

THz Vacuum Microelectronic Devices

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Abstract. Compact vacuum devices of output power even at 1W and at terahertz (THz) frequencies above 100GHz offer enormous applications for wide band communication, imaging radars, and spectroscopy. These active vacuum devices are also required in many more unexplored areas of scientific, industrial and medical applications. Such vacuum devices at frequency above 100GHz are very small in dimension and microelectronic technology is needed for their fabrication. Successful development of THz vacuum microelectronic devices therefore needs fusion of vacuum tube technology with the semi-conductor technology. Significant efforts are being carried out worldwide to develop successfully such compact vacuum devices using available LIGA and DRIE semiconductor technologies. This paper presents some details on THz vacuum microelectronic devices.

1.0 Introduction

Initially vacuum devices were developed in the form of diode, triode, tetrode, pentode, that are being used as high power amplifiers and oscillators at low RF frequency. Subsequently ultra-high vacuum devices were developed in the form of magnetrons, klystrons, travelling wave tubes (TWTs), backward-wave oscillators (BWOs), for their high power applications at microwave frequencies up to 100GHz. These microwave vacuum devices are called slow-wave devices, wherein, the RF wave is slowed down to nearly $1/3^{\text{rd}}$ to $1/10^{\text{th}}$ of light velocity for its synchronism with the accelerated electron beam in an ultra-high vacuum enclosure. During this synchronised interaction of accelerated electron beam with the slowed down RF wave, part of the dc energy of the accelerated electron beam is transferred to the RF wave leading to amplification/generation of high power RF wave. Dimensions of these vacuum devices reduce with increasing RF wave frequency. Therefore, fabrication of these vacuum devices at high frequencies beyond 100GHz is hampered by the ability of present manufacturing technology because of reduced dimensions of critical components, such as RF structures and electron guns. Alternatively, fast wave vacuum devices such as Gyro devices, FEL were developed for generation and amplification of very high power RF waves even up to 200GHz and beyond, but these devices are very large in size and complex.

There is an urgency to develop compact vacuum devices at terahertz (THz) frequencies, above 100GHz, for their enormous applications for wide band communication, imaging radars, spectroscopy, and in many more unexplored areas of scientific, industrial and medical applications. THz devices

provide added diagnostic tool for surface or small depth imaging that is very useful for security purpose, medical and agriculture field. At present, semiconductor devices cannot replace the vacuum devices at THz frequencies for power level even at few mW. Fundamental drawback of semiconductor devices at THz frequency is that electron transport is impeded by the silicon crystal lattice, which places a limit on both the miniaturization and the switching speed of such devices. A solution to this is therefore to create an active electronic device which relies on electron transport through vacuum. Recent developments in microelectronics and micro-electro-mechanical systems (MEMS) technology are being explored for fabrication of small-size RF structure and FEA cold cathode. Such compact and small size THz vacuum devices fabricated using microelectronic technologies are known as vacuum microelectronics devices, the interest in which has grown greatly over the last few years. Applications of such vacuum microelectronics devices include the generation and amplification of THz frequency electromagnetic waves.

2.0 THz TWT/BWO

This paper presents some details on THz TWT using cylindrical beam and sheet beam devices, operating at high frequencies (95GHz and above in THz range), that offer enormous opportunities for creating new markets in the bandwidth-intensive commercial communication areas. These THz TWTs would be required for cellular telephony, wide band mobile communication, and high-speed space/ground data transfer. The development of micro- and nano-satellites for high data-rate communication, is also possible using THz TWTs. Similarly, backward wave oscillators (BWO) in THz range offer new mission capabilities related to imaging radar, medical applications, spectroscopy, and new generation compact ion-sources. Significant efforts are being carried out worldwide to develop successfully such compact THz TWT/BWO vacuum devices using available LIGA and DRIE technologies for field-emitter-array (FEA) cathode, RF structure, and input and output couplers. Design and development of THz TWT/BWO has also been initiated at CEERI, Pilani. Fig.1 shows a schematic diagram of a complete low frequency helix TWT with electron gun, helix slow-wave structure (SWS), input/output couplers, magnetic focusing and single-stage collector. TWTs are used for amplification of low RF signals to high output power over desired frequency band with high efficiency and high gain. 4-stage collector is generally used for high overall efficiency of the TWT.

