with the side regions of the electric field. The use of a wide beam diameter substantially eases the beam alignment and hence assembly requirements.

The double corrugated waveguide circuit was manufactured using the NN1000 DCG HSC nano- CNC milling machine. The tolerances are better than 1.5 % for all the dimensions. The assembly of the DCW is in progress. The challenge is to achieve a good electrical contact between the two halves. Due to the short wavelength, a misalignment or gap of a few microns will affect the performance. The DCW SWS was purposely optimized to support a 160 μm electron beam diameter. The DCW dimensions are listed in TABLE I.

Extensive 3D electromagnetic and particle-in-cell simulations were performed to define the final dimensions of the DCW and optimize the coupler to the output flanges. Fig. 2 shows the dispersion curve for the DCW with the superimposed beam lines for three beam voltages.

Fig. 3 shows the output power variation with time, simulated by two particle-in-cell simulators, CST-PS and MAGIC3D, using the same design parameters. The external focusing magnetic field is computed as 0.65 T. The conductivity of copper is set as 2.353×10^7 S/m to take into consideration of the finite surface roughness of the fabricated DCW.

TABLE I
Dimensions of the Double Corrugated Waveguide Slow Wave Structure of the 0.346 THz BWO

Dimension	Value (μm)
a	1500
b	355
d	120
g	220
h	160
p	170
r	80
s	80
w	80

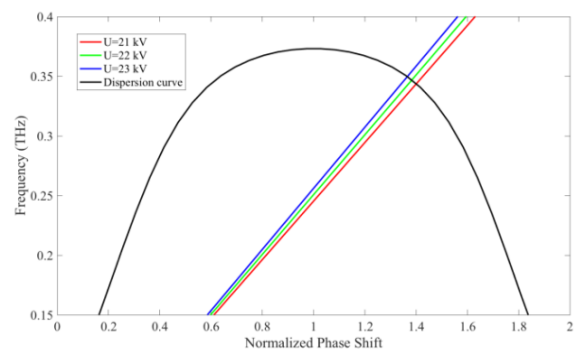

Fig. 2. Dispersion diagram of the DCW with wide electron beam tunnel using the parameters as shown in TABLE I. The electron beam lines are also shown for different beam voltages.

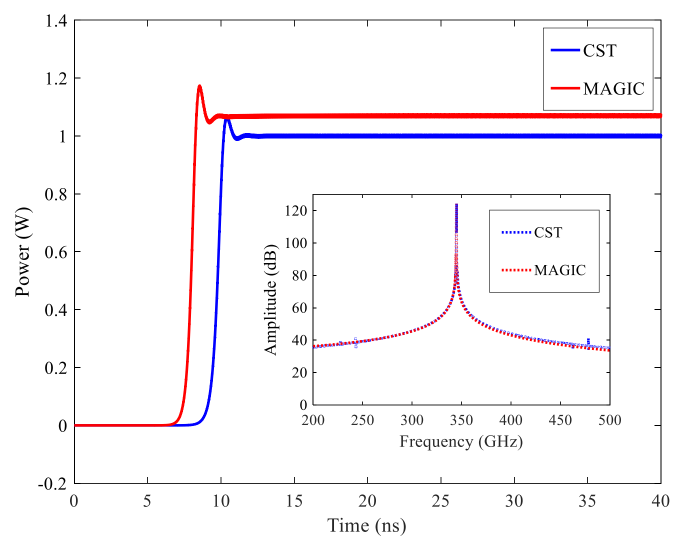

Fig. 3. Output power variation with time from CST Particle Studio and MAGIC3D. The inset shows the spectrum of the output from the designed BWO.

The very good agreement between the two simulators demonstrates the validity of using a wide beam channel in the DCW. The output power of the designed BWO stabilizes around the unprecedented value of 1 W. The corresponding output spectra of the designed BWO from both particle-in-cell simulators are shown in the inset, each showing only one peak at around 0.346 THz.

