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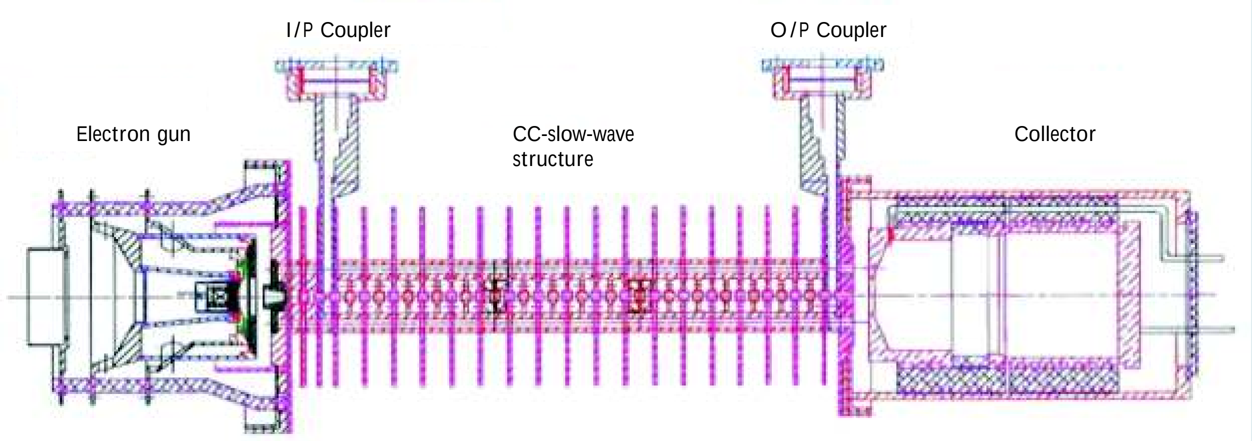
टैक्नोलॉजी फोकस

MICROWAVE TUBES

Microwave tubes are vacuum electron devices capable of generating or amplifying high frequency signals (>300 MHZ) for various Defence and civilian applications in communications, radars, electronic warfare and integrated support measures (ISM) systems. These devices are crucical for most military applications, however, they meet competition from solid-state devices at lower ranges of frequency (<12 GHz) and power (<100W). Among the variety of microwave tubes, DRDO has chosen to focus on the Traveling-wave Tube (TWT), which is most widely used in the present day systems owing to its broadband characteristics. Two different types of TWTs, namely, Helix TWTs and Coupled-Cavity (CC) TWTs have been successfully developed. The capability in TWT development has been leveraged by the development of a microwave power module which is a synergistic combination of a solid-state power amplifier, a power booster TWT, and an electronic power conditioner for both the devices in a single compact module. Critical components of all microwave tubes, the high density cathodes, high energy density rare-earth magnets, Al_2O_3-SiC lossy, ceramics, porous W-Re alloy matrix, etc. have been developed by DRDO. The development and productionisation of some of these devices is being carried out jointly with Bharat Electronics, Bangalore. This issue of Technology Focus covers some of these devices.



MESSAGE

Microwave Tube technology is a strategic technology mastered by only a few countries in the world. It is indeed a matter of pride that DRDO has developed broad-band Helix TWTs, high power coupled cavity TWT's, Microwave Power Modules (MPM), high density cathodes and various related technologies. These devices are highly crucial for self-reliance in development of communication, radar and electronic warfare systems. I am glad that this issue of Technology Focus highlights the developments on Microwave Tube technology in DRDO.

(N Sitaram)
Distinguished Scientist &
Chief Controller R&D

From the Guest Editor

I am happy to present this first issue of Technology Focus in 2008, the Golden Jubilee Year of DRDO, dedicated to a highly specialised and crucial technology of Microwave Tubes. This issue summarizes the developments at DRDO in respect of Traveling-wave Tubes of both the helix and coupled-cavity types, microwave power modules (MPM) and their specialised components such as high emission density cathodes and electronic power conditioner. The technological capability necessary for achieving these devices include: computer-aided-design and simulation, special purpose precision machining; protective atmosphere heat-treatment and brazing, ultra-high vacuum, thin film coating, electronic circuit design for multi-layer PCBs, high frequency measurements, high voltage testing and environmental testing for reliability.

