An Amazing world of Microwave – Terawave

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Dr. Lalit Kumar received his Ph.D. from Birla Institute of Technology & Science, Pilani. He is Director of Microwave Tube Research and Development Centre, Bangalore, since 2003. He was a Scientist at CEERI, Pilani; DAAD Research Fellow at University of Tuebingen, Technical University of Hamburg-Harburg and Philips, Hamburg; Honorary Visiting Research Fellow at Lancaster University, UK; and AICTE-INAE Distinguished Visiting Professor at IT, BHU, Varanasi.

He contributed towards the indigenous development of: coaxial magnetron, helix- and coupled-cavity-traveling wave tubes; multi-beam klystron, microwave power modules and compact transmitters; analysis & computer-aided design codes for microwave tubes. He is leading research and development on ultra high power microwave sources: vircator, relativistic magnetron, BWO and MILO and enabling technology for THz vacuum microelectronic devices.. He received the JC Bose Memorial Award of IETE-1993, Best Project Award of CEERI-1993, IETE-IRSI (83) Award -2001 and DRDO Agni Award for Excellence in Self-Reliance–2003 and 2013.

He is a Fellow-IETE, Fellow and Founder President-Vacuum Electron Devices and Applications (VEDA) Society, India, Senior Member-IEEE; Member - IEEE-EDS Technical Committee on Vacuum Electronics, -Indian Physics Association, -Indian Vacuum Society, -Indo-French Technical Association, and -Magnetics Society of India. He was General Chair-IEEE-IVEC-2011, Bangalore.

Abstract

The electromagnetic radiations in Microwave to Terawave range have been in nature eternally. Currently, they touch every sphere of our lives and have offer amazing possibilities. The technology of microwave is very well established. However, in the domain of mm-wave to Terawave range though relatively less utilized, hold a huge potential. The talk will cover an overview of the Microwave to Terawave Vacuum – Electronics Technology. Some of the contribution made by the author and his team over the past few decades will be covered. The potential applications and future challenges in this will be discussed. The need for skill development in this critical technology will be highlighted.

I. INTRODUCTION

Microwave vacuum electronic devices (MVEDs), popularly called as microwave tubes are an essential component of many civilian, defence and industrial systems, such as, terrestrial and satellite communications, broadcasting transmitters, radars, electronic warfare systems, missiles, industrial- and domestic-ovens, medical imaging systems, hyperthermia machines, particle accelerators and fusion reactors. Conventional microwave tubes, like, klystron, magnetron, crossed-field amplifier, travelling-wave tube and backward wave oscillator, and many variants or hybrids of them, have been widely used in many of the civilian, defence and industrial systems. The magnetron, which was a workhorse for radars, in now found in every household, fitted in the microwave oven.

The ever increasing demand of spectrum has been pushing the requirements to higher frequency, bandwidth and higher powers. However, the available average power (P) of these devices is, however, limited by the Pf^2 -law (f - frequency). A major breakthrough in MVEDs came with the development of gyrotron devices based on cyclotron-resonance interaction that removed the transverse dimension restriction and could deliver hundreds of kilowatts of power at mm-wave frequencies. Further, the invention of a number of new devices, like, ubitron, orotron, free-electron lasers (FEL), relativistic- and multi-beam-variants of conventional devices, ultra-high peak power devices like virtual cathode oscillator (vircator), magnetically insulated line oscillator (MILO), could offer unsurpassed performance in terms of output power and other characteristics at high frequencies. At the same time, the conventional devices are still going strong owing to the significant improvements in the performance by optimization of their design through modern CAD technique and use of new techniques, materials, fabrication and processing equipment.

More recently, a synergistic combination of a solid-state amplifier and a short-TWT based upon gain sharing has given rise to a new product: the microwave power module (MPM) that offers the best advantages of solid-state and vacuum electronic device technology. This synergy has become total in vacuum microelectronic devices that combine the collision-free ballistics of electrons in vacuum and micro-fabrication techniques to get the best advantages of both the technologies. The availability of high performance MVEDs and MPMs offering multi-octave bandwidth, higher gain, higher average and peak power (~GW), longer life and higher reliability over the frequencies right up to the mm-wave/sub mm-wave (THz-range) have enhanced the performance of many of the systems. It has opened up newer avenues of applications, such as, high resolution radars, multi-beam jammers, towed decoys, mm-wave seekers for missile system, mm-wave high data-rate secure communication systems, light weight compact satellites and satellite communication terminals, deep-space exploration, mm / THz-wave imaging, plasma heating for fusion, directed energy weapon, solar power beaming, microwave power transmission, microwave propulsion, weather control and so on.