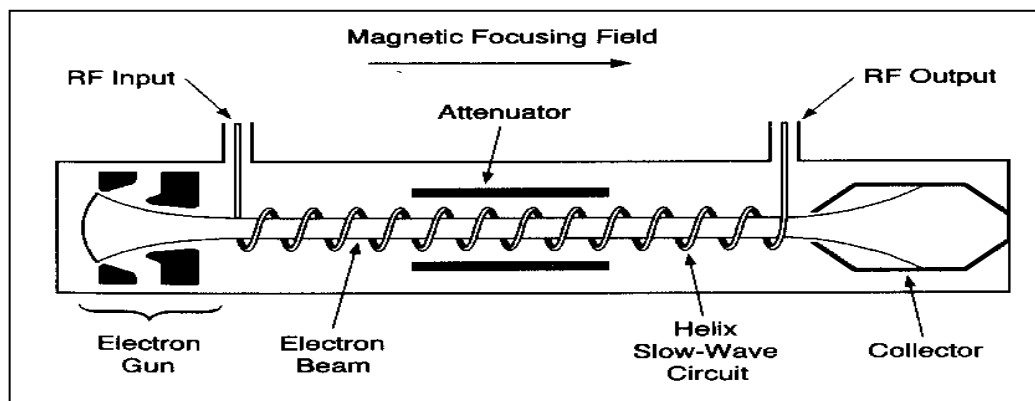


Fig. 1: schematic diagram of a complete low frequency helix TWT

In recent past, CEERI has successfully carried out design and development of C-band 60W space TWT[1], and Ku-band 140W space TWT[2], jointly with BEL, Bangalore, as shown in Fig.2.



Design and development of Ka-band space TWT of frequency around 20GHz with helix SWS has been initiated. Helix radius decreases with increasing frequency, as shown in Table-I:

Table-I: Helix radius for TWT of different frequency and power level

Frequency Band / Power level	Helix radius
C-band (3.4-4.2GHz/200W)	2.30 mm
Ku-band (10.7-13.0GHz/250W)	0.80 mm
K/Ka-band (18-32GHz/100W)	0.40 mm
Q-band (37-42GHz/50W)	0.24 mm
V-band (60-65GHz/30W)	0.16 mm
W-band (95GHz/10W)	0.10 mm
Sub-mm band (300GHz/1W)	0.032 mm

Small-size of helix of radius in microns for a 95GHz TWT is not possible to fabricate by conventional technique. Therefore, there is a need of different types of RF structures for TWTs of THz frequencies that can be fabricated by microelectronic technology. RF structures for 95GHz TWT using cylindrical electron beam are folded waveguide slow-wave structure (FW-SWS) and coupled-cavity SWS (CC-SWS). CEERI has carried out design of FW-SWS for a 300GHz TWT [3] and FEA cathode [4].

3.0 THz TWT/BWO using cylindrical beam

Development work carried out at Seoul National University (SNU) using CEERI developed electron for their 95GHz TWT/BWO, are discussed in this section.

3.1 Electron gun assembly for 95GHz TWT/BWO

An electron gun assembly, as shown in Fig.3[5], has been developed at CEERI based on SNU design for a 95GHz FW-TWT/BWO. The gun was made to achieve cylindrical beam of beam radius 0.18mm at beam voltage 12kV and beam current 50mA. Thermionic tungsten dispenser cathode of diameter 1.20mm has been used. The gun performance was tested both at CEERI and SNU and found acceptable as per the requirement.