The device development is synergised with Bharat Electronics to translate the device designs into production. Several DRDO labs, academic and research institutes outside DRDO have also helped in various ways in developing these technologies. We acknowledge their contributions.

I wish to thank the editorial team of Technology Focus for their untiring effort to bring out this issue in a nice presentable form.

(Dr Lalit Kumar)
Director
MTRDC, Bangalore

TRAVELING-WAVE TUBES

Traveling-wave tubes are microwave tubes of special design, made using a broadband circuit in which a beam of electrons interacts continuously with guided electromagnetic field to amplify microwaves.

A TWT comprises an electron gun to produce a pencil shaped electron beam, a focusing system to focus the electron beam, a slow wave structure (SWS) to slow down the microwave signal to approximately the same velocity as of the electrons in the beam, and a collector to collect the final beam. When the electron beam interacts with the microwave signal, it amplifies the microwave signals by transferring a part of its kinetic energy to the microwave signal. Two major classes of TWTs—the helix TWT for low to medium average / peak power broadband applications and CCTWTs for high average / peak power and narrow band applications—have been developed.

Couple-Cavity TWT

Coupled-cavity TWTs are capable of giving high power output ranging from a few kW to MW at a moderate bandwidth of 10-16 per cent and have a rugged ceramic metal construction. The tubes amplify microwaves for high power pulsed radar systems for ground- and airborne applications. DRDO has developed the design and technology for a family of CCTWTs in three different frequency ranges of S-, X- and Ku-bands. Technologies, like non-intercepting gridded electron gun, brazing of lumped losses in cavities, optimization of severs and couplers, thermal management by liquid cooling, and art of fine-tuning the periodic permanent magnet focusing structure have been mastered. The high density samarium cobalt magnets for the focusing system have also been developed by DRDO. Ceramic components used for construction of CCTWT have been produced indigenously.

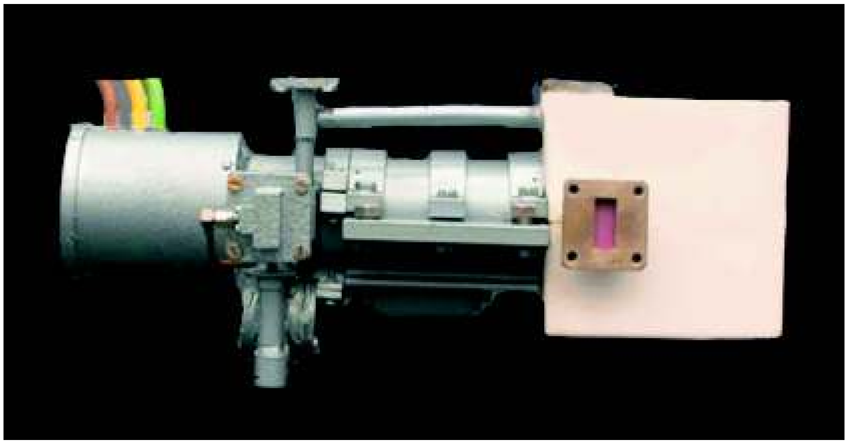
S-Band CCTWT

MPC 2081—130 kW S-band CCTWT

A high power S-band CCTWT has been developed for ground based and airborne surveillance radar applications. The tube employs a non-intercepting gridded electron gun with M-type dispenser cathode. The SWS is a double-slot staggered coupled-cavity structure and operating in cavity mode. Special lossy ceramic buttons, made of BeO-SiC and AlN-Fe composite materials to suppress the onset of oscillations, were brazed by active brazing using a titanium doped braze alloy. The TWT has a co-axial input coupler and a wave-guide output coupler to handle high power at the output. The collector is a single- stage depressed collector with around 24 per cent efficiency. Cooling is provided by anti-freeze ethylene glycol and water mixture. The technology transfer to Bharat Electronics Ltd, Bangalore is under way.