The reason of the improved performance is that the beam, even if the field on the axis is weaker than the DCW in [1], interacts with the side regions of the electric field closer to the pillars where the interaction impedance is higher. The use of a wide beam diameter and wider beam channel substantially ease the beam alignment and hence the DCW fabrication and assembly.

In addition to DCW, another structure suitable for fabrication of a THz BWO was also explored. A novel slow wave structure called a grooved single grating (GSG) structure is designed for the 0.346 THz BWO [8]. The front view and the longitudinal view of this structure are shown in Fig. 4. Dimensions of this structure for a 0.346 THz BWO are listed in TABLE II. The dispersion curve shows that the fundamental wave is the forward wave, so the -1st spatial harmonic is the backward wave with higher impedance (Fig.5), which is suitable for BWO realization. The impedance of the 0.346 THz BWO is calculated by CST Microwave Studio and is about 1.5 Ω on the axis of the electron beam around 0.346 THz.

The dispersion curve of the traditional folded wave guide slow wave structure displays that the fundamental wave is back-ward wave, if the back-ward wave is chosen for operation; the operation voltage would be very high. The -1st spatial harmonic of back-ward wave is chosen for operation, however, the impedance of the -1st spatial harmonic is too low that the output power is very small. The DCW and GSG structure are different from the folded waveguide structure, and its fundamental wave is forward wave with -1st spatial harmonic being backward wave and will have higher impendence and lower operation voltage when the -1st backward wave is used for BWO operation.

The PIC simulation is performed by CST Particle Studio and its result shows that 80 periods of the structure produces an output of 5 W (Fig.6). A copper conductivity of 1.6×10^7 S/m is used to take into account the higher losses due to the surface roughness of 200 nm. The operation current is 50 mA and the voltage is 22 kV. The spectrum of the output signal is shown in Fig.7, indicating an oscillation frequency of 0.346 THz, which can be tuned by operation voltage.

The output power obtained by GSG BWO is very promising and a second BWO will be built with this SWS.

III. Circuits Fabrication

In this section the fabrication of the parts of the 0.346 THz BWO will be described. Two fabrication processes, one based on advanced CNC milling and one based on photolithographic process have been applied depending on the SWS geometry. The DCW BWO is in advanced stage of fabrication. The fabrication of the grooved single grating SWS will be demonstrated.

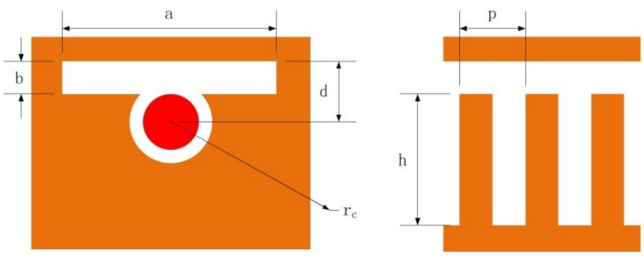

Fig. 4. Schematic view of the grooved single grating from transverse and axial cross-sections.

TABLE II
DIMENSIONS OF THE GROOVED SINGLE GRATING SLOW WAVE STRUCTURE OF THE 0.346 THZ BWO

Dimension	Value (μm)
a	530
b	100
p	185
h	350
r_c	100
d	190

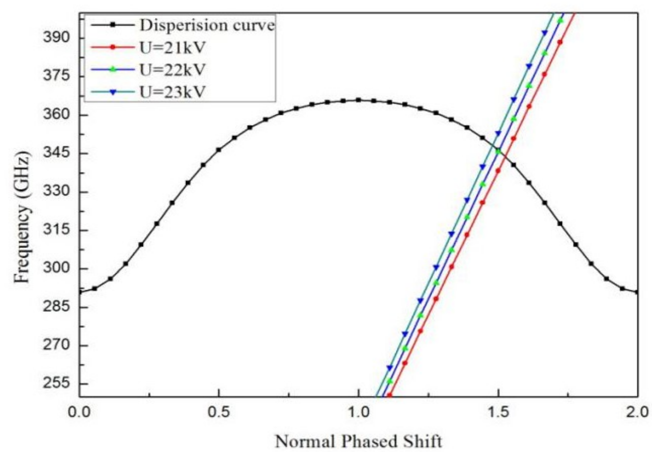

Fig. 5. Dispersion diagram of the grooved single grating SWS of the 0.346 THz BWO.

