Invited Paper

Study of High Frequency Folded Waveguide BWO with MEMS Technology

Jinjun Feng *, Dapeng Ren, Hanyan Li,Ye Tang and Junyi Xing
National Key Laboratory of Science and Technology on Vacuum Electronics，Beijing Vacuum Electronics Research Institute, P. O. Box749-41, 100015
* Email: fengjj@ieee.org

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Abstract: The study of backward wave oscillators with folded waveguide circuits at frequencies at W band and Y band have been carried out in this paper. W band TWT with folded waveguide manufactured with EDM has reached continuous wave 10*W* and pulsed 100*W* at 20% duty in the authors' research group, while for higher frequency devices, we start from W band folded waveguide pencil beam BWO of 100*mW* power level, for which the entire design and simulation have been finished and the permanent magnet system has been assembled and tested. Y band 220*GHz* folded waveguide BWO with pencil beam for practical tubes and sheet beam for transmission experiment are also designed and simulated. The impedance and field flatness across the beam were monitored in the simulation. UV-LIGA and DRIE techniques are investigated for the research of micro-fabrication process for W band folded waveguide slow wave structures.

Keywords: BWO, MEMS, Terahertz

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1. Introduction

High frequency vacuum devices are critical for the systems in the application of biological and chemical material detection, concealed metallic weapon detection, medical imaging, material science, space science etc.[1], and many researches on the design, simulation, process and test have been carried out, especially with the micro-fabrication using LIGA and DRIE. The types of devices include traveling wave tubes(TWT), backward wave oscillator (BWO), extended interaction oscillator(EIO), extended interaction amplifier(EIA) and regenerative TWT oscillator, Smith-Purcell devices, orotron, clinotron, Nanoklystron (reflex klystron) etc. with pencil beam, multiple beam or sheet beam, etc., and the slow wave structures include round and square helix, coupled cavities, folded waveguide, pin-array, vane-loaded waveguide, corrugated waveguide, photonic band gap structure, inter-digital, omniguide and meander strip lines etc., while the frequencies start from 94*GHz* to 220*GHz*, 670*GHz*, 850*GHz*, even up to 1030*GHz* or around[2,3,4,5,6,7,8,9,10]. As the frequencies go up, microfabrication techniques with MEMS have to be used for the manufacturing of the interaction circuits and the coupling systems for its requirement on small size and surface roughness. One of the successful high frequency vacuum power source with microfabrication is the regenerative folded waveguide TWT oscillator with frequency of 0.65*THz* and power of 52*mW* at 3% duty[7].

MEMS techniques with HAR (high aspect ratio) capability have been suggested and implemented for the fabrication of the small-size slow wave structure in microwave tube community. For high frequency vacuum devices, the aspect ratio is not so great but with great depth up to 950 *microns*, which is half of the W-band folded waveguide structure. Table 1 shows the typical dimensions of folded waveguide at different frequencies from Ka band to 560*GHz* based on the authors' preliminary investigation, from which we can see that these microstructures are different from those for RF MEMS and optical MEMS which have smaller size, typically microns to tens of nanometer with over 10 aspect ratio. The frequently used micro-fabrication techniques are the X-ray LIGA, UV-LIGA and DRIE. While X-ray LIGA is expensive and time-consuming with long period of time for waiting X-ray facilities, UV LIGA can be finished within one or two weeks with SU8 and KMPR including exposure, electroplate and milling, DRIE of silicon wafers can been etched followed by conformal coating of metal to form folded waveguide as slow wave structures.

The authors' research group has carried out some research on design and simulation of TWT, BWO, Clinotron, regenerative TWT Oscillator for frequencies from W band to 560*GHz*[11,12,13,14,15]. For practical application, BWOs are investigated for easy test without drive source, then we start from W band BWO and extend this research to 220*GHz* BWO with pencil beam as practical devices and sheet beam as transmission experiment. In this paper, progress on the W band and 220*GHz* BWO will be reported, together with the progress of UV LIGA manufactured W band folded waveguide structure.

Tab. 1 Typical dimensions of folded waveguide structures for devices at different frequencies

Frequency(*GHz*)	Wide side	Narrow Side	Beam Tunnel Radius
35	4.77*mm*	0.8*mm*	0.25*mm*
94	1.9*mm*	0.3*mm*	0.17*mm*
140	1.35*mm*	0.24*mm*	0.1*mm*
220	0.76*mm*	0.16*mm*	80*μm*
560	0.3*mm*	43*μm*	20*μm*

2 W-band BWO

The aim of the project is to assemble a practical BWO at W band with an output power of 100*mW* and around 15*GHz* tuning bandwidth. The design and simulation have been finished and the manufacturing and assembly are under progress. The voltage is 6-12 *KV* and beam current is 12 *mA*. Table 2 shows the dimensions of the designed folded waveguide, and Fig. 1 shows the dispersion properties, where the first space harmonic is chosen in the interaction for low operation voltage.