MVEDs are currently produced by a small number of manufacturers in the USA, Russia, Europe, Japan, China, India, Israel, and South Korea. Worldwide, the MVED industry is based on high skills, high technology, high investment, high risk and a low volume market. A large variety of MVEDs are used in India, as an integral part of several imported systems for all types of applications as described above as well as their spares. Furthermore, new microwave system development at various scientific laboratories and industries also requires latest MVEDs. The self-reliance in MVEDs for all such systems and particularly those required for strategic applications is a huge challenge. This situation was realized in the country fairly early and the development activity was initiated in early fifties. Several institutions: Calcutta University, Tata Institute of Fundamental Research, Delhi University, National Physical Laboratory, Central Electronics Engineering Research Institute, and Bharat Electronics laid the foundation of microwave tube research, development and production in the country. In seventies and later newer centres: Centre of Research in Microwave Tubes-BHU, Microwave Tube Research & Development Centre (MTRDC), Society for Applications in Microwave Electronics Engineering Research (SAMEER) were founded to carryout focused R&D on microwave tubes. These institutions have made significant contributions in the indigenous design and development of helix- and CC-TWTs, klystrons, magnetrons, carcinotrons, and MPMs for applications in defence, space, and high-energy accelerators. Some of these technologies have been transferred to the industry. Presently, Bharat Electronics, Bangalore, is the only Indian company having a regular product-line and an excellent production capability for such devices. Earlier, a variety of magnetrons with CEERI know-how were also produced by Central Electronics Limited, Sahibabad, for defence applications, but the operations have been shut down way back in nineties. Pilani Electron Tube Development Ltd., Sangrur is involved in production of triodes for

induction heaters. Several academic institutions: IITs-Delhi, -Bombay and -Roorkee, Devi Ahilya Vishwavidyalaya (DAVV), Indore, NIT-Trichy, Pune University, University of Burdwan and others undertook research and made significant contributions to this area.

Over the last few decades, the technologies for development of electron tubes in the country have matured well and a very sound foundation has now been established for the *'ab-initio'* design and development of microwave vacuum electronic devices. This has become possible through establishment of excellence in computer-aided design (CAD) and maturation of relevant technologies. Indigenous design and development of a variety of microwave tubes has been completed by various institutions for application in defence, space, and high-energy accelerator applications: fixed frequency- and tunable-magnetrons, tunable co-axial magnetron for radar and accelerators; pulsed- and CW- carcinotrons for radar; high power multi-cavity klystrons for troposcatter communications and accelerators; pulsed- and CW-helix-TWTs for radar, EW and space communications; pulsed CCTWTs for radar; and MPMs for EW and satellite data-link. Many of these devices have been productionized and some are in the pipeline. Besides these devices, development of high emission density dispenser cathodes (B-, M-, MM-type) and Ferro-electric cathodes has also been carried out.

Presently, India has a robust triad of academia-R&D laboratories and industries to take up any challenges in this area. The Indian microwave community is closely knit together in the Vacuum Electronics Device & Application Society (VEDA-S) and connected to the international MVED community through the IEEE-EDS-Vacuum Electronics Committee and contributes regularly to the IEEE – International Vacuum Electronics Conference (IEEE-IVEC), the first Indian edition of which (IVEC-2011) was held in 2011.

This paper highlights the indigenous development of various devices, such as broadband mm-wave TWTs, mini- and midi-TWTs, coaxial magnetron, multi-beam klystron, MPM and compact MPM based transmitters carried by the author and his teams at MTRDC, Bangalore and CEERI, Pilani with participation of Bharat Electronics, Bangalore and in partnership of many academic institutions listed above.

