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Microfabricated Terahertz Vacuum Electron Devices: Technology, Capabilities and Performance Overview

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ABSTRACT

Recent technological innovations in electronics and photonics are now enabling THz research to be realized in defence as well as civil sectors. Undoubtedly, microfabricated vacuum electron devices (MVEDs) are capable to fulfil the source requirement. In last couple of years, development of high definition electromagnetic simulation codes, advancement in micro-&-nano fabrication and further characterization techniques, development of high current density hot (thermionic) and cold (CNT and FEA) emitters, and progress in ultra-high vacuum window research have been the driving force behind the extraordinary development in MVEDs. In this article, the importance of THz region and need of THz MVEDs are presented. Furthermore, fabrication approaches of promising planar microfabrication compatible slow-wave structures, high current density electron beam generation for THz MVEDs have been reviewed. Finally, state-of-the art THz MVEDs and future trends are discussed.

Key words: Terahertz (THz), Microfabricated vacuum electron devices (MVEDs), Electron beam, Slow-wave structure (SWS), Traveling wave tube (TWT), Amplifier

INTRODUCTION

This paper attempts to present an overview of microfabricated vacuum electron devices (MVEDs), operation at THz region. Vacuum electronic science and technology is both old and new. The horizon of MVEDs is showing continue progress, because of revolutionary advances based on new design approaches, with the advent of novel concept and new physics based three-dimensional simulation design tools, advanced micro-&-nano fabrication and characterization techniques, and high performance vacuum grade materials. In addition, novel electromagnetic structures are capable to produce coherent radiation sources with unprecedented compactness, power, bandwidth, and efficiency.

The electronics devices are approaching microwave to Millimter wave (MMW) region [Fig. 1]. These devices are primarily based on the conduction current J. Besides that, the Photonics devices are approaching Infrared region to Submillimeter wave (Sub-MMW) region. These devices are principally work on displacement current $\partial D/\partial t$. The connubial region of MMW and Sub-MMW, typically 0.1 THz – 3 THz are still under research, so this 'T-ray' frequency gap called 'THz-Gap' [Fig. 1]. T-ray is trying to fill the gap between electronics and photonics with employing components from both sides. It is having some distinctive properties, such as it can be absorbed by water, transmits through many common barrier materials, nearly no biological hazards, non-ionizing, and wavelength corresponds to molecular rotational & vibrational wavelengths. Hence, these properties make it suitable to develop systems mainly for modern wireless communication and contraband security applications [1-4, 6]. A few major application areas are listed in Table -1, those are still in pre-mature phases.

Preliminary Challenges to Develop THz Systems

The generation of THz radiation presents preliminary challenge toward development of THz systems. Electronics is dominated in microwave region ($h\nu/kT<<1$) because here transport of electrons play an important role. But in other hand, because of fabrication limitations and electrical breakdown mechanism it is very challenging to make electronic devices operate above 0.1 THz. In addition, electronic power of vacuum electronic devices fall ~ $1/f^2$, where f is the operating frequency. The alternative approach for THz generation is using photonics, which is dominated in infrared ($h\nu/kT>>1$). These types of devices are influenced by quantum mechanical transit of electrons. Moreover, the photon energy (hv) is low compare to thermal effects (kT) at THz frequencies, which resultantly limits the performance of optical techniques. Therefore, these concerns produce the renowned 'THz gap' (hv/ kT~1) [Fig. 1], where amplifier and signal generator technologies are still lacking with MVEDs.

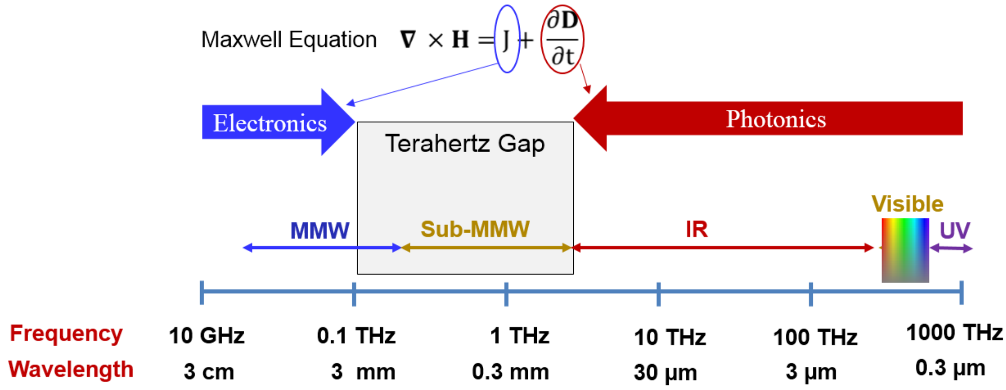


Fig. 1 THz-gap: connubial region of MMW and sub-MMW

Table -1 Present and futuristic THz applications

Communication and Information Technology	Secure wireless communication	Instant data transfer (> 30-100 GB/s)	Covert satellite and tactical communication in space
Security	Contraband safety inspection	Screening of people	Non-contact postal screening and Biometrics
Semiconductor and Industrial Applications	Fault analysis in next generation LSI circuits and wafers	Drug inspection	Nanocomposites Material evaluation and inspection of solar cells
Earth and Space Science	Environmental/ air-pollution monitoring	Monitoring of new born Galaxies	Study of invisible dark universe and new solar system
Basic Science	THz spectroscopy	Study of Metamaterials	Cancer imaging and on-site diagnosis