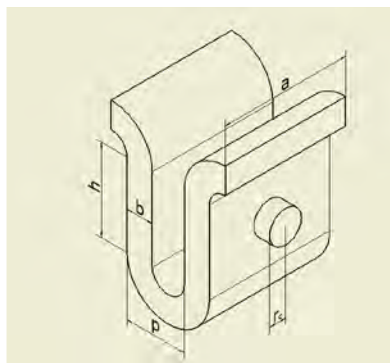


Fig. 1 Schematic dimensions diagram of pencil beam folded waveguide

Tab. 2 Dimensions of the folded waveguide for W band BWO

Wide side(a)	Narrow side(b)	Straight section (h)	Period (p)	Beam tunnel radius (r_c)
1.9*mm*	0.2*mm*	1*mm*	0.6*mm*	0.175*mm*

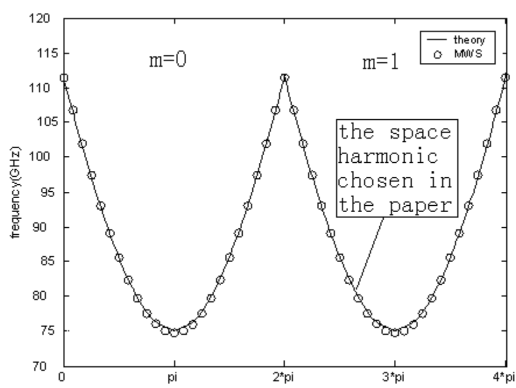


Fig. 2 Frequency vs. the phase shift per period. The solid line is obtained through calculation and the circle line is from Microwave Studio (*MWS*)

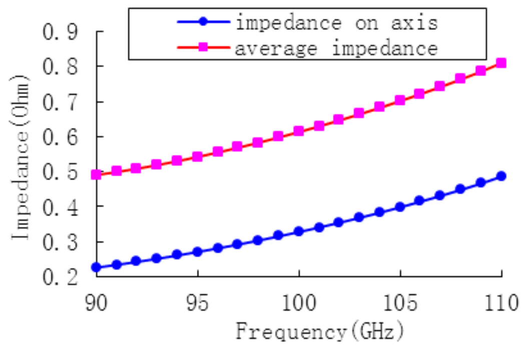


Fig. 3 The axial impedance and average impedance from CST Microwave studio

Fig. 4 and Fig. 5 show the characteristic of tuning and the output power, respectively. The simulation has a good agreement with theoretic calculation, and the operation frequency is from 90-107*GHz*, and operation voltage is from 6*kV* to 12*kV*.

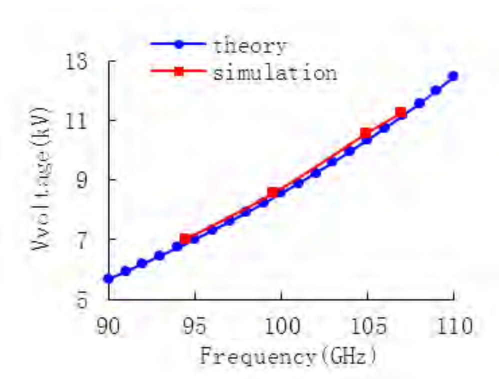


Fig. 4 The tuning characteristic of the W band BWO from calculation

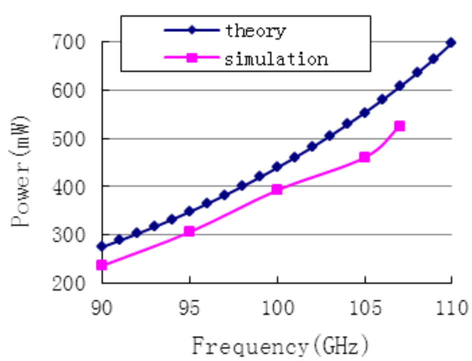


Fig. 5 The output power calculated by theory and simulated for W band BWO

Using CST Particle Studio for the beam-wave interaction, the output signal of the simulation result is shown in Fig. 6 with the beam current 12*mA* and voltage 7.5*kV* under focusing permanent magnetic field of 6000*Gauss*. The output signal spectrum is analyzed by FFT and the results are shown in Fig. 7, which indicates that the system oscillates at 99.36*GHz* with an output power of 392.967*mW* which is calculated by Poyting vector through monitoring the electric field and the magnetic field at the output port, for comparison, the output power from the small signal theory calculation is 458.8*mW*.