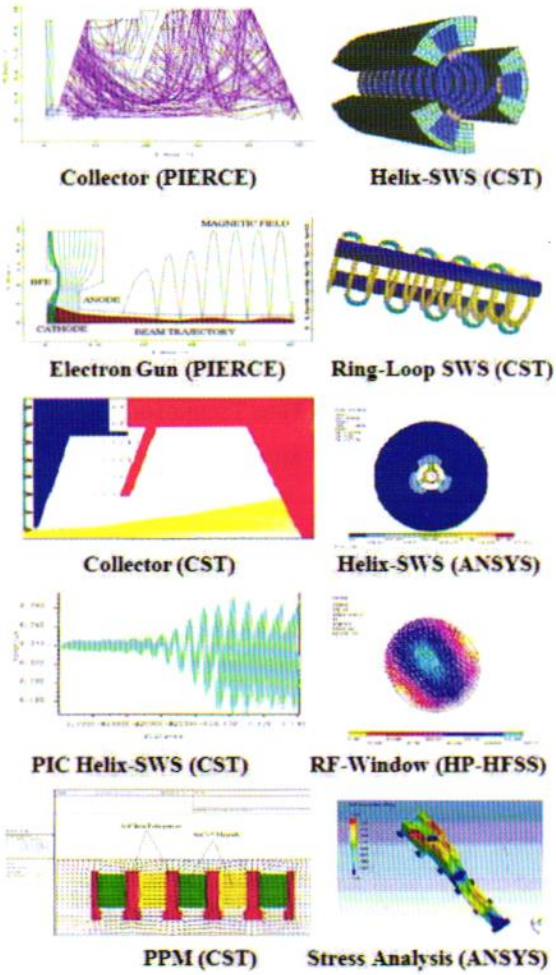
II. Analysis and Computer-Aided-Design

An MVED typically consists of a source of electrons, an arrangement of high voltage electrodes or an electron gun, a magnet system, a microwave interaction circuit with input/output vacuum window, and a spent beam collector. The MVEDs are classified as oscillators or amplifiers depending on their function and as 'linear beam' or a 'crossed-field' device depending on whether the DC electric and magnetic fields in the device are parallel or perpendicular to each other respectively, or as slow-wave or fast-wave depending on phase velocity of the wave relative to the velocity of light, or even as relativistic or non-relativistic depending on the range of velocity of electrons. Their basic principle of operation lies in the conversion of the potential or kinetic energy of a highly accelerated electron beam into high frequency electromagnetic energy, by its interaction with the background or imposed RF electromagnetic fields on an interaction circuit.

Advanced analytical models and simulation codes were developed for electron guns; magnetic focusing structures; multi-stage depressed collectors; helix-, coupled-cavity-, helix-derived, and wave-guide-derived slow-wave structures (SWSs); RF cavities; coaxial and waveguide transitions; and RF windows. Some of the special purpose codes like, electron optical code PIERCE (Program for Improved Electron Ray-tracing in Collector and Electron guns) that include simulation of multiple electron / ion species in gun and simulation of multiple generations of true secondary and elastically- or in-elastically scattered primary electrons in collector, 3-D package for simulation of depressed collectors LKOBRA. The capability has been further extended, by establishing design methodology of RF structures using commercially available 3-D electromagnetic codes MAFIA /CST Microwave Studio and High Frequency Structure Simulator (HFSS). To go beyond the parametric codes for the prediction of device performance, the simultaneous simulation of circuit and electron beam capability of particle-in-cell (PIC) simulation in MAFIA/ CST Particle Studio and MAGIC has been exploited at MTRDC, for complete simulation of a variety of microwave tubes. This has been helpful in optimization of the devices and reducing the hardware iterations.

Furthermore, optimization of device performance, under stressful service environment, requires a detailed thermal and structural modeling. ANSYS and other similar packages are the tools used as a

part of the engineering design for linear and non-linear analyses. Coupled-field analysis of interference modeling and thermal contact resistance modeling using contact elements, and coupled thermal/structural analysis has been carried out.



Typical CAD models carried out at MTRDC

A. Electron-optics:

Program for Improved Electron Ray-tracing in Collectors and Electron-guns (*PIERCE*): A 2.5-dimensional program for high accuracy simulation of axisymmetric electron guns including grids and magnetic field, and multi-element depressed collectors, with facility for simulation of secondary electron and ion trajectories and several new features was developed. The program has been extensively used by many researchers for simulation of various types of diode and gridded electron guns and collectors at CEERI, MTRDC, BEL and other institutes.

***LKOBRA*: A package for 3-dimensional simulation of multielement depressed collectors** was developed under an ESA contract at Engineering Department, Lancaster Uni (UK). The package is based on a 3-D code KOBRA3 originally developed by another group. It is in use at Lancaster Uni, UK, TTE, Ulm, Germany, and ESA/ESTEC, The Netherlands. It incorporates simulation of primary and secondary trajectory automatically geometry file creation and detailed analysis of collector profile and its performance. It was the first 3D collector code to run on a micro-computer.

B. Electron Beam Focusing:

In a conventional PPM structure (which is used for focusing in majority of the linear beam tubes) the axial magnetic field is near sinusoidal in nature with a small period, which is limited by the beam stiffness factor; $\lambda p/L$, (where λp is the plasma wavelength and L is the periodic length). A stable or satisfactory electron beam transmission through the focusing structure is achieved when $\lambda p / L > 2.7$ for CW tubes and >3.2 for pulsed tubes. However, in some cases increased periodic length beyond the above mentioned limit offers certain advantages, which is called long-periodic focusing, and there the stable beam transmission is achieved by careful profiling of the axial magnetic field. For example, in coupled cavity traveling wave tubes (CC-TWTs), presence of coupling irises results in deterioration of electron beam transmission with conventional PPM focusing. Hence, in CC-TWTs, use of long periodic focusing improves the beam transmission. In mm wave TWTs, use of long-periodic focusing reduces the parts count & cost, and the cost of assembling the TWT.