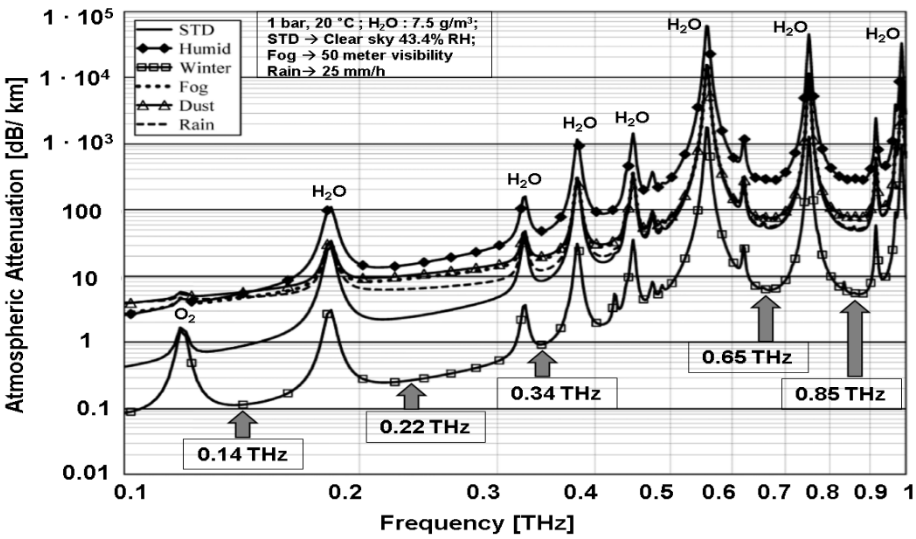


Fig. 2 Atmospheric attenuation versus frequency graph with characterized universal windows [5]

Furthermore, development of efficient outdoor THz systems for modern communication and sensing applications are more challenging. The major obstacle is atmosphere. The atmosphere absorbs millimetre and terahertz radiation up to some extent. Actually, many absorption peaks arise from the various gases which form atmospheric air [Fig. 2]. It has a strong and variable effect due to presence of large variations of water vapour content that occur due to natural weather conditions. Atmospheric attenuation increases as operation frequency goes high. Therefore atmospheric absorption is characterised by atmospheric attenuation, which rises from 4 dB/km to 500 dB/km for frequency range 0.1 THz to 1 THz. It is lowest near the universally accepted atmospheric windows 0.14, 0.22, 0.34, 0.65, 0.85 THz [5]. Based on the headway of MVEDs, the building of THz systems operational infrastructure is going on near these operational 'windows'.

One of the primary reasons for moving towards THz region is to achieve high bandwidth datalinks for compact and highly movable systems for secure communication and sensing applications. At THz frequency, small antenna size is required compare to microwave frequency, because antenna diameter inversely proportional to frequency.

In this manuscript, initially the key technologies requires for development of sources for THz generation is briefly explained. Preceding section contains the state-of-the art reported major sub-components of MVEDs. In next section emphasizes the reported state-of-the art MVEDs with systematic analysis of parameters such as power, efficiency, gain, etc. Finally, the conclusion and future scope of MVEDs is discussed.

TECHNOLOGIES FOR THz GENERATION

There are numerous ways to generate 'T-ray' either from MVEDs or solid-state devices (SSDs). Both convert electrons kinetic energy to EM energy. In VEDs, electrons motion and electric fields present in vacuum; but in SSDs, electrons stream and electric fields present in solid semiconductor. In THz region (0.1 THz - 3 THz), mainly using sources are frequency multiplier conventional solid-state devices, Gunn diode, Impatt diodes, GaAs amplifier, GaN amplifier, THz Quantum-cascade laser, and difference-frequency generation [7]. The reported average power of these SSDs is μW to less than one W in THz region. Above 0.1 THz, MVEDs show merit over SSDs. When high power density is needed for high power generation, the MVEDs show advantages in terms of managing and removing waste heat from devices which result high breakdown limits. But, in other hand, it desire ultra-high vacuum packaging challenge and high voltage requirement. The current research activities on development of THz MVEDs are shown in Fig. 3. It is clear that mostly two types of MVEDs are dominating. First type is standing wave tubes (SWTs): such as extended interaction klystron (EIK) and extended interaction oscillator (EIO). The second type is traveling wave tubes (TWTs): such as backward wave oscillator (BWO), Clinotron, and folded wave guide/ helix TWT amplifier [8].