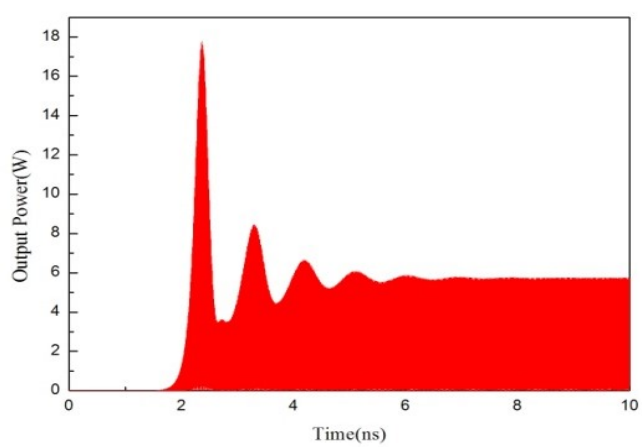

Fig. 6. The output signal of the circuit

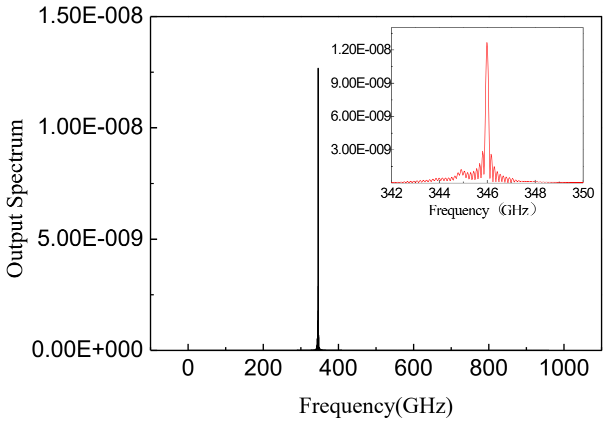

Fig. 7. The FFT analysis of the output signal

A. DCW circuit

The assembly of the DCW circuit is shown in Fig.8. It consists of two halves to be assembled as a full circuit in a cylinder with diameter of 3 mm, which subsequently will be inserted into the existing magnet system at BVERI.

The DCW circuit is in fabrication phase by using the NN1000 DCG HSC nano-CNC milling machine developed by Digital Technology Laboratory, subsidiary of DMG – MORI, in Davis CA as a prototype machine for advancement of nano-precision manufacturing capabilities [9, 10]. The DCW circuit is manufactured employing CNC milling technology to create the micro pillars as is shown in Fig.9 and the average surface roughness (Ra) across pillar surfaces is about 124 nm after copper bright dip cleaning. Conventional high precision CNC milling technology is employed to machine the waveguide and beam structures around the circuit as shown in Fig.10 and the average surface roughness (Ra) across the beam tunnel is about 113 nm. Diffusion bonding will be employed to create the proper bond and alignment between the circuit halves. Finally, outside machining operation will be used to turn the assembly into the cylindrical part ready for alignment with the vacuum envelope and the magnetic confinement structure of the BWO.

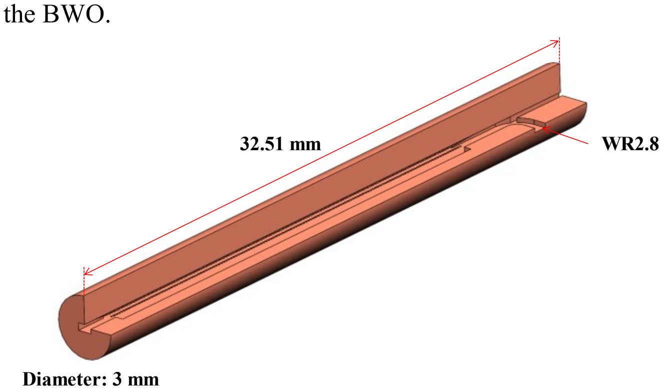

Fig. 8. Assembled DCW with the joint area for the coupler and RF windows.