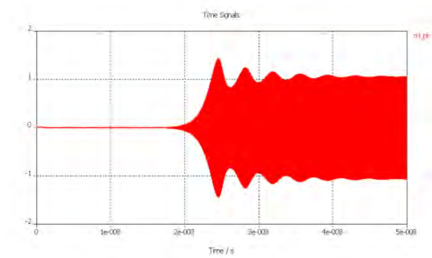


Fig. 6 The output signal of the simulation by Particle Studio

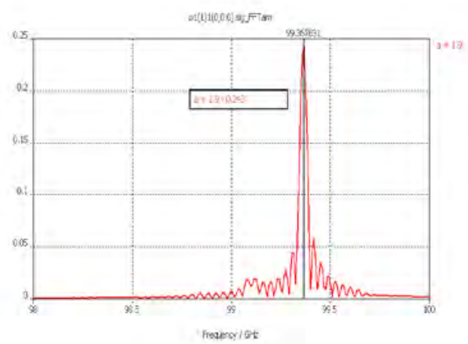
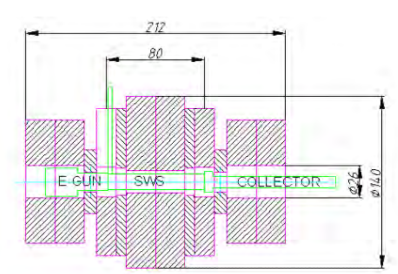
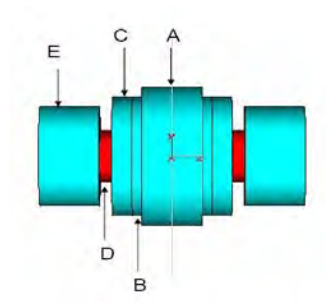


Fig. 7 The FFT result of the output signal with oscillation frequency of 99.36*GHz*

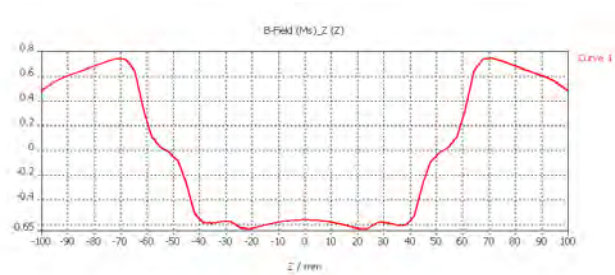
Plane cathode and permanent magnet system for the electron optics system are chosen for less beam fluctuation, and the gun is immerged in the magnetic field. The intensity of permanent magnet is greater than 5800 *Gauss* in the interaction section of 80*mm* length. Fig. 9(a) shows the cross section of the magnetic system and its relative position to the electron gun, interaction section and the collectors. The permanent magnetic system consists of the main magnet, secondary magnets, C-type magnets for RF coupling, pole-pieces and opposite magnets arranged from center to the end, and all parts are assembled and fixed inside a stainless steel barrel with a total weight of around 30*Kgs*. Fig. 8 shows the assembled magnetic system with inner diameter of 24*mm*, outer diameter of 180*mm* and length of 230*mm*. Fig. 9(b) shows the solid model for computer simulation and Fig. 9(c) is the simulation results of the magnetic system which can be compared with those tested results shown in Fig. 10. The uniform magnetic field area is from -40*mm* to 40*mm*, and the permanent magnet system is realized by piling Sm_2Co_{17} magnets. The tested field is above 6000*Gauss*, and the fluctuation is less than 5% as is shown in Fig. 10. The test of the magnet field is implemented point-by-point with 5*mm* spacing. The gun is assembled successfully and the beam transmission ratio will be tested soon. Attenuators used for the matching have been finished by using carburized porous Al_2O_3 similar to that of W band TWT[16]. The prototype is expected to be finished and tested in the next year.

Fig. 8 The picture of the permanent magnet for W band BWO





(a) (b)



(c)

Fig. 9 (a) The relative position of the permanent magnets and parts of BWO, (b) the stacks of magnets solid model for simulation, where A is for main magnet, B for secondary magnets, C for C-type magnets for RF coupling, D for pole-pieces and D for opposite magnets, 9(c) Simulation results of the magnetic field.

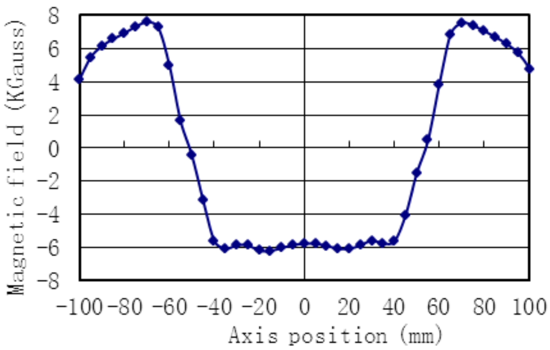


Fig. 10 The measured magnetic field for the permanent magnet focus system (a better picture is needed with explanation)

3. Y-band pencil beam folded waveguide BWO

Y-band is for the frequency range from 170*GHz* to 260*GHz* in which 220*GHz* is one of the transmission windows of millimeter wave. For a practical 220*GHz* BWO, a pencil beam is selected for easy realization. We aim at 10*mW* power and 30*GHz* tuning bandwidth. The design processes of high frequency circuit and electron optics are the same as that used for W band BWO. The designed tuning voltage is 9-18*KV*, beam current 4mA, beam radius 0.08*mm* and attenuators of carburized porous Al_2O_3 will be used. Table. 3 shows the designed dimensions of the folded waveguide slow wave structure.