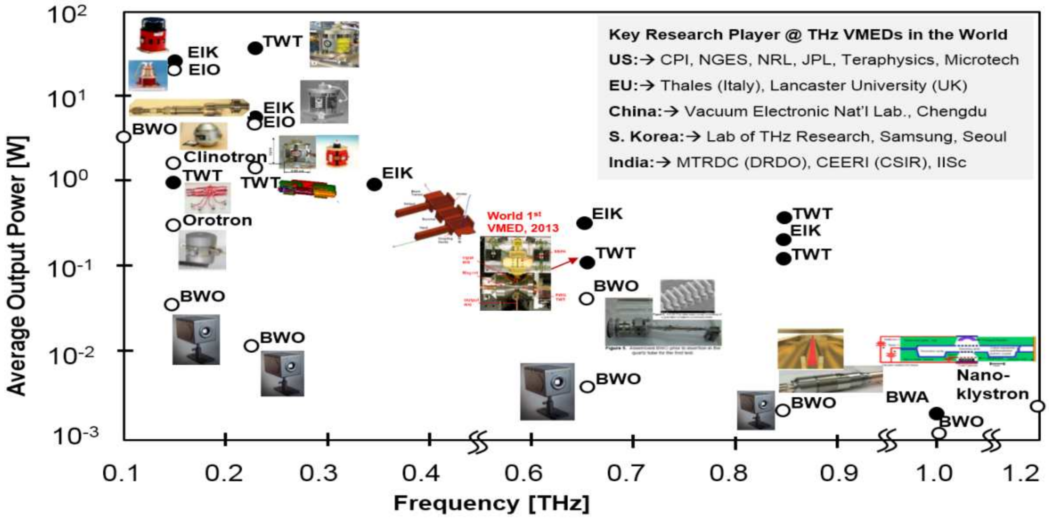


Fig. 3 Recently reported THz MVEDs development activities in terms of average output power versus frequency

Key Technologies Involved for Realization of MVEDs

In the THz region, the dimensions of a vacuum device scale with operating frequency. Accordingly, structure dimensions become micron scale size and desire surface roughness becomes order of a few hundred nanometers [13]. Therefore, firstly it requires precise electromagnetic design simulators, further it desires sophisticated process control with precise microfabrication techniques [Fig. 4]. The precision from conventional micromachining techniques cannot sustain as operational wavelength approach to micron scale dimensions. The advancement in the development of microfabrication technologies like UV-LIGA (a German acronym for lithography, electroplating, and molding) and deep reactive ion etching (DRIE) [9] make them capable to provide surface roughness less than the skin depth. Further, THz source development research requires novel cold (CNT/ FEA) and hot (Thermionic) electron emitters, efficient electromagnetic structures, thermal management in compact vacuum sealed device, and finally THz measurement components. From Levush et al. [10], estimated peak RF power for TWT devices, $P_{out} = N \times 24\ (J/f^2)^{4/3}\ (V_b)^{13/6}$. This clearly defines the technological challenges for realizing the THz source. Consequently, for obtaining the moderate power, the THz MVEDs require high beam current density (≥ 50 – 1000 A/cm^2) with magnetic field requirement of 0.2 – 1 Tesla [11].

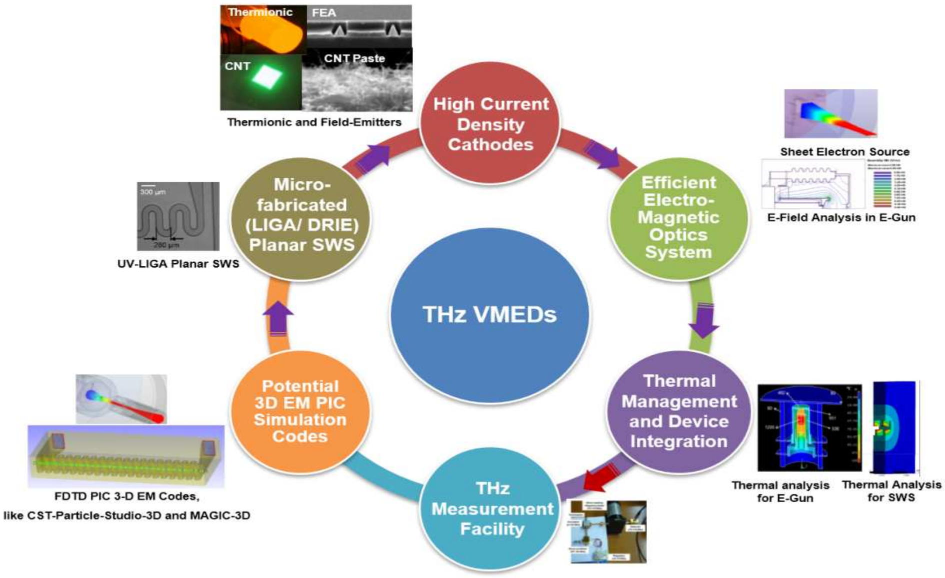
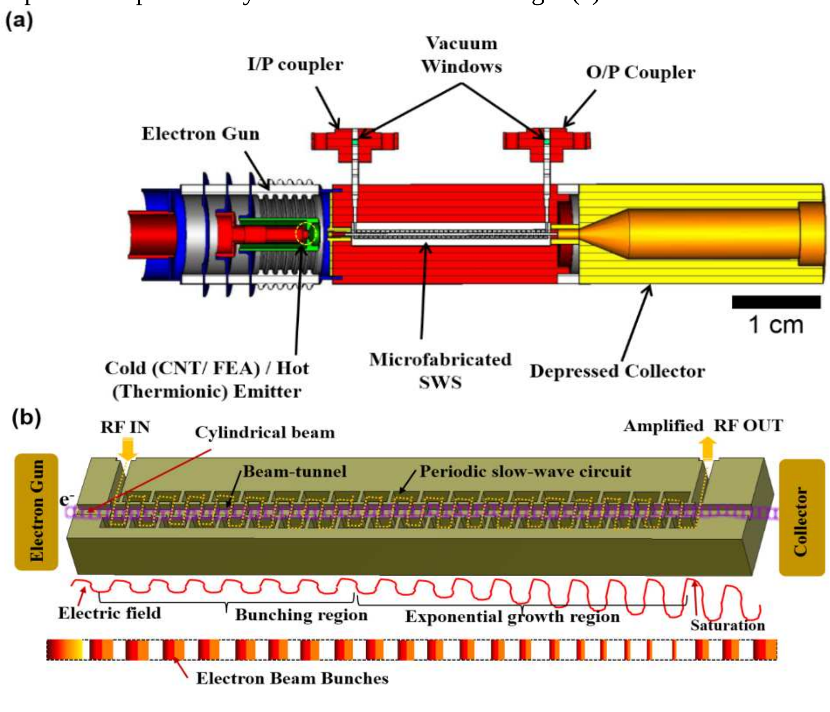