The design of a long-periodic focusing structure is more complex than that of a conventional single periodic structure as it requires the shaping of the axial magnetic field with specified harmonic strength. The shaping of the axial magnetic field is done with introduction of number of floating pole-pieces between the main pole-pieces. A simple analytical approach has been developed for the design of long periodic permanent magnet structure at MTRDC. The method is based on analytical formulations, and hence design and optimization takes very less time. The code based on these formulations has been made using

MATLAB. Analytically computed axial magnetic field is compared with FEM simulation and measured results found to show a very good agreement.

C. Microwave Interaction Structures:

Helix-SWS: Analytical models for dispersion and interaction impedance characteristics of broad-band helix and helix derived (ring-loop and ring-bar) SWSs, including various types of inhomogeneous and anisotropic loading: vane-, semi-vane-, and chiral-loading; effects of dielectric loss, conductivity loss, attenuator and sever loss, meander-line resonant loss; and helix-to-coaxial / waveguide couplers; coaxial windows, analysis of π-mode stop bands in asymmetric SWS. Small and large-signal analysis for broadband multi-dispersion circuits, BWO-oscillation startup conditions for uniform and step-tapered helix SWS. The highly cited 'Modified infinite number of vanes model' (MINV) for segment-loaded helix SWS was proposed by the author and the co-workers. Methodology for 3-D electromagnetic simulation for cold characteristics, and 3D-particle-in-cell simulation for hot-characteristics – determination and optimization have been established.

Coupled-cavity SWS: Analytical models and 3D-simulation and cold test experiments for dispersion, impedance characteristics of single- and double- slot space harmonic coupled-cavity SWS, inverted slot-mode and inductively coupled inter-digital SWS, disc-loaded waveguides, resonant-loss loaded CC-SWS, waveguide couplers and pill-box- and resonant block- windows.

Gyrotron Devices: Gyrotron is a fast-wave device based on cyclotron resonance interaction of a hollow electron beam with the transverse electric field in an overmoded open cavity. It is capable of generating MW of power at mm-wave frequency. Analytical models and 3D-simulation and cold test experiments for dispersion and impedance characteristics of vane-loaded hollow-waveguide and coaxial waveguide gyro-TWT structures, waveguide window and coupling structures, wrap-around TE_{10} - TE_{01} mode converters were developed. Design and assembly of a low voltage (15 kV) magnetron injection gun to produce a hollow electron beam as a learning model was made and tested.

The output mode content identification of a gyrotron is a very important measurement. A software based on beat-phenomenon between various modes with different phase velocity in the gyrotron output was developed. An instrument to record the beat pattern on thermal paper by connecting it at the output of the gyrotron has also been developed and successfully tested on a 70 GHz 200 kW gyrotron at Phillips-Valvo.

Large Signal Analysis & Particle-in-cell (PIC) Modeling: Large-signal analysis and 3-D PIC modeling of helix TWT, coupled-cavity TWTs, gyrotron, Gyro-TWT, multi-beam klystron, relativistic magnetron, and axial-, coaxial- and multi-beam- vircators led to establishment of state-of-art design capability and highly optimized designs of microwave tubes.

III. Electron Tube Technology

The development of MVEDs being technology intensive and highly interdisciplinary, a very sound base in electron tube technology has been established. An advanced microwave tube facility named after Acharya J. C. Bose was established at MTRDC in 2011. It is a full-fledged facility for developing fully engineered and environmentally tested models of microwave tubes particularly TWTs, multi-beam klystron and cathodes.

A number of specialized techniques for development of gridded electron gun, such as, grid fabrication by photolithography, chemical etching and electric discharge machining (EDM), and cold forming were developed. The grids made by the EDM process were successfully used in several helix- and coupled-cavity TWTs. Technologies like vane-loaded barrel fabrication by brazing of segments and by wire-cut EDM, hot stuffing of helix-rod bundle into an integral pole-piece barrel using induction heating, brazed-helix structure, coated-vane slow-wave structure are some of the unique technologies developed indigenously.