Tab. 3 Structure dimensions of folded waveguide structure for Y band BWO

Wide side(a)	Narrow side(b)	Straight section (h)	Period (p)	Beam tunnel radius (r_c)
0.76*mm*	0.16*mm*	0.52*mm*	0.36*mm*	0.1*mm*

Fig. 11 shows the dispersion curve together the beam voltage line, and Fig. 12 shows frequency tuning with the voltage, from which it can been seen that the voltage varies from 9*KV* to 18*KV* for 220±15*GHz* tuning. Fig. 13 shows the axial impedance and the corresponding average impedance, and it is seen that the impedance is quite small in Y-band.

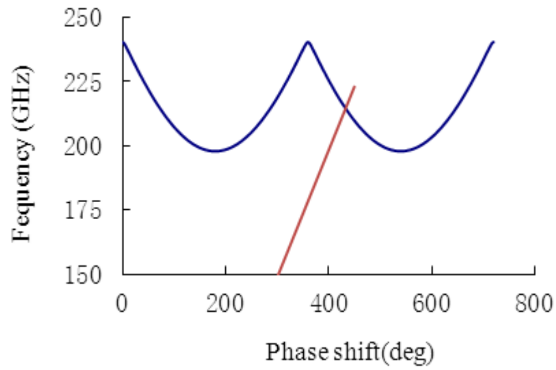


Fig. 11 The dispersion curve and the beam voltage line of 220*GHz* pencil beam BWO

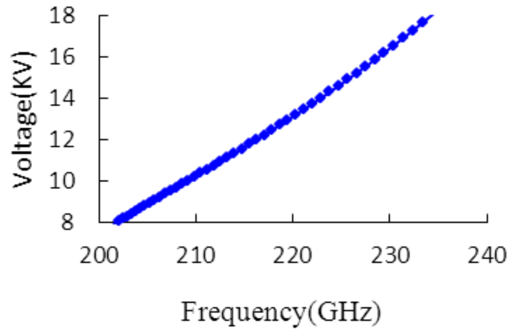


Fig. 12 Frequency tuning with the voltage of 220*GHz* pencil beam BWO

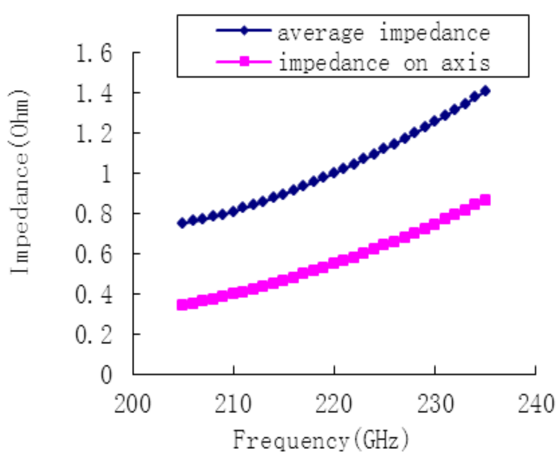


Fig. 13 The axial impedance and the corresponding average impedance

4. Y-band sheet beam BWO

The Y-band sheet beam BWO as beam transmission experiment is designed and optimized with MWS (Microwaves Studio) and Particle Studio. We aim at 10*mW* power and 30*GHz* tuning bandwidth. A period Y-band sheet beam FWG is shown in Fig. 14. The designed folded waveguide SWS parameters are shown in Tab. 4.

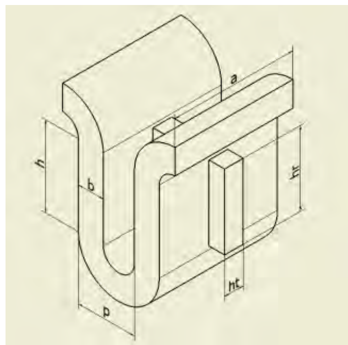


Fig. 14 Schematic diagram of a period of FWG for sheet beam transmission

Tab. 4 Y-band sheet beam FWG Structure dimensions

Wide side(a)	Narrow side(b)	Straight section (h)	Period (p)	Tunnel width (ht)	Tunnel height (hr)
0.76*mm*	0.16*mm*	0.52*mm*	0.36*mm*	0.12*mm*	0.48*mm*

Fig. 15 shows the dispersion curve together the beam voltage line, and Fig. 16 shows frequency tuning with the voltage, from which it can be seen that the voltage varies from 9*KV* to 18*KV* for 220±15*GHz* tuning, and the beam current is 10*mA*. Fig. 17 shows the impedance at point A and B, where A is at the center of the beam tunnel and B is at the position of a quarter to the edge of the tunnel, from which it is seen that the impedance is smaller than that in pencil beam FWG and impedance at point A is smaller than that at point B. The flatness of the axial field Ez is also monitored through Microwave Studio Eigen-Mode solver and is shown in Figure 18, and it is seen that the field close to the edge is greater than that at the center.