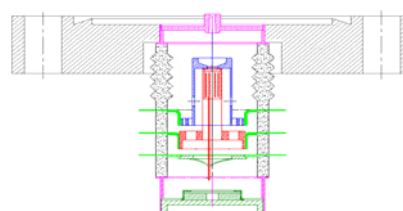


Fig.3: Electron gun assembly and its demountable UHV assembly with 95 GHz FW-BWO [5]

This CEERI developed electron gun assembly has been used by SNU [6] in their 95GHz TWT/BWO using both FW-SWS and CC-SWS.

3.2 FW-SWS for 95GHz TWT/BWO

Folded-waveguide slow-wave structure (FW-SWS) is being used for THz TWT, as shown in Fig.4(a). Fig.4(b) shows FW-SWS with inbuilt couplers at both input and output ends of the SWS. FW-SWS is selected for THz application because of its high impedance, wide bandwidth and compatibility of its fabrication by LIGA and DRIE processes. Dimensions of the LIGA-fabricated FW-SWS, as shown in Fig.4(c)[7] for a 95GHz TWT/BWO are as follows: broad wall dimension (a) 1.80mm; narrow wall dimension (b) 0.30mm; period (p) 0.70mm; width (H) 1.50mm. Broad wall dimension 1.80mm is achieved by joining two halves (top and bottom) each of height (h) 0.90mm. Each half of the circuit with half beam hole is fabricated using two-step LIGA process[8] that has been developed to construct three-dimensional microstructure with the beam tunnel. The beam tunnel is patterned in the middle of the slow wave structure during the second step. The two-step LIGA process gets over the problem of circuit feature distortion and other mechanical and thermal damages to the LIGA-circuit caused by post-process operation such as EDM process for the beam tunnel.

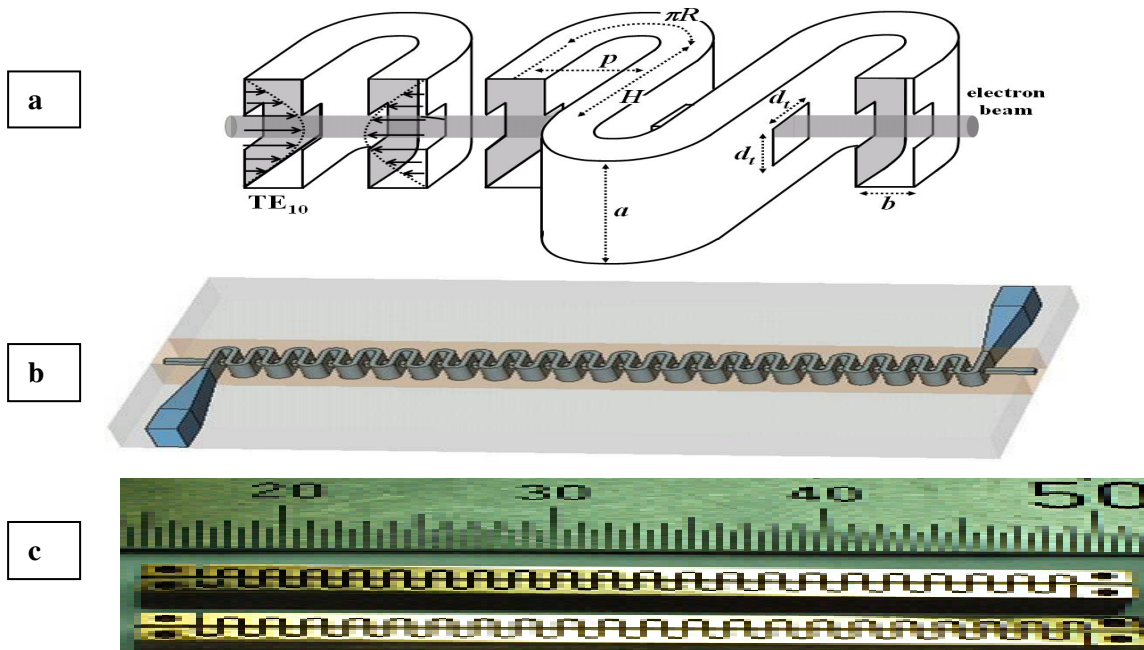


Fig.4: Folded Waveguide SWS: (a) schematic, (b) with couplers, (c) fabricated half structures [5]

The quality of micro-fabricated circuits is being diagnosed by examining rf characteristics and surface finish. The measured feature tolerance and alignment tolerance were reported better than 2-3microns, and measured surface roughness was reported about 20-70nm. Therefore, LIGA-fabricated circuits implying the two-step LIGA microfabrication has potential applications up to the submillimeter wave region even at 300GHz and beyond.