Fig. 4 Key Technology involved in realization of THz MVEDs

OVERVIEW OF COMPONENTS OF MVEDs

Traveling wave tube (TWT) amplifier is one of the most established MVE sources for THz radiation. The schematic half cut-view of THz TWT is shown in Fig. 5(a). It is capable to generate rf power 1 - 10^3 watts at THz frequencies. Principally, electron beam density and current modulation induces a 'modified' wave within or onto the planar slow-wave structure (SWS) [Fig. 5(b)]. This modified wave has the same frequency as the original wave, but possesses a unique and important feature. The phase of the induced wave is such that the electron bunches appear in decelerating regions of the wave's electric field. The kinetic energy lost by these electrons is transferred to the wave, showing up as continuously increasing wave amplitude. The phase-diagram for the fundamental TE_{01} mode in planar folded waveguide (FW) and planar coupled-cavity like SWSs is shown in Fig. 5(c).



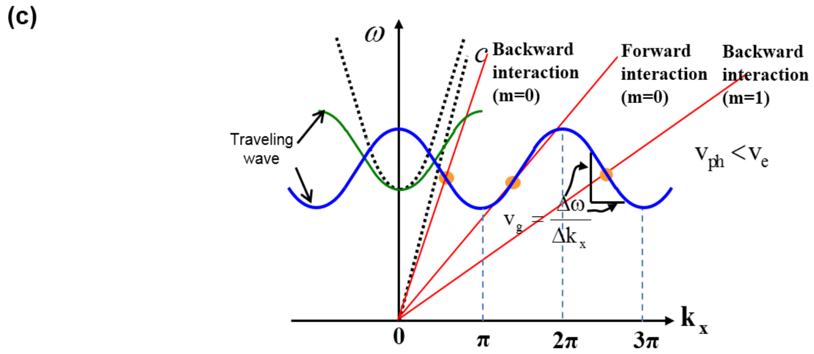


Fig. 5 Schematic of THz TWT: (a) half-cut view, (b) principle of electron beam bunching in presence of rf interaction, and (c) dispersion (ω – k_x) diagram [4]

Overview of Planar SWS Design and Fabrication

The heart of any MVED is periodic SWS. It supports the induced coherent traveling and standing electromagnetic waves in TWTs and SWTs, respectively. The transverse size ‘a’ and period ‘p’ [Inset Fig. 6(a)] of the SWS decrease accordingly to the operating frequency increase. In the THz range, the SWS dimensions reduce to micron scale, so it is too delicate to be fabricated by conventional micromachining [4]. Thus, for development of modern terahertz vacuum electron devices (VEDs) efficient novel SWSs designs and further supportive microfabrication technologies are needed. In esteem of high frequency THz VEDs development, lately, design and microfabrication of several novel SWSs have been reported in the literature [19-37]. As brief summary, microfabrication compatible planar SWSs have been tabulated [Table 2]. In general, planar folded waveguide [16, 19-23], coupled cavity [24-25], vane loaded waveguide [26, 27], sine waveguide [28], and corrugated waveguide [29, 30] types planar SWSs are formed completely by vacuum grade non-magnetic metal. These structures are capable to manage higher output power with better thermal dissipation. On the other hand, meander-line [31] and planar helix [32-34] type complex SWSs show poor thermal handling competence.

One of the most promising microfabrication compatible THz SWS is FW SWS. Its dispersive properties (without presence of electron beam) are simulated using Eigen-frequency and transient-frequency solvers [12] [Fig. 6(a)]. The waveguide period 'p' was analytically calculated from phase-shift 'φ' (= $k_x p$) = ($2\pi f_0/v_e$) p, where, $\varphi = 3\pi/2$, f_0 in GHz, $v_e = \beta c \sim 0.2c$ ($V_b \sim 10$ kV). Here, 'β' relates with relativistic energy factor 'γ' like as: $\gamma = 1+ eV_b /m_e c^2 = (1-\beta^2)^{1/2}$; e and m_e represent the charge and rest mass of electron, respectively. The FW height 'a' has been chosen ratio of center frequency (f_0) to cut-off frequency (f_c) ~ 1.2 for its TE_{10} mode. Furthermore, hot properties (in presence of electron beam) of SWS have been analysed using three-dimensional Particle-in-Cell (PIC) electromagnetic simulation [12]. The single section FW TWT gives output power almost 2 Watts with gain 20 dB [Fig. 6(b)]. The inset Figure shows the simulation model with bunched electron beam in-presence of input rf signal.