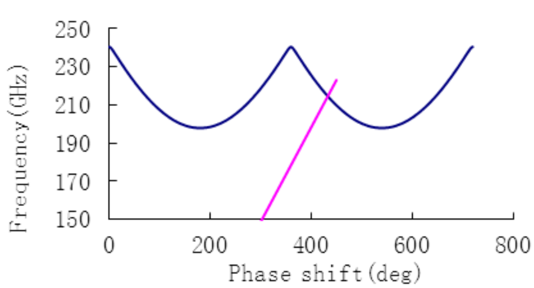


Fig. 15 The dispersion curve and the beam voltage line for 220*GHz* sheet beam BWO

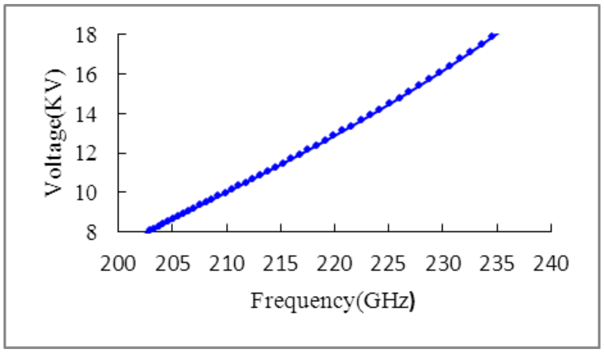


Fig. 16 Frequency tuning with the voltageof 220*GHz* sheet beam BWO

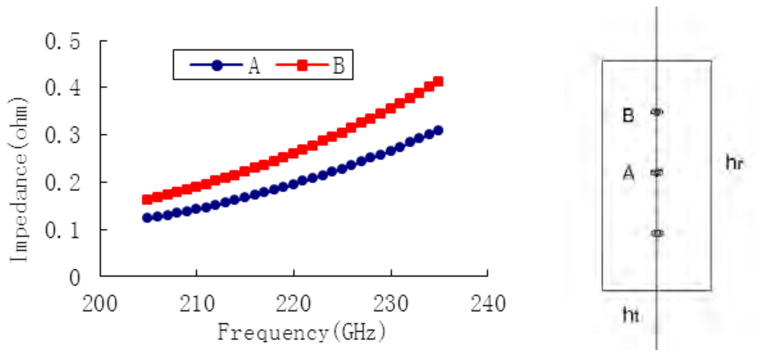


Fig. 17 The impedance at position A and B in the beam tunnel

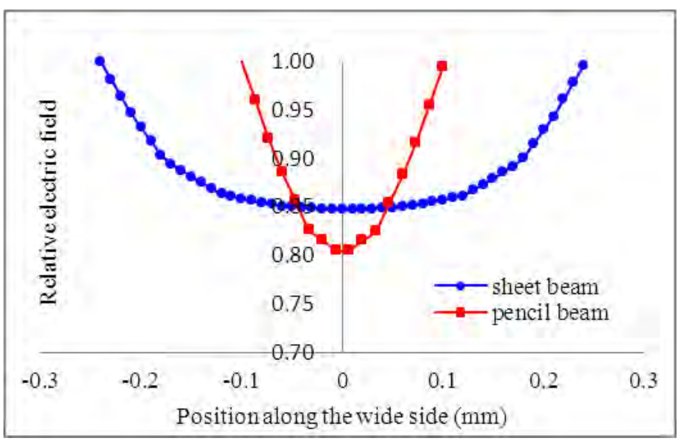
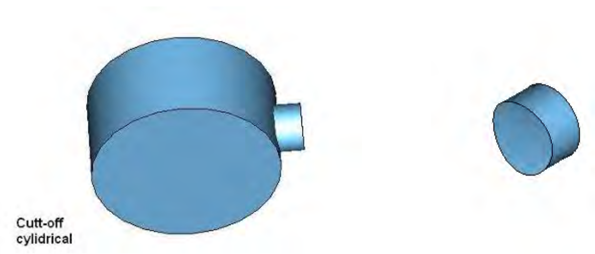