X-Band CCTWT

An X-band CCTWT for airborne radars has been developed in collaboration with ISTOK, Russia. The tube uses an inter-digital SWS (also referred to as inverted-slot-mode circuit). The TWT is highly efficient and compact compared to the conventional CCTWT, and comprises a non-intercepting shadow gridded electron gun, a periodic collector with off-axis beam entrance hole, and a liquid cooling arrangement. The tube is lighter and smaller compared to other competitive products. This tube has passed all electrical tests for radar performance and environmental tests for safety of flight. The technology has been transferred to Bharat Electronics Ltd, Bangalore for the limited series production of the TWT.



MPC 4068—6.5 kW X-band CCTWT

Ku-band CCTWT

A lightweight and compact Ku-band CCTWT has been developed for airborne radars in collaboration with ISTOK, Russia. The tube uses a non-intercepting gridded gun with M-type cathode. The SWS is a three-section conventional fundamental backward-wave space-harmonic structure consisting of a series of cavities coupled through staggered kidney shaped slots. A lossy dielectric ring made of aluminium-nitride and iron composite is being used in the sever cavities. The focusing of the electron beam is accom-plished by periodic permanent magnet focusing system, which uses $SmCo_5$ magnets. A two-stage depressed collector improves the overall efficiency of the tube. It can operate at dual duty ratios of 0.5 per cent for 10 minutes without cooling and 2.5 per cent with liquid cooling continuously. It meets stringent specifications of environmental tests for airborne applications.

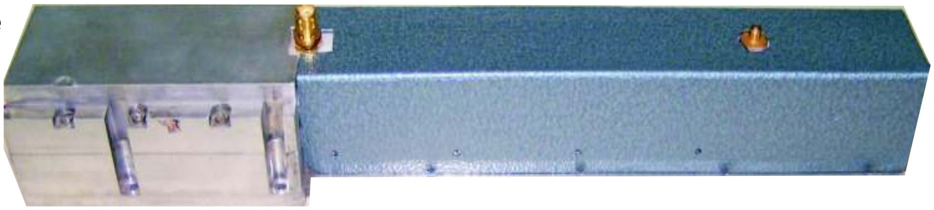
MPC 5070—10 kW Ku-band CCTWT

CCTWT Characteristics

Characteristics	MPC 2081	MPC 4068	MPC 5070
Frequency	S-band	X-band	Ku-band
Bandwidth (MHz)	400	200	500
Peak output power	130 kW (min)	6.5 kW (min)	10 kW (min)
Gain at rated power	47 dB	38 dB	45 dB
Focusing	Periodic permanent magnet (PPM)	PPM	PPM
Pulsing	Non intercepting grid	Non intercepting grid	Non intercepting grid
Cooling	Liquid	Liquid	Liquid
Applications	Surveillance radar	Airborne radar	Airborne radar

Helix TWTs

Helix TWTs are broadband amplifiers suitable for communi-cation, radar and EW jammers. They derive their name from the microwave propagating structure: helix. The TWTs are capable of delivering a few hundred watts of continuous wave (CW) power or a few kilowatts of pulsed power over more than two octave bandwidth. The indigenous design and development of helix TWTs by DRDO has resulted in successful development of different helix TWTs for various applications.



MCH 4555—300 W helix TWT

The device technology has been mastered, as tubes have passed all environmental specificat-ions for safety of flight for airborne applications. A 1.5 kW X-Ku band pulsed helix TWT and a 200 W and 300 W, X-Ku band helix TWT have been developed jointly with Bharat Electronics. Development of various other TWTs is being pursued to enhance the power output and the frequency range. Several new technologies such as vane-loaded SWS; semi-vane loaded and ring loop slow-wave structures; pitch tapering for high efficiency; multi-stage depressed collectors; four-stage-ceramic envelope for collector; compact electron gun; brazed helix circuits; and hot stuffing technology for SWS assembly are being pursued.