Since the conventional micromachining techniques become inadequate at frequency above the 0.1 THz. Hence, microfabrication technologies are crucial for next promising atmospheric window frequency 0.22 THz and higher THz frequencies for fabricating planar SWSs [Fig. 7]. Microfabrication techniques [38] especially X-ray LIGA, UV-LIGA, and DRIE are promptly gaining interest for the advancement of MVEDs, particularly for the fabrication of sub-wavelength feature size planar SWSs. X-ray LIGA technique is capable for generating the 1:100 vertical aspect ratio SWSs at the cost of very huge synchrotron X-ray source facility and requirement of expensive gold mask [39]. In other hand, UV-LIGA process needs inexpensive Chrome/ Mylar masks and table-top UV source. These MEMS techniques are friendly with novel planar SWSs listed in Table-2.

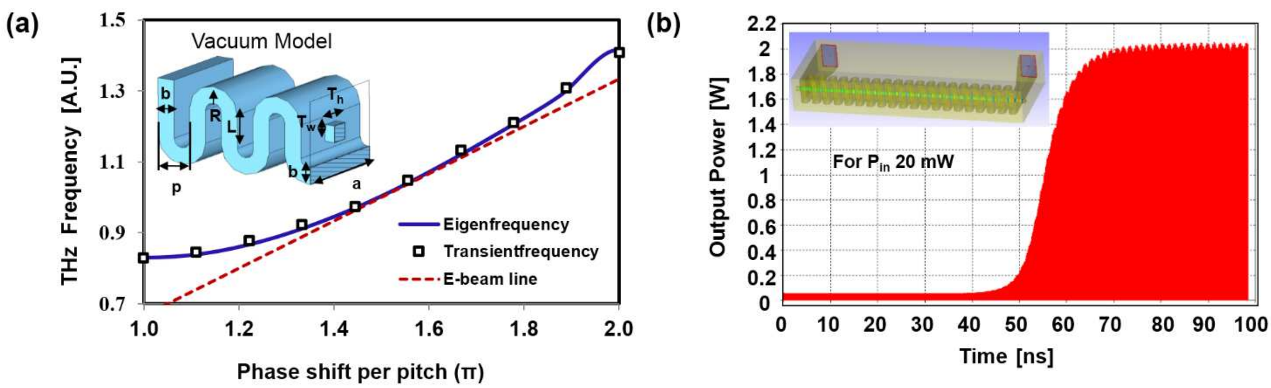


Fig. 6 THz FWTWT amplifier (a) simulated dispersion plot, and (b) simulated output power versus time (inset Fig. shows view of simulated FW SWS model)

Table -2 Summary of Planar Microfabrication Compatible SWSs for THz VEDs

SWS Type	Pros of SWS	Limitation of SWS	Year	Freq. (THz)	Process Adopted	Photoresist Employed	Reference
Folded Waveguide	• Very wide bandwidth ~ 20% • Planar lithographic circuit	• Sensitive to variation in waveguide depth	2004	0.4	DRIE; X-Ray-LIGA; UV-LIGA	PMMA; SU-8	Bhattacharjee [19]
			2006	0.1	X-ray LIGA	PMMA	Shin [20]
			2009	0.22	DRIE	SOI technique	Tucek [21]
			2010	0.22	UV-LIGA	SU-8	Zheng [22]
			2013	0.22	UV-LIGA	SU-8, 2150	Srivastava [16]
			2013	0.65, 0.85, 1.0, 1.5	UV-LIGA	SU-8, 3000	Joye [23]
Coupled-Cavity	• High power capacity • Self-aligned cavities	• Narrow band-width	2009	0.1	X-Ray LIGA	PMMA	Srivastava [24]
			2010	0.1	DRIE	Multi wafer bonding	Baik [25]
Vane loaded waveguide	• Simple structure • Broad-bandwidth ~ 30%	• Upper & Lower halves vanes alignment is challenging	2009	0.22	UV-LIGA; DRIE	KMPR (UV-LIGA)	Shin [26]
			2011	0.22	Nano-CNC	--	Baig [27]
Sine waveguide	• Simple structure • Low ohmic losses	• Show merit only in-presence of sheet beam technology	2011	0.14, 0.22, 0.65, 1.0	NA	NA	Xu [28]
Double corrugated waveguide	• Effective interaction impedance still with round beam	• Expensive X-ray LIGA facility require for isolated pillar fabrication	2011	1	UV-LIGA on Copper & Gold substrate	SU-8	Paloni [29]
			2013	1	X-Ray LIGA	PMMA	Paloni [30]
Raised mender-Line	• Simple structure • High gain per unit length (~ 60% shorter SWS length compare to FWSWS)	• Low thermal dissipation • Selective metallization is quite challenging	2009	0.095	DRIE and UV-LIGA	AZ1827, AZ5214E	Sengele [31]
Circular/ Square / Planar Helix	• Extremely wide bandwidth	• Complex 3-D Fabrication • Needs insulations	2009	0.095	CVD, RIE and UV-LIGA	---	Dayton [32]
			2011	0.65	CVD, RIE and UV-LIGA	Dry file	Lueck [33]
			2011	0.095	Lift-off and UV LIGA	MaN-1440, AZ40XT-11D, dry film	Chua [34]
Grating Structure	• Simple structure	• Limited bandwidth • Limited stability	2010	0.22	UV-LIGA	SU-8	Joye [35]
EIK ladder structure (with sheet beam)	• High R/Q value (i.e. large values of the gain-bandwidth)	• Require high beam voltage ≥ 19.5 kV • Structure topology generated un-desired modes	2010	0.22, 0.65, 0.85, 1.0	UV & X-ray LIGA; Sink & Wire-EDM; Laser machine	----	Dobbs [36]
			2013	0.22, 0.65, 0.85, 1.0	UV-LIGA	SU-8	Joye [23]
Re-entrance cavity-Reflex klystron	• Simple structure	• Require ultra-high current > 1 kA/cm^2	2002	1.2	DRIE	SOI; then gold-plating	Manohara [37]