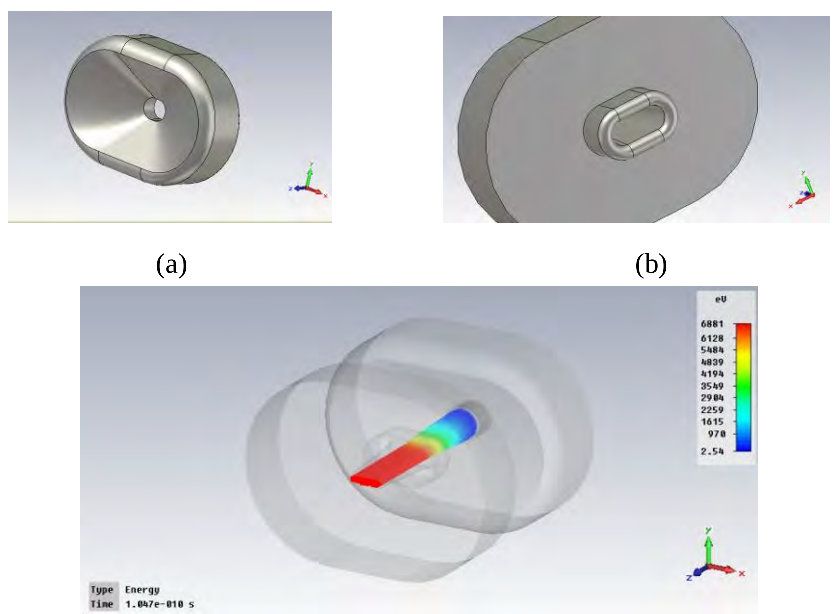
Fig. 18 Relative axial electric field distribution of the rectangular tunnel for sheet beam and that for the pencil beam. It is seen that the flatness of the filed across the width of 0.48*mm*, and the results are consistent with that in Fig. 18 that the impedance at point A is smaller than that at point B.

For sheet beam electron gun, the electro-static focusing method is selected with a circle cross-section cathode cut by a column. The gun consists of a cathode, a focusing electrode and an anode. Generally, a PPM system will be used for long distance sheet beam transmission and avoiding the Dioctron effect, but for high frequency BWO, the interaction section is short and the uniform magnetic field can be used before the stable transmission is destroyed. The cathode is formed through a circular cathode being cutoff by a cylinder as is shown in Fig. 19. Through the compressing of the electrostatic gun, an elliptical beam can be obtained with long and short axis of 0.2*mm* and 0.04*mm*, respectively, and the beam forming in the gun area is shown in Fig. 20.



(a) (b)

Fig. 19 (a) figure shows the forming of the cathode where a small cathode button is cut-off by a large cylindrical, and the (b) picture shows the finished cathode solid model. Here, the radii of the cathode and the cut-off cylinder are 0.2*mm* and 4.5*mm*, respectively, then the emitted electrons will be compressed into 0.4*mm*×0.08*mm* through the electro-static gun for the beam tunnel of 0.48*mm*×0.12*mm*.



(a) (b)

(c)

Fig. 20 (a) The focusing electrode solid model; (b) the anode solid model;(c)the simulated trajectory of the electrostatic focusing electron gun, where the anode-cathode distance is 1.22*mm*, the racetrack anode voltage is 6.9*KV*.

5. Micro-fabrication using DRIE and LIGA

We have facilities for DRIE and UV-LIGA process. Both methods have been used for the research for W band folded waveguide fabrication although CW, 10*W*, TWT and pulsed 100*W* TWT which have been tested with folded waveguide structure being manufactured by EDM and milling[17]. This research is the start of micro-fabrication for future high frequency vacuum devices and all of the micro-fabrication experiment in this paper is for W band devices, because the depth is the deepest structure here after.

DRIE is an anisotropic reactive ion process for micro-fabricating HAR structures in silicon through many repeated cycles of etching followed by passivation of sidewalls via polymerization. The two-step DRIE method allows one to directly produce serpentine waveguides by etching serpentine trenches and coating them with the copper thin film. The first etching step is for forming the trench geometry and the second step etching is for forming the beam tunnel.

The process starts with a 4-inch silicon wafer with thickness of 1.2 *mm*, and the main process is as follows:

(1) Spin-coat AZ4620 resist with a thickness of 14μm;
(2) Softbake: 110 ℃ for 80 *Seconds*;
(3) Expose resist;
(4) Develop for 5*min*, rinse with deionized water, and then blow dry;
(5) Etched by STS LPX ASE^{TM};
(6) Removing AZ4620 with acetone, rinse with deionized water, then dry with a gentle stream of nitrogen.

Fig. 21 and Fig. 22 show SEM picture of the trenches after the first step etching. The W band serpentine trench is approximately 946μm deep (half of the structure) and its profile is 91° at etching rate of 3.3$\mu m/min$. The DRIE fabrication on silicon makes the sidewall average roughness about 0.2μm.