B. Grooved single grating (GSG) circuit

Different from the DCW which is suitable to be built by nano-CNC milling technology, the complex shape of the grooved single grating circuit requires it to be fabricated using

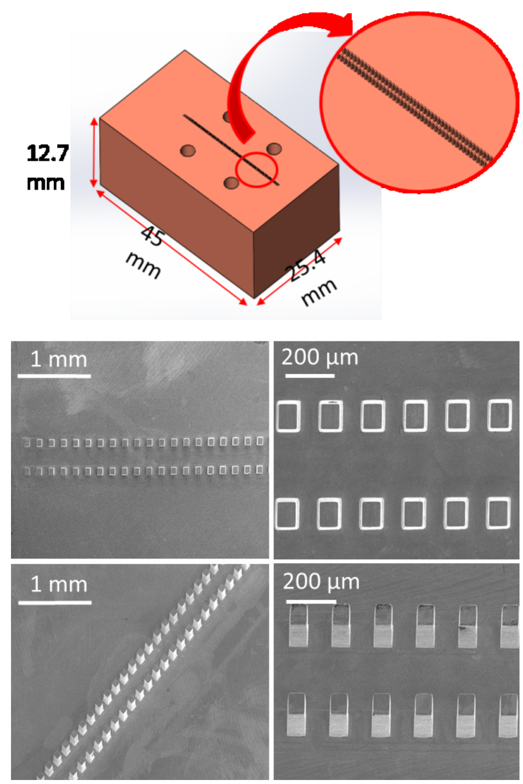

Fig. 9. Schematic of the DCW top circuit (top) and its SEM images (bottom).

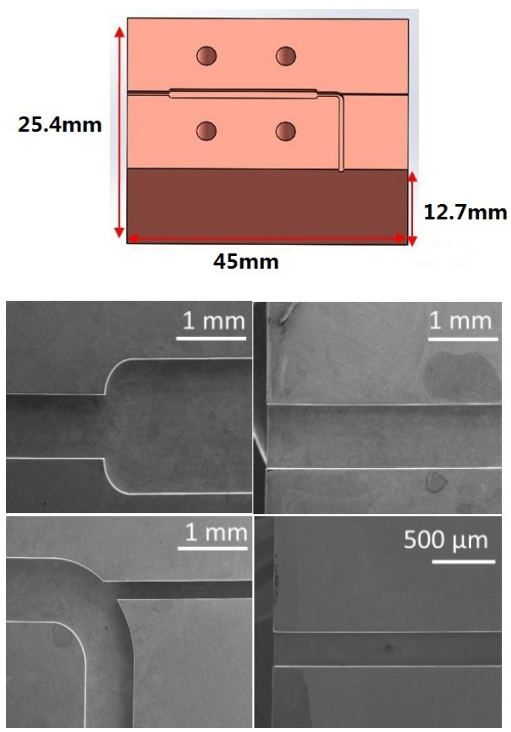

Fig. 10. Schematic of the DCW bottom circuit (top) and its SEM images (bottom).

UV-LIGA micro-electro-mechanical technologies. This technology has been already investigated for the fabrication of circuits in W-band and 220 GHz traveling wave tubes [11, 12]. SU-8 photoresist has been employed in the process because of its excellent resolution, good vertical sidewall profiles, and good component shape. The SU-8 mold is copper electroformed to produce metallic microstructures. After SU-8 removal, the electron beam groove and the shape of the circuit are EDM-cut, as shown in Fig.11. The accuracy of the dimensions of the fabricated circuit is about 1 μm.