The two-step UV LIGA process for FW SWS is shown in Fig. 8. The discussed FW SWS is having aspect-ratio between rectangular waveguide narrow-side 'b', period 'p', and waveguide height 'a' ~ 1:2:8 [Inset Fig. 6(a)]. The SU-8 photoresist has capability for forming high vertical aspect ratio SWSs [14-16], but it is disreputably hard to remove [17, 41]. Another promising MicroChem, Corp. KMPR series photoresist [18], which is easy to remove. However, it must be stored below -10 °C, so more difficult to use.

Hence, for discussed THz planar FW SWS fabrication, an epoxy-based negative photoresist SU-8 2150 has been chosen because of its high viscosity (76.75%), ability to coat extremely thick layer (almost 1 mm). The SWS is having symmetric two halves along the beam-tunnel axis, so two-step UV-LIGA is considered for the fabrication of FW with beam-tunnel [Fig. 8]. This two-step UV-LIGA process consists of first cycle of UV-LIGA which contains the forming of the FW [Fig. 8(a-d)], and the second cycle for UV-LIGA contains forming a remaining FW with beam tunnel [Fig. 8(e-g)].

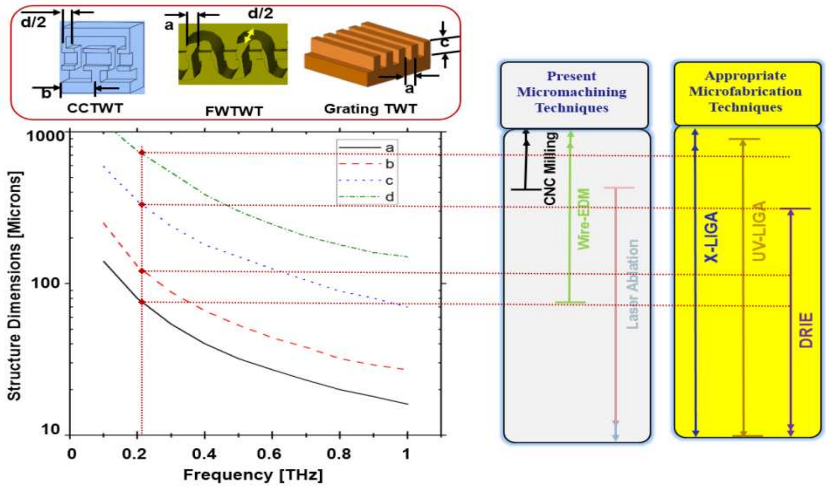


Fig. 7 Appropriate micromachining and microfabrication techniques at THz frequency for different types of planar SWSs, like as coupled-cavity (CC) TWT, FW TWT, and grating TWT

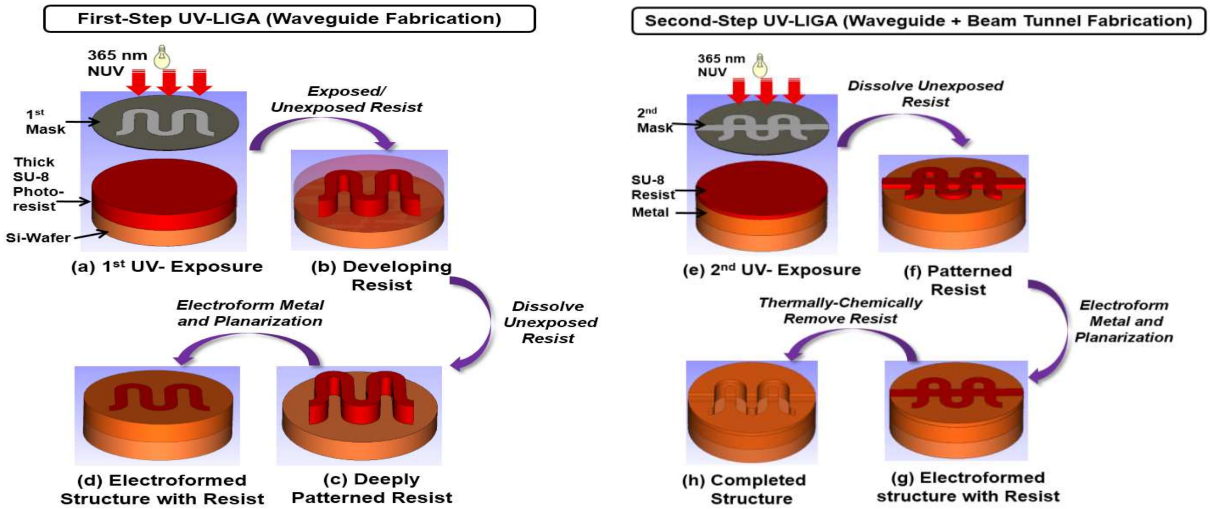


Fig. 8 Schematic of the two-step UV-LIGA process for creating a metal folded waveguide SWS with beam-tunnel. First step microfabrication (a-d) shows folded waveguide formation, and subsequent second step (e-h) includes formation of remaining folded waveguide with beam-tunnel structure