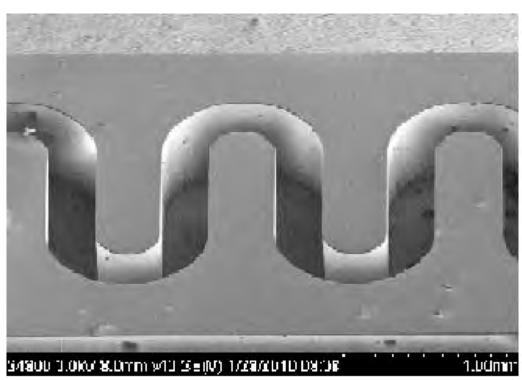


Fig. 21 SEM image of the serpentine trenches fabricated by the first step DRIE on silicon wafer

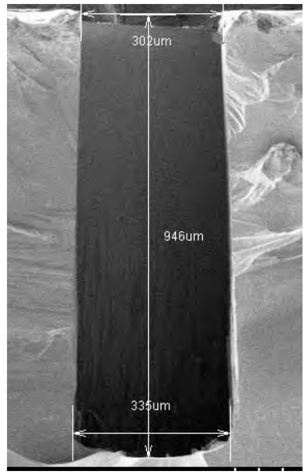
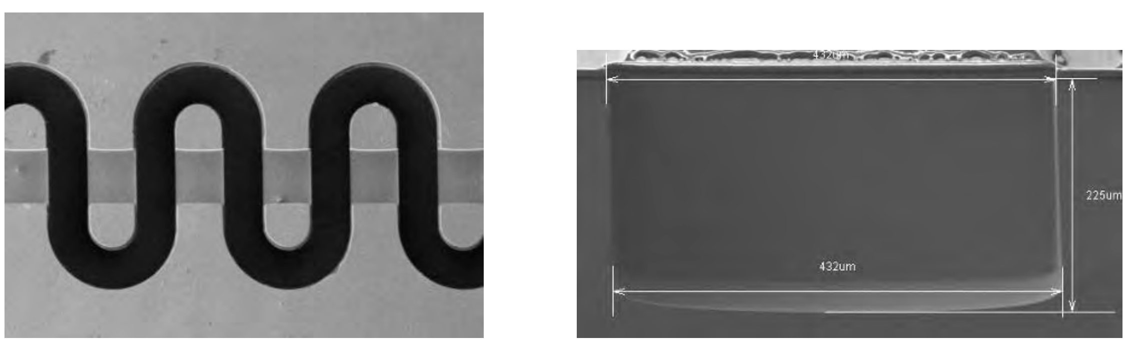


Fig. 22 Cross section SEM view of the serpentine trench fabricated by the first step DRIE, it can be seen that the width is about 302μm on the top and is 335μm at the bottom of the trench, and the depth is 946μm.

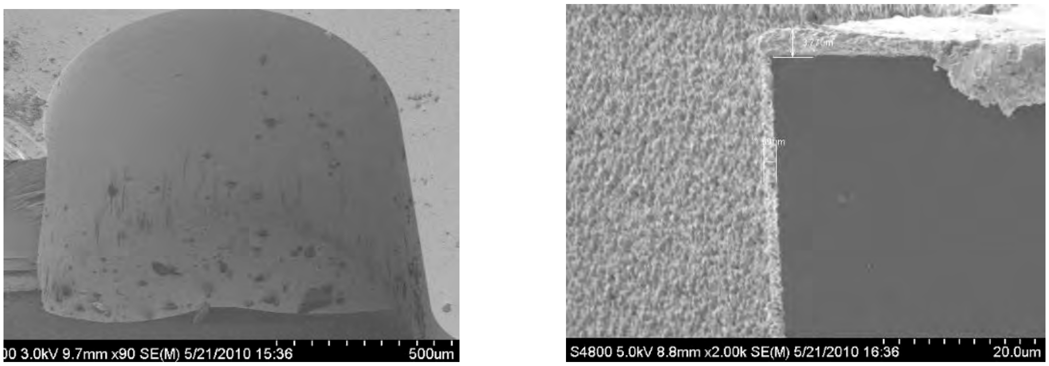
In the experiment, vertical profile and surface finish always conflict with each other, and the etching conditions have to be optimized by adjusting the pressure, ration of the etching time to passivation time and the coupling RF power.

Then the beam tunnel is etched and the SEM pictures are shown in Fig. 23. The next step following serpentine trench is to evaporate 1.5μm copper on the wafer. Fig. 24 is a close-up view of the copper-coated DRIE trench sidewall. For subsequent welding of the two halves folded waveguide, the samples were fired at 780 ℃ in hydrogen ambient, and the peeling of copper films was observed and will be investigated and solved later.



(a) (b)

Fig. 23 (a) SEM picture of the W band serpentine trenches with beam tunnels after two-step DRIE. (b) Magnified view of the structures with 225μm depth and 432μm width.