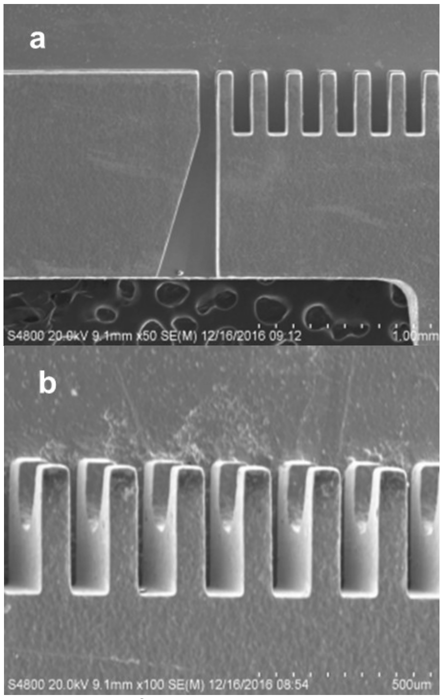

Fig. 11. SEM images of grooved single grating circuit: (a) output section of the circuit; (b) enlarged image of the grooved single gratings.

There are many researches on the UV LIGA for the higher frequencies vacuum devices [13, 14, 15, 16, and 17]. In this paper, the UV-LIGA process starts with the preparation of 4 in diameter oxygen-free copper wafers. The wafer is lapped and polished on both sides, then cleaned with acetone in an ultrasonic cleaning bath for 5 minutes, rinsed with de-ionized water, and then air dried with filtered, pressurized nitrogen, followed by a dehydration bake in an oven. The main processes for an SU-8 layer include: (1) Dispense SU-8 on the 4 in wafer and spin at low rotation speed; (2) Soft bake for a long period of time up to several hours depending on the SU-8 thickness; (3) UV light exposure; (4) Post-exposure bake on a level hotplate; (5) Development in Microchem SU-8 developer; (6) Copper electroforming; (7) SU-8 removal. In this process, the extra high internal stress from SU-8 after baking is a critical problem associated with the use of very thick photoresist. The stress makes SU-8 crack, wrinkle and strip from the copper wafer. In order to reduce the internal stress, experimental research has been conducted to optimize the process, including the soft bake time and temperature and the relaxation time with the responding spin speed. Using the optimized process, patterned SU-8 as a micro-mold has been successfully fabricated with good adhesion between SU-8 and the copper wafer.

The GSG (Grooved Single Grating) circuit has been assembled and cold tested by vector network analyzer and the frequency extended module. The operation frequency of the vector network analyzer is from 325 GHz to 500 GHz. The SWS is connected to the window by clamps, and the cold test result shows the VSWR near 346 GHz is less than 2.5. Fig 12 shows the comparison of the simulated and tested VSWR of the GSG circuit from 340 GHz to 350 GHz, which shows that there is greater fluctuation for the tested VSWR.

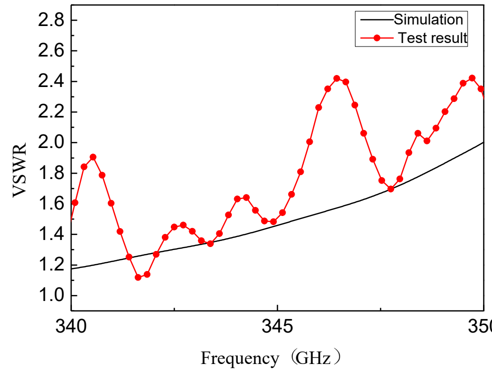

Fig. 12. Comparison of the simulated and tested VSWR of the GSG circuit.

IV. Electron Gun and Magnetic Field

To produce a pencil electron beam with a diameter of 160 μm, a Pierce's electron gun, a periodic permanent magnet (PPM) system, and a collector have been designed and fabricated. The Pierce's electron gun consists of a circular M-type cathode of 0.45 mm radius, a focus electrode for pulse modulation and an anode. The simulation of the electron gun is performed by Vector Fields Opera software. In the simulation, 51 mA of current is emitted at 22 kV.