FW-SWS for 95GHz BWO[9] has been designed for synchronism of the backward RF wave at 95GHz with the electron beam of 12kV, 50mA, and beam radius 0.18mm. Output power about 5 watts at 50mA operational beam current is expected. The transmission loss in the circuit was measured about 6dB, and this amounts about 54dB/m attenuation around 95GHz.

3.3 CC-SWS for 95GHz TWT/BWO

TWT/BWO with coupled cavity slow-wave structure (CC-SWS), as shown in Fig.5(a), has also been designed at SNU for 95GHz operation with electron beam of 12kV, 50mA, and beam radius 0.18mm. CC-SWS has much higher impedance than that for FW-SWS and therefore it provides higher gain per unit length and output power. 2-step LIGA process has been used for fabricating the CC-SWS on copper substrate and DRIE process has been used for fabricating the CC-SWS on silicon-wafer. Fig.5(b)[9] shows one half (lower/upper) of the structure with and without half beam tunnel. The half of beam tunnel has been developed in the second step of 2-step LIGA process. Both lower and upper halves are joined together to make complete slow-wave structure with the beam tunnel.

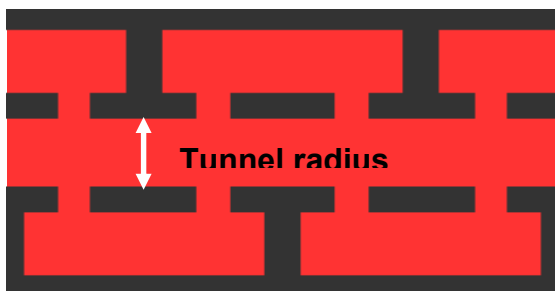


Fig.5(a): Coupled-Cavity SWS



Fig.5(b): One-half of CC-SWS on Si-wafer[8]

Both FW-SWS and CC-SWS are basically formed with planer structures and cylindrical beam is used. Therefore, these devices are complex to fabricate and have low electronic efficiency.

4.0 THz TWT/BWO using sheet beam

Like multi-beam vacuum devices, sheet beam vacuum devices have many advantages because sheet beam geometry has significantly higher beam current capacity, decreased beam voltage, reduced power densities, lower voltage gradients and increased bandwidth compared than the round-beam geometries. For sheet beam of width ‘w’ and thickness ‘a’, as shown in Fig.6(a), operating frequency (f) of a device is inversely proportional to its dimension (a), as decided by the following equation:

$$\text{beam current} \propto w \cdot a \propto f^{-1}; \text{width } w \text{ is in ignorable coordinate.}$$

Whereas, for round beam of diameter ‘a’, as shown in Fig.6(b), operating frequency (f) of a device is inversely proportional to square of dimension (a), as decided by the following equation::

$$\text{beam current} \propto a^2 \propto f^{-2}; \theta \text{ is ignorable coordinate.}$$

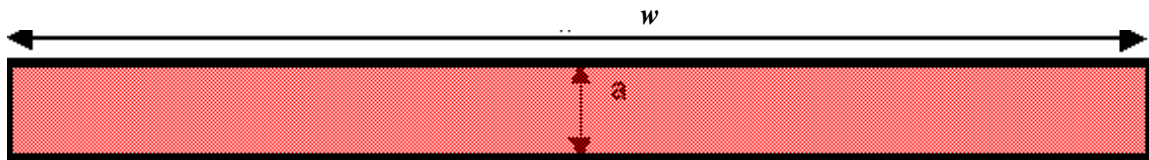


Fig.6(a): Sheet beam of width ‘w’ and thickness ‘a’

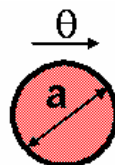


Fig.6(b): Cylindrical beam of diameter ‘a’

Therefore, the power output of a sheet beam TWT/BWO falls only linearly as a function of increasing frequency, making it more suitable for high frequency applications. Whereas, the power output of a round beam TWT/BWO falls quadratically with increasing frequency, making it less efficient for high frequency applications. Also, sheet beam geometry is inherently suited to planer micro-fabrication technology for vacuum device.