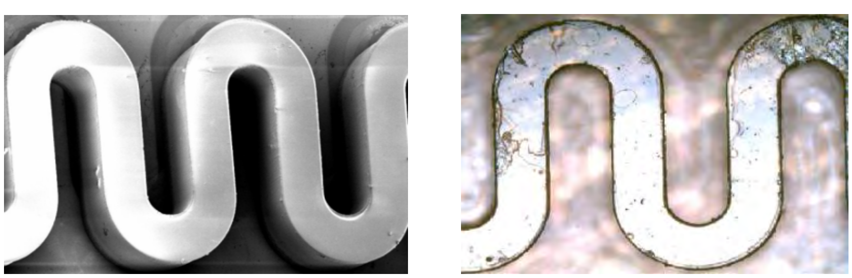
(a) (b)

Fig. 24 (a) Close-up view of a copper-coated DRIE trench sidewall. (b) Profile of the structure coated with 1.5*μm* copper film

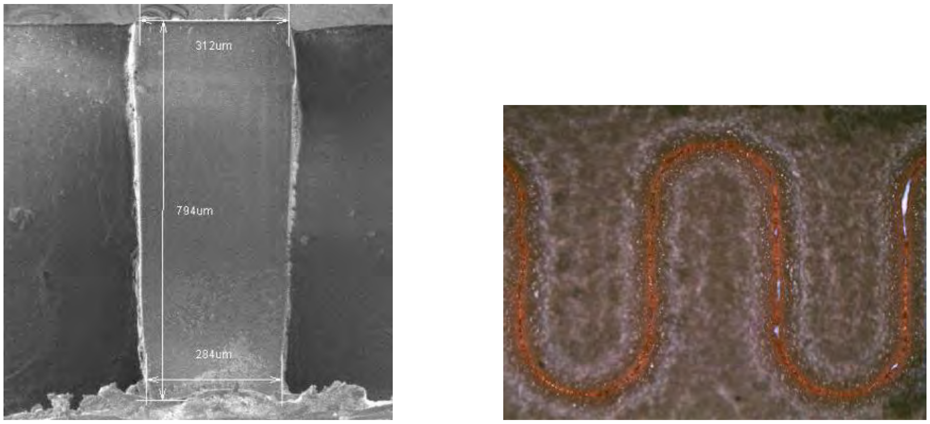
Two-step UV-LIGA is investigated for the fabrication of W band folded wavguide with square beam tunnel. The two-step UV-LIGA process consists of repetition of entire UV-LIGA procedures such as exposure, development, electroplating, lapping, and so on. The first cycle is for the forming of the SWS circuit and the second layer is for forming a beam tunnel. The UV-LIGA process starts from a 4 *inches* copper wafer with 0.1*μm* R_z. The main processes for a SU-8 layer are as follows:

(1) Spin on an OmniCoat layer at 1000*rmp* for 20*Sec*;
(2) Bake OmniCoat layer at 100 ℃ on a hotplate for 3*min*;
(3) Dispense SU-8 2150 on the 4-inch wafer and spin at 300*rpm* for 40*s*;
(4) Soft bake at 65 ℃ for 15*min* on a level hotplate and at 95 ℃ for 8*Hrs*;
(5) UV exposure with a hard contact aligner for 5*min*;
(6) Post-exposure bake at 65 ℃ for 15*min* on a level hotplate and at 95 ℃ for 25*min*;
(7) Development in Microchem SU-8 developer for 30*min*;
(8) Copper electroforming;
(9) Lapping the surface of the wafer.

Fig. 25 illustrates the SU-8 electroplating mold obtained after exposure and resist development. The mold is approximately 794*μm* high with 91° profile



(a)



(b) (c)

Fig. 25 (a) SU-8 mold on the copper wafer obtained after the first step exposure and resist development；(b) profile of the SU-8 mold；(c) the SU-8 structure covered with over-plated copper

The extra high internal stress from SU-8 after baking is a critical problem of using thick SU-8. The stress makes SU-8 molds crack, wrinkle, and strip from the copper wafer. In order to reduce the internal stress, experimental research has been conducted to optimize the process, in terms of spin speed, the soft bake time and temperature, the exposure time, the post exposure time and temperature and the relaxation time. Using the optimized process, patterned SU-8 as micro molds has been successfully fabricated. The adhesion failure problem between SU-8 and copper layers is successfully solved by applying an Omnicoat layer between the two layers. And the second step UV-LIGA for beam tunnel is under progress.

6. Conclusion

In this paper, W band folded waveguide BWO is designed and the simulation shows an output power of over 100mW. The permanent magnets for beam focusing have been built and tested with uniform-field of 5800$Gauss$ within the interaction length of 80mm. Y band folded waveguide BWOs with pencil beam and sheet beam are preliminary designed with the parameters for the guns and beam confinement system determined, and the simulation shows the sheet beam can fit the rectangular beam tunnel. UV LIGA and DRIE processes are studied for current W band BWO and future Y band and higher frequency devices, some technique problems will be solved and a certain period of time is necessary for its application from laboratory prototype to practical devices.

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