MPH 4563—1.5 kW helix TWT

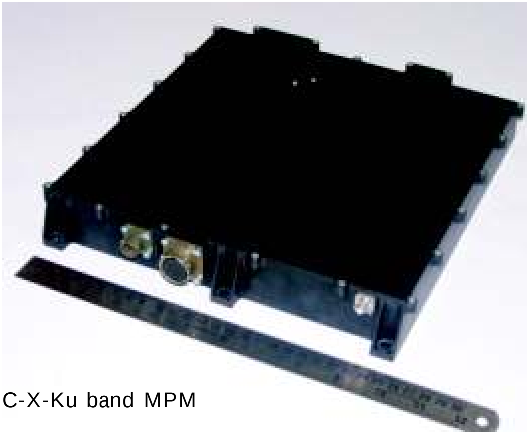
Helix TWT Characteristics

Characteristics	MPH 4563	MCH 4553	MCH 4555 *
Frequency	X-Ku band	X-Ku band	X-Ku band
Bandwidth (GHz)	10	10	11.5
Peak output power (W)	1500	200	300
Gain at rated power (dB)	45	35	35
Modulation	Intercepting grid	Beam forming electrode	Beam forming electrode
Focusing	PPM	PPM	PPM
Cooling	Base plate	Base plate	Base plate
Weight (kg)	4	3.5	3.5

*under development

MICROWAVE POWER MODULES

A microwave power module (MPM) is a highly compact, efficient amplifier module combining the best attributes of solid-state and vacuum device technologies. It consists of a solid-state amplifier, a vacuum power booster TWT, an electronic power conditioner to provide all voltages for the operation of both the devices, a modulator and a microprocessor controller for monitoring, control and communication, all integrated in a compact module. A pair of 100 W power MPMs has been developed by DRDO. Their design and technology is suitable for communication, radar, radar jammer systems for various applications for ground-based, ship-borne and airborne applications. It can also be used as a laboratory amplifier.



C-X-Ku band MPM

Microwave Power Module Characteristics

Frequency	C-X-Ku Band	Ku Band*
Peak output power (W)	80 -100	100
Gain (dB)	50	50
Control & Monitoring	Microcontroller	Microcontroller
Weight (kg)	4.6	7
Dimensions	12" x 10" x 1 .5"	12" x 9" x 5"

*under development

Electronic Power Conditioner for MPM

An electronic power conditioner (EPC) is a high efficiency, compact dc-dc converter designed to deliver conditioned power to various electrodes of TWT and to the solid-state phased array (SSPA) with built-in fault monitoring, sequencing, protection, command interface modules and housekeeping function.

DRDO has been involved in this high technology area and has developed a highly compact EPC. The power converters, employed in EPC, switches at 100 kHz and incorporates soft-switching techniques for achieving high power conversion density and an efficiency of approximately 92 per cent. The high voltage rectifier and filter section employs ultra-fast reverse recovery diodes and high energy density surface-mount chip capacitors. Various modules of EPC are:

Magnetics: The high voltage power converter uses a specially developed planar transformer employing soft-ferrite core and multi-layer printed circuit board (PCB) with blind and buried vias. Power inductor has also been developed for the resonating inductance for the power converter. The planar inductor has metal core for managing heat dissipation.

Modulator: The EPC has an ultra-fast beam modulator to facilitate pulsed operation of the MPM. It handles pulses from 90 ns to CW mode with a maximum 150 kHz pulse repetition frequency (PRF). The modulator is also capable of handling a PRF of 1 MHz in burst mode and has demonstrated throughput delay lesser than 80 ns.

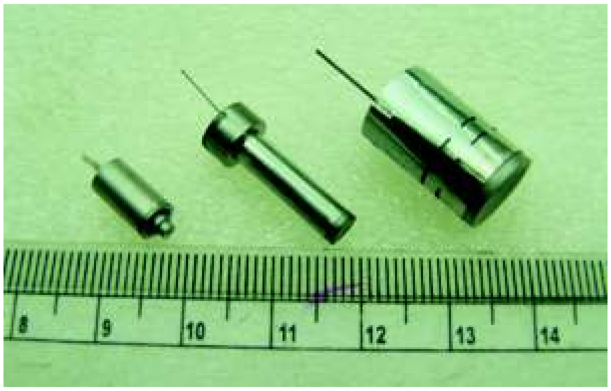
Thermal Management: A major challenge for achieving higher power conversion density has been met with innovative thermal management techniques. An infrared imaging facility is being used for observing real-time thermal images to identify hotspots on the PCBs and to take corrective measures for providing thermal path to the thermal images to identify hotspots on the PCBs and to take corrective measures for providing thermal path to the modules reaching temperatures beyond permissible limits. Advanced cooling technique using special conformable heat conducting material is also being used for removing heat from PCBs populated on both the sides.