Typical microwave tube components developed at MTRDC

IV. Travelling-Wave Tubes

Traveling wave tube (TWT) uses a broadband circuit in which a beam of electrons interacts continuously with guided electromagnetic field to amplify microwaves. A TWT consists of an electron gun to produce a pencil shaped electron beam, a focusing system to focus the electron beam, a SWS to slow down the microwave signal to approximately the same velocity as the electrons in the beam and a collector to collect the final beam. When the electron beam interacts with the microwave signal, it transfers a part of its kinetic energy to the microwave signal, thereby amplifying it. Two major classes of TWTs are: the helix TWT for low to medium average/peak power broadband applications and coupled cavity TWTs (CC-TWTs) for high average/peak power and narrow band applications.

A. Coupled-cavity Traveling Wave Tube:

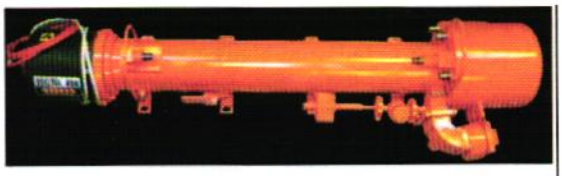
The CC-TWTs are all-metal ceramic tubes capable of high power (~MW) and moderate bandwidth (~15%) were developed to meet the requirements of high average power amplifier. A major project for development of a family of CC-TWTs in S-, C-, X- and Ku-bands for various radar applications was taken, up by MTRDC. A number of new technologies such as for fabrication of shadow-gridded electron gun, distributed- and resonant-loss loading of cavities, development of $SmCo_5$ magnets with good homogeneity, and thermal management were some of the key areas addressed. Under this programme collaboration was initiated with a foreign partner on joint development of X- and Ku-band CC-TWTs.

- **X-band pulsed Coupled-Cavity TWT** for airborne multi-mode radar has unique features: 6.5 kW (peak) power, shadow gridded electron gun, inter-digital slow-wave structure operating in the slot-mode, PPM focusing, single-stage depressed collector, complete ceramic-metal construction, small size, light weight, liquid cooled and high efficiency.
- **S-band pulsed Coupled-Cavity TWT** is the largest (1.5 m tall) and highest power CC-TWT developed in India for surveillance radar. Unique features are 130 kW peak power, non-intercepting gridded electron gun, PPM focusing, single-stage depressed collector, liquid cooling, high gain, wide bandwidth and high efficiency.
- **Ku-band pulsed Coupled-Cavity TWT** for airborne radar delivers 10 kW (peak) power. Salient features: shadow gridded electron gun, PPM focusing, two-stage depressed collector, capable of operating at two duty cycles (0.5 % without cooling and 2.5% with liquid cooling), high gain, high efficiency and light weight.

B. Helix Traveling Wave Tube:

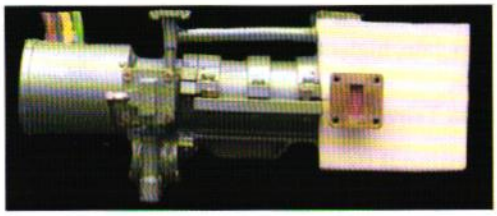
Conventional Helix TWTs

- **S-band pulsed Helix TWT**, capable to deliver 30 W peak power was developed as a pre-amplifier for 3-D Static radar of Air force. This was the first all ceramic-to-metal sealed gridded TWT developed in India with a single-gridded electron gun, a tungsten-wire helix supported by 3 alumina rods with attenuator coating inside a metal envelope, single-stage isolated collector, air cooling and permanent magnet mount with bucking coils focusing system.
- **X-Ku band CW Helix TWT** jointly developed with Bharat Electronics to deliver 300 W for EW applications. It uses a BFE controlled electron gun, vane-loaded helix SWS and 2-stage collector.
- **C-Ku band pulsed helix TWT** was developed to deliver 1.5 kW power at 4% duty for EW transmitter. It consists of shadow gridded electron gun for pulsed operation, vane loaded negative dispersion helix-pitch and tapered high efficiency SWS, single-stage high efficiency depressed collector.
- **Millimeter-wave Helix TWT** is the 40 W, highest bandwidth millimeter-wave Ku-Ka-band TWT, which uses a very thin diameter electron beam (0.35mm), highly broadband vane-loaded SWS and 2-stage tilted-electric field collector. This TWT was jointly developed with foreign partner.