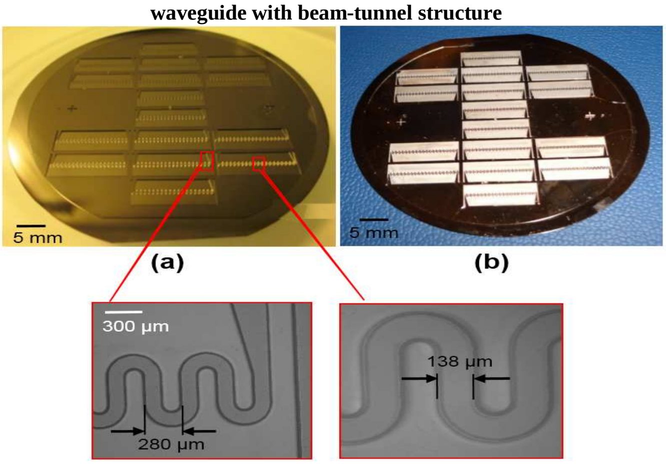


Fig. 9 Optical images of THz FW SWS: (a) fabricated mold (before electroplating) made from thick SU-8 photoresist on 2-inch diameter wafer using UV-LIGA process, and (b) generated metal SWS after electroplating. Profilometer images show clearly waveguide and transition coupler region [16]

The FW SWS mold and subsequently metal structures have been fabricated within desired tolerance ± 2 µm for the next generation THz VME TWTs [Fig. 9 (a) and Fig. 9(b)]. One of the merits of above implemented microfabrication technology, production cost would be reduced through mass production.

High Density Beam Generation and Transport

In MVEDs, device power is dependent on frequency (f), beam voltage (V_b), current (I_b), and current density (J_b) as follows: $P \propto f^{-2} \propto V_b \propto I_b \propto J_b$. Hence, with keeping in mind moderate beam voltage (V_b < 20 kV), device power can be increased only with increasing beam current density. Hence, THz MVEDs desire minimum beam current density $J_b \geq 50$ A/cm^2, which is difficult to generate from either thermionic emitter or cold (CNT/ FEA) emitters [4], as shown in review of reported current densities of different types of cold (CNT and FEA) and hot (thermionic) cathodes [Fig. 10(a)]. The standard M-type dispenser cathodes are normally work on cathode loading less than 10 A/cm^2 with keeping its life-time ~ 10,000 hours. The under research state-of-the-art Scandate cathodes [42] reported current density ≥ 50 A/cm^2 with cathode life a few 100's hours. Very recently reported another research stage Scandate cathode tested in TWT at emission currents of 5-10 A/cm^2 with probable life greater than 50000 hours at operating temperature below 900 °C_b [43]. The field emitter array (FEA) and carbon nano tube (CNT) cathodes provide maximum cathode loading ~ 0.5 A/cm^2 with keeping their reasonable life-time ~ 100 hours [44, 45]. Hence, high current density beam can be formed using round-beam cathode [46, 47] and sheet/ elliptical beam cathodes [48, 49] after beam area compression. The cylindrical beam electron gun was designed using M-type dispenser cathode, and after that twenty fold beam-area compression, analytically obtained desire current density 50 A/cm^2 at beam-minima position [Fig. 10(b)]. Experimentally, developed electron gun meets the designed electron-optics to accomplish the beam current requirement for 0.1 THz MVED [24] [Fig. 10(c)].

No-doubt, sheet electron beam offer much higher power than is feasible with cylindrical electron beam of comparable current density because much less space-charge force (SCF) exist in sheet beam. The reported sheet beam [48, 49] has shown uniform current density 100 A/cm^2, typically for 0.5 THz MVED [50]. But, sheet beam transport under magnetic-field still a big challenge for researchers at THz region.