Communication and Control: The EPC has a microcontroller onboard for fault handling, sequencing and communication interface requirements. Work is now on for configuring multiple MPMs on a MilCAN bus, for facilitating simultaneous command and control of MPMs for various applications.

State-of-the-art techniques including digital signal processing (DSP), field programmable gate array (FPGA) and mixed signal power manager integrated circuits are being explored for developing second generation of EPCs to offer extended flexibilities in operation and further miniaturisation.

ELECTRON EMITTERS FOR MICROWAVE TUBES

A cathode, the emitter of electrons, is the most important part of any microwave tube and is the main life determining component of the tube. Present day devices use a tungsten dispenser cathode, which consists of a porous tungsten pellet impregnated with barium calcium aluminates and indirectly heated alumina potted heater, and operates at a temperature of 1050 °C. B-type cathode is the most common type of dispenser cathode with impregnate comprising the oxides of barium, calcium and aluminum in the molar ratio of 5:3:2. The B-type dispenser cathode, when coated on its emitting surface with a thin film of osmium or osmium-ruthenium or osmium-iridium is known as M-type cathode, which has reduced work function with a higher emission density at a lower operating temperature (~ 1000 °C). Work function reducing materials when mixed in the tungsten matrix make a mixed metal (MM) type cathode which are more rugged against ion bombardment. These cathodes have been developed and tested for emission density, life, reliability, and heater ruggedness.



Dispenser cathodes

Technology for dispenser cathodes has been mastered and a number of cathodes have been made for tubes under development at DRDO. Several batches of cathodes for helix TWTs, CCTWTs and magnetrons have been developed and tested in actual tube environment. Their performance has been at par with imported equivalents. Productionisation of the cathodes at a private sector industry has been undertaken.

Thermionic Dispenser Cathodes Specifications

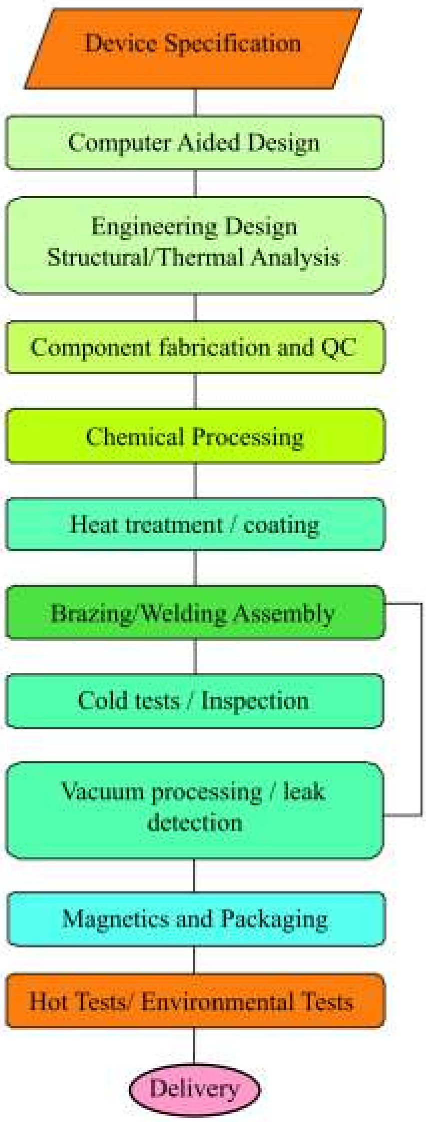
Type	B-type	M-type	MM-type
Matrix	Tungsten	Tungsten (with Os-Ru coating)	Tungsten Iridium
Impregnant (BaO:CaO: Al_2O_3)	5:3:2	5:3:2	5:3:2 with Li_2O_3
Emiiter diameter (mm)	1.4–30	1.4–30	1.4–5
Current density (A/cm^2)	5	15	30
Operating temperature (°C)	1100	1050	1050