S-band CC-TWT

Ku-band CC-TWT



X-band CC-TWT

C-Ku band Mini Helix TWT

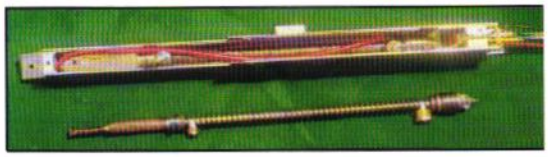
Typical TWTs developed at MTRDC

Mini-TWTs

- **X-Ku band Mini-Helix TWT** (*CEERI*): First indigenous 40 W, highly compact gain and phase matched Mini TWT with integral pole-piece 2-section barrel, Sm-Co PPM focusing structure, vane-loaded helix SWS, single-stage depressed collector, compact adjustable BFE controlled shielded electron gun using dispenser cathode, conduction cooled through base plate and tight tolerance control for offering gain and phase matched performance. This was the first mini-TWT developed in India at par with contemporary TWT.
- **C-Ku band CW Mini Helix TWT** is 80 W, short gain, high efficiency power booster Mini-TWT developed jointly with Bharat Electronics for MPMs and MPM based Transmitters. It uses BFE modulated electron gun, multi-dispersion semi-vane loaded helix SWS, 4-stage single-ceramic collector and compact electron gun with integral getter.
- **C-Ku band CW Mini Helix TWT** (200 W) is a compact power booster 200 W Mini TWT with 3-stage thermally efficient collector for MPMs and Transmitters, which is jointly developed with Bharat Electronics and meets RF and limited environmental specifications.

Several other variants of the short gain mini-TWT at 100-350 W are under development.

S-band pulsed Helix TWT



X-Ku band CW Mini-Helix TWT

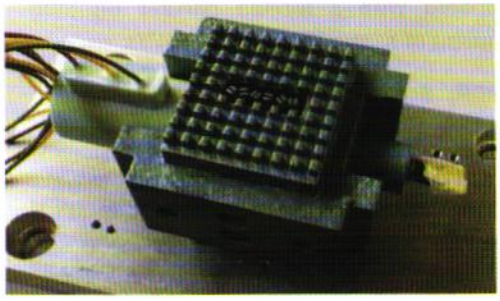
Typical TWTs developed at CSIR-CEERI

V. Miniature Multi-Beam Klystron

A multi-beam klystron is a highly efficient compact and unique device utilizing several independent beamlets, surpassing single beam perveance by several folds, launched into the same chain of cavities to give the advantage of paralleling several klystrons into a single vacuum envelope. The technology for high frequency miniature MBKs, particularly, is closely guarded.

Ku-band pulsed MBK is the first Indian MBK prototypes. It uses 19 electron beamlets in a highly compact klystron that delivered 150-200 W (pulsed) power. This device is a critical item required for airborne radar application.

A higher power variant is also under finial stage of delivery.

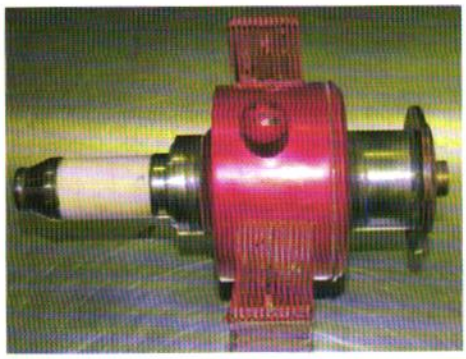


A typical MBK Proto at test bench (MTRDC)

VI. Coaxial Magnetron

X-band Coaxial Magnetron (CEERI) was the first indigenously developed all ceramic-metal construction 200 kW tuneable coaxial magnetron for fire control radar as all the earlier magnetrons in India were glass-metal versions. Its unique features are: fully ceramic-metal window and

indirectly heated S-type dispenser cathode assembly, broadband tuning with mechanically tuned Plunger with counter, 11 % bandwidth, and integral Alnico magnet system.



X-band 200 kW (Pulsed) Tuneable Coaxial Magnetron

VII. Microwave Power Module (MPM)

An MPM is a synergistic combination of a solid-sate power amplifier and a TWT-amplifier in gain-sharing mode with both powered by an intelligent, high performance, compact electronic power conditioner and integrated into a single compact, lightweight module. It offers the advantages of about five times saving in weight, 2-3 times higher efficiency and higher reliability as compared to a TWTA.

The indigenous design and development of MPMs was initiated at MTRDC from scratch. The critical sub-modules: highly compact high efficiency, microprocessor-controlled, rugged, multi-output electronic power conditioner to power up the mini-TWT and solid-state amplifier and provide monitoring and control functions, thermal management and ruggedized monolithic chassis have been developed in-house. Initially, imported mini-TWTs have been used in the MPMs to shorten the development time, but parallel, indigenous development of min-TWTs has been pursued with considerable success. Design and engineering prototype development a family of power booster mini-TWTs in C-Ku band have been developed for the MPM and MPM based transmitters.