The electron beam emitted by the electron gun is then confined by the PPM system. This system consists of several pairs of samarium cobalt magnets which provide a periodic z-directional magnetic field. The periodicity of the system is 6.4 mm and the peak magnetic flux density is 0.5 T. In the Opera simulation, the electron beam is well confined in a radius of 0.1 mm as is shown in Fig. 13.

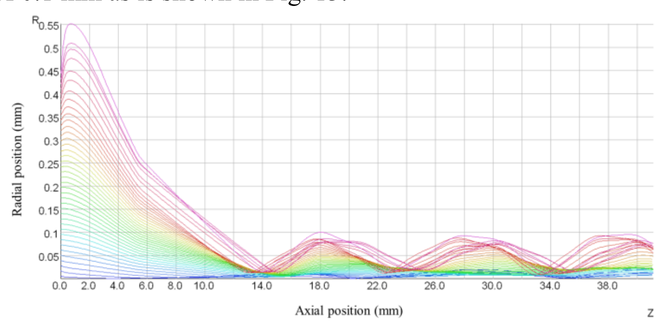

Fig. 13. Simulation result of the electron beam emitted from the cathode and confined by the PPM system.

To demonstrate the design of the electron gun and magnetic field, a beamstick prototype has been built and tested. The beamstick prototype consists of a Pierce's gun, a PPM system, a collector and a drift tube. It is nearly identical to the BWO except that a drift tube is used instead of the circuit and the RF window. The drift tube is a simple cylindrical tunnel in copper with inner radius of 0.12 mm, the same size as the beam tunnel of the circuit. In the test (Fig. 14), 54 mA of current is emitted from the electron gun at 22 kV and 50 mA of current is received by the collector. The transmission ratio of this prototype is 92.6%.

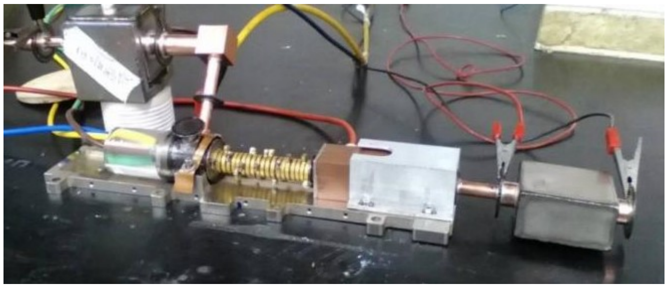

Fig. 14. Beamstick prototype

V. RF Window

The RF window is a key component of the BWO. It must provide very low microwave loss and at the same time to be vacuum-sealed from the atmosphere. The RF window for the BWO is a pill-box window and will be assembled to the circuit body by brazing (Fig.15) the window disk to metallic frames. A pillbox window with a composite microwave plasma chemical vapor deposition (MPCVD) diamond disk has been simulated and optimized using HFSS software. In the design, the relative dielectric constant of diamond is set as 5.6 and the thickness of the disk is 0.15 mm. Fig.16 shows the S11 simulation result of the window which is lower than -20 dB from 320 to 360 GHz.