Space charge force (SCF) for sheet beam is decided primarily by its thickness ' a ', and not by its width ' w ', whereas for round beam, SCF is decided by area (a^2). Therefore, SCF for sheet beam is considerably less compared to that for round beam. Similarly magnetic field (B) requirement for focussing of sheet beam is inversely proportional to (width)² but for round beam, B-field requirement is inversely proportional to (diameter). Therefore, beam current capacity is more and magnetic field requirement is drastically reduced for sheet beam. Sheet beam technology development requires thin sheet beam formation with uniformity of current density across beam width, stable beam transport, circuit stability, and uniform beam-wave interaction across beam width. The generating, forming and focusing of electron beam are the key technologies of the sheet beam vacuum devices. Elliptical sheet beams are easy to focusing than rectangular sheet beams.

4.1 Sheet beam electron gun

Sheet beam electron gun has been designed at SNU [10] for generation of sheet beam of beam voltage 12kV and beam current 20mA. Flat rectangular cathode of size 600 μ m x 100 μ m is used to generate sheet beam of width x thickness: 600 μ m x 30 μ m, as shown in Fig.7. Distances between cathode to special shaped anode and BFE were selected respectively 2.50mm and 0.14mm.

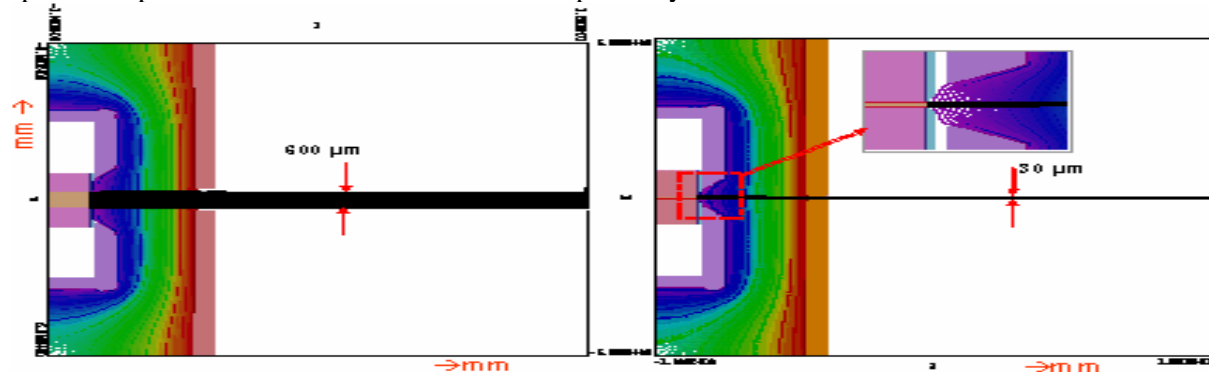


Fig.7: Sheet beam electron gun with electron trajectories in two different planes [10]

Sheet beam electron gun has been designed at SNU for 95GHz/220GHz Extended Interaction Oscillator (EIO), 300GHz Orotron (Open Metal Grating Structure), and for 500GHz counter-streaming electron beam oscillator (CSEBO) [11]. This sheet beam electron gun with planer thermionic dispenser cathode is being developed at CEERI, Pilani, under CEERI-SNU collaboration.