MTRDC has achieved success in development of high efficiency for MPM. The EPC has very high conversion efficiency ~92 % and enhanced power conversion density of more than 40W/cu-inch. An ultra-fast pulse modulator with a throughput delay less than 60 ns, PRF up to 250 kHz in continuous mode and 3.5 MHz in burst mode have been achieved. Several variants of these EPCs with input prime power of 28 V DC / 270 VDC and 115 VAC 400 Hz have been developed.

Several variants of MPMs have been developed to suit various defence and civilian applications. Some of the MPMs have been productionized at Bharat Electronics and integrated in systems.

- C-Ku-band CW MPM for EW
- X-band Pulsed MPM for Radar

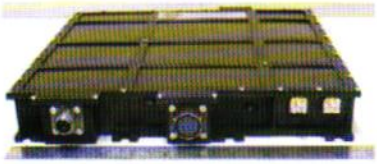
VIII. MPM based Transmitters (MPM-Tx)

Highly compact full-fledged rugged transmitters have been developed using MPM by incorporating innovative thermal management, input / output power and VSWR, sensing and control, and microprocessor based programmable communication and control as per the mission requirements. The following transmitters have been developed to various stages, jointly with BEL and support from private agencies.

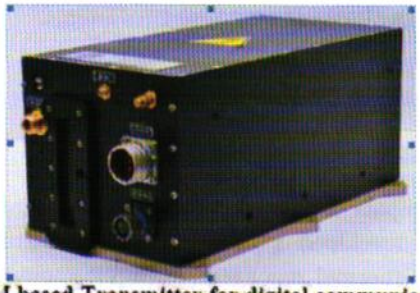
- Low Power CW/Pulsed MPM-Transmitters for EW System
- High Power Pulsed Transmitter for EW System
- MPM based Transmitter for Digital Satellite Communication
- Pulsed MPM based Transmitter for Radar

The MPMs and the MPM based transmitters resulted in huge saving of ~50% in prime power (efficiency), weight, volume and increased reliability, compared to a TWTA. These MPMs are comparable (better in a few aspects, but somewhat heavier) in specifications to commercially available MPMs and offer huge savings (50%) over the imported units. Some initial versions use imported TWTs. A new productionisation of MPM has been launched by Bharat Electronics based on the technology from MTRDC.

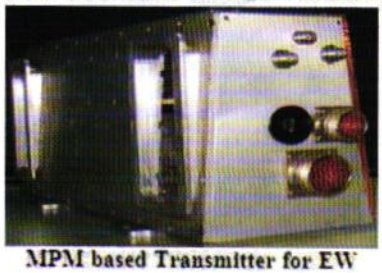
Pulsed MPM for radar



CW-MPM



MPM based Transmitter for digital communication



MPM based Transmitter for EW

IX. High Power Microwave Devices

High power microwave devices are defined as those delivering >100 MW peak power at frequency above 300 MHz. The devices capable of delivering such powers are virtual cathode oscillator (vircator), relativistic-magnetron, -klystron, and -BWO, magnetically insulated line oscillator (MILO), free electron laser and relativistic diffraction generators. Several advanced countries have developed these devices for application as non-lethal weapons targeting electronic systems without any collateral damage. MTRDC has initiated exploratory work in this area jointly with sister laboratories. R& D on vircator (axial, Coaxial, and triode type), diffractive output relativistic magnetron, relativistic BWO and MILO has been initiated. Basic designs of the devices were made with parametric equations, large signal analysis and 3-D PIC analysis of devices was carried out to predict detailed performance. Cold test models of the device were tested using higher order mode exciters. Experimental studies on these devices have been carried by evacuation the devices to high vacuum level and driving by high voltage pule generators, like, Tesla transformer and Marx generator coupled to a pulse forming line for pulse compression. The operating range of the pulse power experiments has been typically, 200-600 kV voltage and 4-16 kA current, 50-100 ns duration and single shot operation. Typical vircator and relativistic magnetron have delivered ~100 MW output power in S-band frequency range.

Research on cathodes for HPM sources has also been initiated and Carbon fiber tuft cathode has been assembled at tested. Such a cathode was tested in a vircator and an emission current density ~350A/cm^2) has been measured. Shot to shot emission repeatability was also observed.