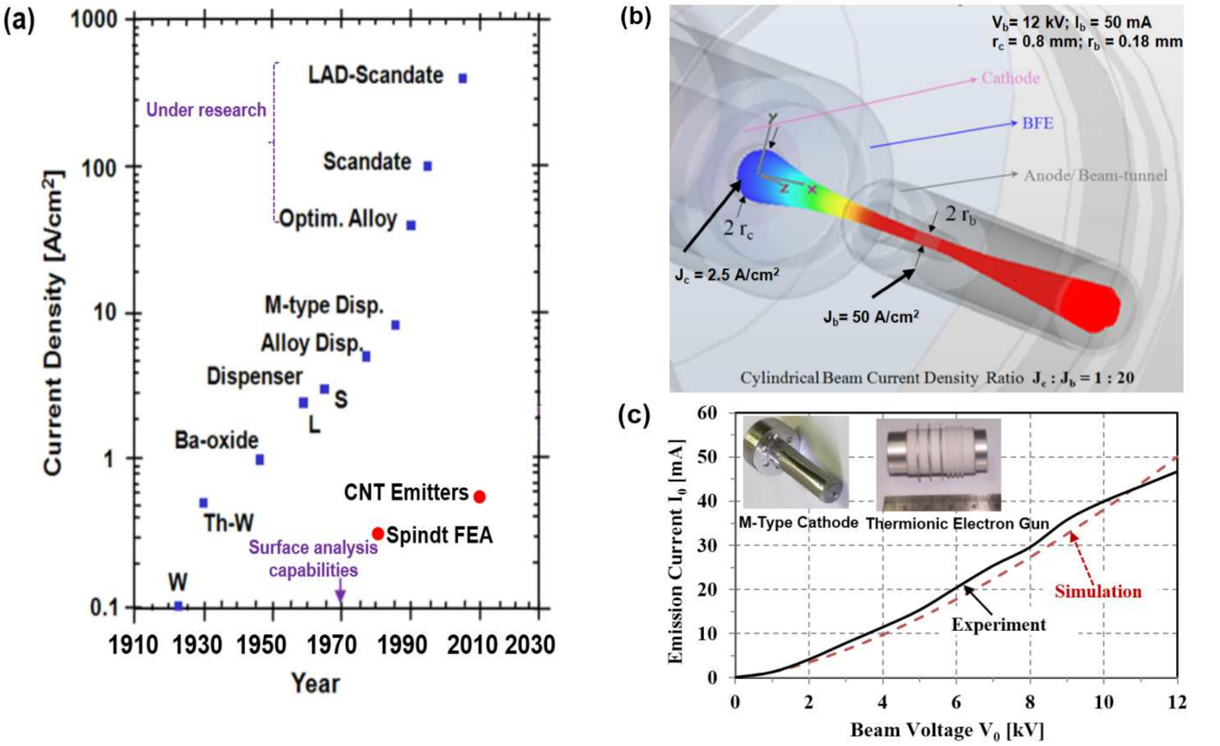


Fig. 10 Electron gun for THz devices: (a) Review of different types of cathodes in terms of current density, (b) simulated electro-optics plot of high current density beam formation, and (c) comparison of experiment versus simulation results. Inset Figures show the tested electron gun assembly using typical M-type thermionic cathode. [46, 47]

ANALYSIS OF STATE-OF-THE-ART THz MVEDs

A few years ago, Unites-States government has started advanced program for development of next generation '**Hi**gh **F**requency **I**ntegrated **V**acuum **E**lectronics (HiFive)' devices under by '**D**efense **A**dvanced **R**esearch **P**rogram **A**gency (DARPA)' and '**M**icrosystems **T**echnologies **O**ffice (MTO) [51]. In this program, Northrop Grumman Electronic System (NGES) agency is involved in developing the compact, integrated power amplifiers in the frequency spectrum 0.22 THz to 1.0 THz. Similarly, European-Union (EU) has also started 'OPTHER-program' for developing 1 THz MVE amplifies [30]. A few frontier countries and their reported recent major projects are listed in Table 3.

Table -3 Summary of Experimentally Demonstrated State-of-the Art THz MVEDs

Agency Name, Country	Device Type	Freq. (THz)	Pout (W)	Gain (dB)	Efficiency (%)	Bandwidth (%)	Reference
SAMSUNG, Korea and CCR, US	BWO	0.1 THz	6 W	NA	1%	NA	Baik [52]
CPI, Canada	EIO	0.214 THz	6 W	---	---	2% electronic tuning	Steer [53]
CPI, Canada	EIK	0.218 THz	7 W	23.6 dB	----	0.14%	Hyttinen [54]
NRL,CPI, and Beam-wave research, US (DARPA HiFIVE)	FW TWT amplifier	0.218 THz	64 W	14 dB	4 %	6.8 %	Joye [55]
NGES, US (DARPA HiFIVE)	Power FWTWT Amplifier	0.214 THz	54.2 W	38.5 dB	2.1%	2.3%	Kreischer [56]
NGFS and Teledyne scientific, US (DARPA HiFIVE)	FWTWT SSPA power modular	0.65 THz	108 mW	21.5 dB	0.44%	6.8 %	Tucek [57]
NGES, US (DARPA HiFIVE)	FWTWT vacuum electronic power amplifier	0.85 THz	50 mW	26 dB	1.1%	5 %	Tucek [58]
Lancaster Univ., UK and Thales, France (EU-OPTHER project)	Backward wave amplifier	1 THz	2.5 mW (target)	10 dB	0.001%	NA	Paoloni [30]
JPL- NASA, US	Nanoklystron	1.2 THz	3 mW (target)	---	0.02%	NA	Siegel [59]

CONCLUSION

The recent advancement in design and development of THz MVE devices and their relevant technologies, which fairly capable to fill the 'THz gap'. Furthermore, reported current research gives appearance that these devices can significantly advance the available coherent source power in the terahertz frequency range, making that possible many defence and civil applications which require wide bandwidth and high power well above 0.1 THz. Still, a significant research has to be performed in the areas of reliable cold emitter development, thermal management and vacuum packaging for making next generation 'compact MVE devices on chip'.

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