4.2 Planer RF structure for sheet beam TWT/BWO

Planer RF structure that is compatible to sheet beam and has high impedance, is selected for TWT/BWO. With this objective, double-ridge waveguide, as shown in Fig.8, is designed for RF wave of frequency 95GHz synchronized with 12.0kV electron beam. Double-ridge waveguide for millimeter or sub-millimeter wave band, has other merits of being easily made by micromachining, large transverse dimension and good heat dissipation. Dimensions of double-ridge waveguide are selected as follows: period (p)=0.5mm; waveguide height ($2b$)=2.10mm; vane height (d)=0.61mm; vane separation (s)=0.25mm; waveguide width (w)=20.0mm; and sheet beam

dimensions=10mm x 0.5 mm. This structure can be used for 95GHz TWT of power output more than 100W. The design can be compressed for low power application.

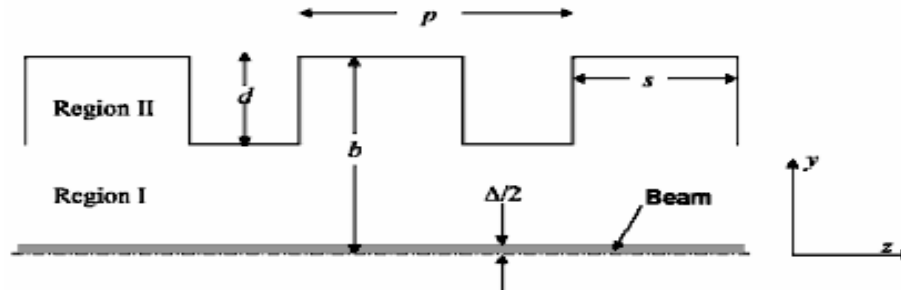


Fig.8: Double-ridge waveguide structure

A double ridged waveguide geometry with sheet beam, and the waveguide structure with waveguide match coupler at one end, for a 95GHz, 100W TWT/BWO is shown in Fig.9 [12,13].

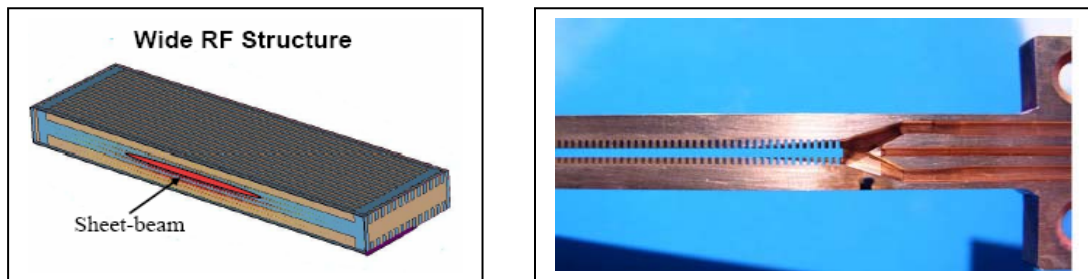


Fig.9: Planer Ridged Waveguide with sheet beam & RF structure with waveguide match coupler[13]

Other planer structures suitable for THz TWT/BWO with sheet beam are:

- (i) Meander line slow-wave structure,
- (ii) Single-side vane loaded open structure,
- (iii) Single-side vane loaded waveguide structure,
- (iv) Sheet beam coupled-cavity SWS.

In sheet beam coupled-cavity SWS, 5-coupling slots connect consecutive rectangular cavities [14]. The slots are distributed evenly around the periphery, including one slot along a side wall, and the pattern is alternated so that consecutive sets of slots are offset, as in the traditional double staggered ladder structure.

5.0 Integration of complete vacuum device

Complete vacuum device with cathode, grid, anode, cavity and collector, could be fabricated by microelectronic technology, only for triode and klystron. A typical example for a reflex klystron is shown in Fig.10 [15]. It shows, integrated vacuum microelectronic reflex klystron for THz frequencies that has been fabricated on silicon using micromachining. The cathode is composed of a carbon nanotube field emitter array (FEA) with integrated grid. The cavity, beam and output waveguide are etched from two silicon wafers, which are later joined by thermo-compression bonding. The repeller and cathode are drop-in-parts and vacuum sealing is performed in the last step.