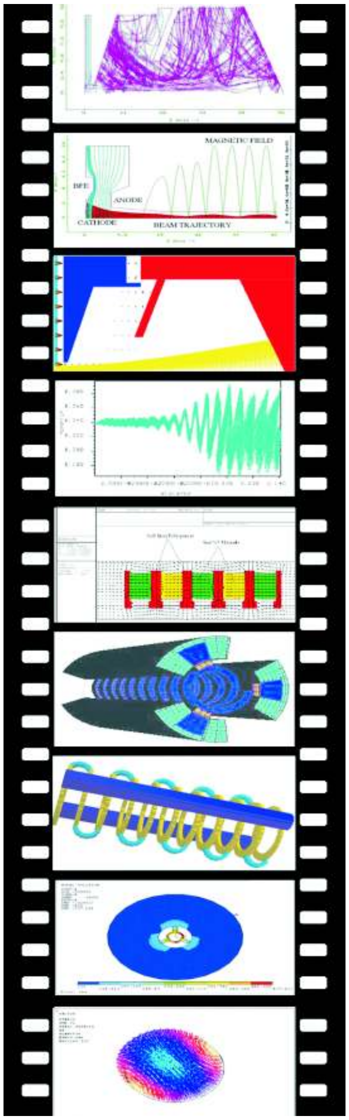
MICROWAVE TUBE TECHNOLOGY

The design and development of a microwave tube involves the following processes and facilities:

Computer-Aided Design

DRDO has established computer-aided design capability for *ab initio* design and simulation of microwave tubes and their sub-assemblies. It has greatly helped in cutting down the number of device prototype iterations. The capability is currently being leveraged to achieve 'first-pass design success'. A family of codes have been developed in-house for synthesis of electron gun, magnetron injection gun and collector; 2.5-D electron trajectory simulation in electron guns and collectors including facilities for simulation of secondary electrons; 2-D large signal Lagrangian codes for helix and CCTWTs; and packages for helix and CC SWS, pillbox windows, periodic permanent magnet system.





Commercial 3-D electro-magnetic codes are being used for detailed analysis of electromagnetic circuits. Optimisation using neural network algorithm has also been implemented. 3-D particle-in-cell (PIC) simulation for full physics analysis of the complete device is being implemented. Engineering drawings are done in standard solid models drafting package. Circuit design is carried out with electronic CAD packages. Thermal and structural analysis of various assemblies is carried out using 3-D FEM codes.

Microwave Tube Component Technology

Special purpose machining facilities for fabricating specialised microwave tube components have been established. The facilities include CNC machines for precision turning and milling operations, center-less grinder, honing machine, ceramic dicing machine, laser interferometer-based precision helix winding machine, and high-It

Folded waveguide SWS, and components and assemblies (top)

Clockwise from top left: helix after winding and assembled along with APBN rods; electron gun assembly; various types of grids

Septums used in the SWS of CC-SWS and collector parts

precision 30 micron wire-electron discharge machine. High-precision components made of special electron tube materials such as OFHC copper, beryllium-copper alloy, copper-nickel alloy, copper-tungsten alloy, nickel, consumable electrode core iron, low carbon steel, kovar, tantalum, molybdenum, tungsten, samarium-cobalt magnetic material, etc. are being routinely fabricated in-house. A precision metrology facility which includes laser assisted pitch checking machine with accuracy better than 1 micron, industrial boroscope system, high resolution 3-axis stereo zoom microscopes, profile projectors, and bench comparators, etc. supports these facilities.