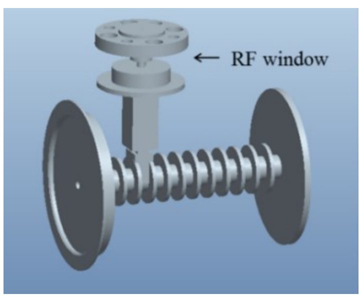

Fig. 15. 3D solid model of the window and the SWS

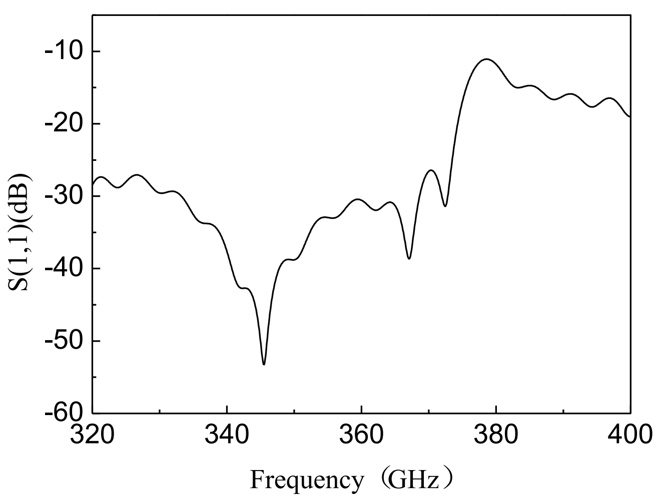

Fig. 16. Simulation result of S11 for the RF window with diamond disk

The 0.15 mm disk thickness poses some problems to mechanical properties of conventional polycrystalline diamond (PCD) films. It is, therefore, desirable to engineer a composite film of PCD and ultra-nanocrystalline diamond (UNCD) for the window, as to combine the advantages of PCD and UNCD [18].

Diamond films were produced on an N-type Si (100) wafer using a 6 kW, 2.45 GHz MPCVD reactor (DiamoTek 700) [19]. The windows were assembled by brazing the diamond disks to metallic frames using Ag-Cu fillers. Then insertion losses of the windows were measured by a microwave source and a power meter. Fig.17 shows the comparison of the simulation results and measured results for the insertion losses of the RF windows, which show that the insertion losses of the windows are better than 3 dB from 330 to 350 GHz.

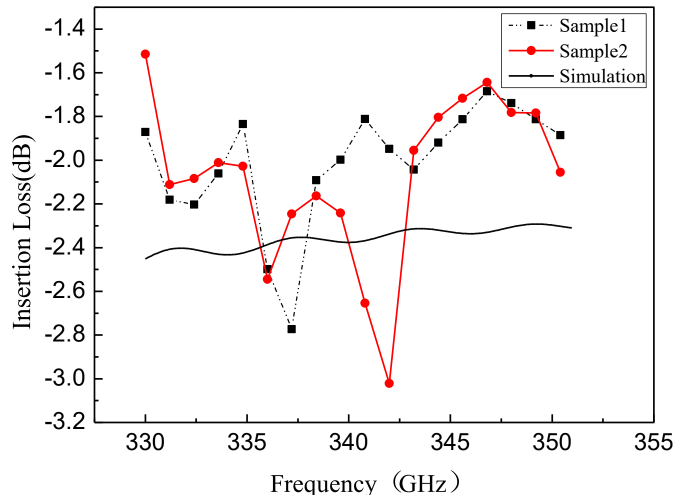

Fig. 17. Comparison of the simulated and measured results for the insertion losses of the RF windows.

VI. Conclusion

The fabricated parts for the first 0.346 THz BWO for plasma diagnostic have been presented. Two different slow wave circuits, the double corrugated waveguide and the grooved single grating, have been designed, simulated, and fabricated. Two advanced micromechanical technologies have been successfully adopted. The double corrugated waveguide circuit was manufactured using the NN1000 DCG HSC nano-CNC milling machine and the grooved single grating circuit was fabricated using UV-LIGA. The electron beam optic system consisting of a Pierce's gun, a PPM system and a collector has been experimentally demonstrated with over 50 mA of current at 22 kV. A pill-box window with MPCVD diamond disk has also been demonstrated and will be assembled to the circuit. The assembly and measurements of the 0.346 THz BWO will be a breakthrough in the field of THz vacuum electron devices.

Acknowledgment

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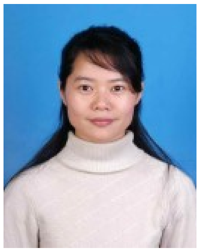

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