Coaxial vircator and pulse power system setup

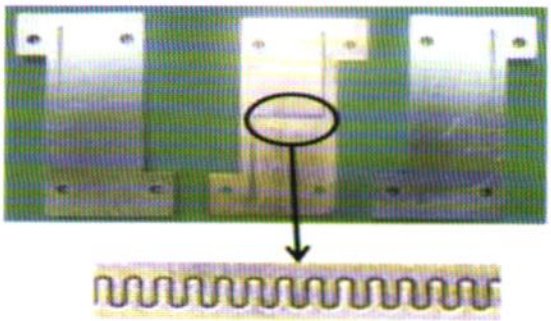
X. Vacuum Microelectronic Devices

Vacuum microelectronics is a new area combining best of the both the solid-state and vacuum electronic technologies: micro fabrication technology and collision less ballistics of the electrons in vacuum along with field emitter arrays derived from CNT or S-tips. This technology offers great promise for development of planner TWT and BWO up to THz frequencies. Basic enabling technology development in this area has been jointly carried out with SSPL, New Delhi and other sister institutions.

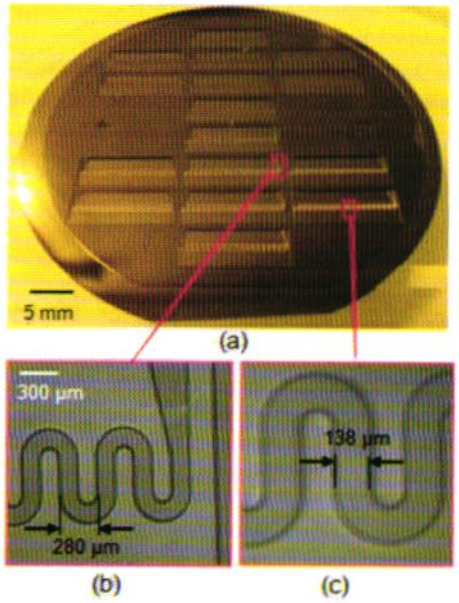
Field Emitter: Field emitter arrays consisting of vertically aligned selectively grown CNTs were developed by CVD process and tested, which provided current density ~140 mA/cm^2. Similarly, Silicon field emitter arrays (10^5 Tips/cm^{2}developed by SITAR) has achieved experimentally ~300 mA/cm^2 current density.

FETRODE: A field emission triode (FETRODE) has also been assembled and tested. In addition, Carbon Fiber Explosive Emission Cathodes have been fabricated for high power microwave applications.

Planar Slow-wave Structure: Planar serpentine waveguide SWSs (Ka- and W-band) were fabricated using a 30 μm wire EDM machine. A THz folded waveguide slow-wave structure (FWSWS) has also been realized by UV-LIGA process on a silicon substrate jointly with a sister laboratory.



W-band Folded Waveguide Slow-wave Structure



Optical image of FWSWS molds made from SU-8 photoresist on 2-inch diameter wafer using UV-LIGA process (a) and its profilometer images (b & c).

XI. Conclusion

Microwave Vacuum Electronic Devices (MVED), which are crucial for all defence and civilian microwave system have been discussed. The development of new class of devices, particularly, gyro-devices and synergistic combination of vacuum electronic- and solid-state-devices- the microwave power module and vacuum microelectronic devices have been introduced. Some of the contributions made by the author and his team at MTRDC and CEERI towards analysis, CAD codes, indigenous design and development of specific MVEDs jointly with various partners have been summarized.

Considering the global trend in this device technology area, the following projections and conclusions are proposed.

1. The conventional MVEDs will still continue to improve in their performance by exploiting advanced simulation models, modern materials, innovative technological processes, high precision machinery, precise measuring instruments, and process equipment with intelligent control.
2. Energy efficient and low-voltage devices utilizing cold cathodes / low temperature cathodes, and energy recovery collectors will achieve theoretical limits and find use in civilian applications.
3. The new applications in industrial heating, particle accelerators, power generation, space power beaming, microwave power transmission, DEW, deep-space exploration, and microwave-propulsion etc. will push the ultra-high power sources towards maturity of sealed-off devices..
4. Modularly in MVED assembly and in MPMs will lead to reduced inventories / larger production lots which in turn will lead to cost reduction. Lean manufacturing will make even smaller lots profitable and will provide quickest delivery time.
5. Statistical process control, quality management system and enterprise resource planning (ERP), will increase reliability and traceability and usher in just-in-time (JIT) trend resulting in reduced costs and time delays.
6. The devices will become smarter by inclusion of sensors processors, and iterative learning control modules. The device will thus gradually turn intelligent and 'cognitive'.
7. The vacuum microelectronics technology will pave the way for moderate power mass produced vacuum devices exceeding the power levels of wide-bandgap semi-conductor devices.

The Microwave application spectrum has spread from RF to THz in frequency and Watts to Terawatts in power and these VMEDs are poised to penetrate every sphere of human life in the universe.

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