Protective Atmosphere Brazing and Assembly

A dedicated clean room facility (class 10, 000) with laminar flow benches and dedicated spot welding stations, vacuum desiccators and metrology instruments is used for assembly of device components. An excellent facility for carrying out brazing and heat-treatment of components and sub-assemblies of microwave tubes, in protective atmosphere of vacuum or hydrogen/nitrogen has been established. A variety of vacuum and hydrogen furnaces and RF induction heater for heat treatment and brazing, using noble metals and refractory alloys up to 2400 °C, and special metal joining facilities like TIG, laser and spot welding have been established. Expertise for ceramic-to-metal seals using pre-metallised ceramics and active brazing of ceramics for brazing hard-to-wet materials like lossy BeO-SiC and AIN-SiC has been mastered. Processes for brazed helix SWS in which BeO rods are brazed to a

Furnance room

Clean room facility

like lossy BeO-SiC and AIN-SiC has been mastered. Processes for brazed helix SWS in which BeO rods are brazed to a copper helix using active filler alloy sputtered onto the copper helix has also been established.

Thin Film Technology

Thin film coatings in microwave tubes are used as secondary electron suppressive coatings, microwave lossy coatings, emission enhancing coatings on cathodes, expandable coatings for metal-to-ceramic active brazing. RF-DC sputtering, electron beam and thermal evaporation systems are being used for coating various types of metallic, refractory and ceramic thin films.

Thin film coating facility

Ultra-high Vacuum Facilities

Fully automated ultra-high vacuum (UHV) facilities processing stations with baking facility up to 600 °C to achieve sealed-off device-vacuum level up to 5 x 10^{-9} Torr achieved by using a combination of turbo-molecular pump and ion-pump equipped with suitable vacuum gauges in conjunction with residual gas analyzers are functional. An UHV electron beam analyzer system has been developed for independent evaluation of electron guns before their integration with the devices. Mass spectrometer leak detectors are routinely used for checking all tube assemblies to a leak rate of 10^{-12} Torr litre/second.

Microwave Test Facility

Microwave test facility for microwave tube testing comprises of two distinct facilities: (i) Cold Test Facility where the device assemblies are characterised and tuned for their microwave characteristics in the absence of the electron beam, and (ii) Hot Test Facility, where the green tubes are high voltage conditioned, tested and adjusted for their performance and aged to achieve hard vacuum.

Cold Test Facility

A full-fledged facility for microwave measurements on device circuits in the range of 2-50 GHz has been set up. This facility includes a number of different types of scalar and vector network analysers, performance network analysers with time-domain options and a wide variety of special probes for dielectric constant measurement. Special measurements of microwave circuit such as phase-velocity and interaction impedance on slow-wave structures; like helix, coupled cavity, folded waveguide and ring loop-SWS; measurements in over-moded waveguide/cavity resonators for virtual cathode oscillators; insertion loss and transmission loss measurement on RF windows and couplers; dielectric constant measurements on materials having very low or very high dielectric losses (internal attenuators) can be made in the facility.

Hot test facility

Hot Test Facility

Excellent facility for 'hot test' evaluation of microwave tube prototypes up to 50 GHz frequency has also been established. This test facility includes sophisticated universal high-voltage power supplies and microwave test benches for automatic exhaustive characterisation of TWTs for gain, power, AM-PM conversion, spurious, harmonic and noise spectrum. Compact/mobile vibration table and cold/hot chambers are also there for full environmental characterisation of the devices.


RF Windows

CONCLUSION

Excellent facilities have been established in DRDO to incubate the technologies required for developing the state-of-the-art microwave tubes. Some of them like the electron beam analyzer system (EBA), the helix winding and helix pitch measurement system, the wire EDM machine, the microwave tube hot-test set up etc. are unique. This facility is available for the development of a wide variety of microwave tubes and for other applications too. The technology for ceramic RF windows both waveguide and co-axial, high voltage-seals and high-voltage feedthroughs where seals are brazed with metallized ceramics is also useful in other applications.

Looking towards the future, DRDO is now gearing up to work on carbon nanotube-based field emitter arrays, which will act as the electron source for power booster micro TWT. Vacuum microelectronics is the newly emerging technology that marries the advantages of solid-state devices and the microwave tubes. It inherits the compactness and batch production feature of SSPA and the high power capability of a microwave tube thus offering the advantage of both. Envisaging the requirement of high power and high frequency in the microwave and millimeter wave RF sources, work has already started in the area of gyro devices. DRDO has initiated steps in developing a range of MPMs extending the frequency range of mm-waves and further extending the capability to develop complete transmitter modules.


HV seals

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