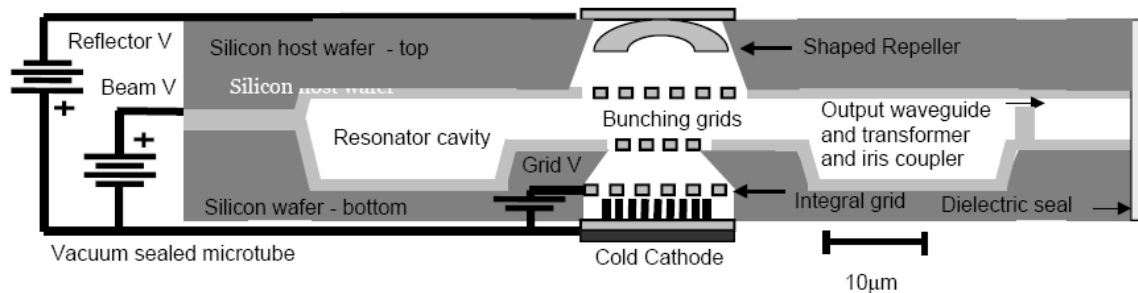


Fig.10: Schematic cross-section of a micro-fabricated THz klystron [15]

For a complete TWT, integration of gun assembly, SWS assembly and collector are required with alignments of assemblies within a tolerance of less than 5 microns for a 100GHz TWT. For experimental evaluation of a 95GHz FW-BWO with permanent magnets focusing, Seoul National University (SNU) developed demountable set up, as shown in Fig.11.

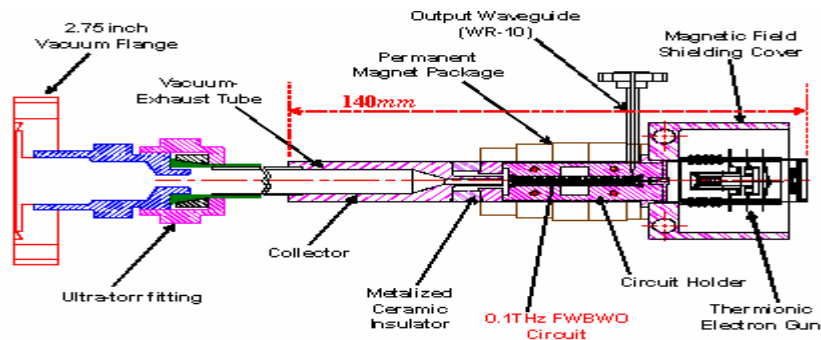


Fig.11: Schematic diagram of 95 GHz FW-BWO on a demountable UHV test set up

For the success of a THz TWT, there is a need to assemble the complete tube leak tight, and to vacuum process the tube on ultra-high vacuum system to achieve ultimate vacuum better than 10^{-9} torr. There is also a need to use some form of getter in a compact THz TWT for long life.

6. Conclusion

THz vacuum microelectronic devices (T-VMD) have enormous applications in different sectors, and it is being optimally predicted that T-VMD would be widely used for communication, security, medical diagnostic and treatment, and many other scientific and industrial applications, in near future. Microelectronic technologies like LIGA and DRIE are being explored worldwide for the successful development of THz vacuum devices for their operation above 100GHz. Both cylindrical beam and sheet beam are presently being tried with THz vacuum devices. Sheet-beam vacuum devices in THz range offer many advantages over the vacuum devices employing cylindrical beam in terms of higher gain per unit length, higher power and wider bandwidth capabilities, shorter circuit length, and easy magnetic field focusing. This is because of relatively lower space charge force of sheet beam compared to that of cylindrical beam. In addition to that, sheet beam devices have planer structures that are easy to fabricate by semiconductor technologies. Many planer structures including double ridge waveguide are being explored for THz vacuum microelectronic devices. Large-numbers of vacuum devices can now be produced in one-set of operation like semiconductor devices that would help to reduce both cost and time and would improve both reliability and repeatability in production of T-VMD employing field-emitter arrays (FEA) cathode.

7. Acknowledgement

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