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**Title of the Chapter: “High Power Microwave Sources and Applications”**

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**Abstract:**

The applications of conventional microwave tubes are limited due to basic nature of interaction structures used herein. However, the range of applications of microwave tubes is growing to the millimeter wave range where there are several important applications present. Some of these applications are high resolution radar, high information density communication, deep space and specialized satellite communication, advanced high gradient linear accelerators, superconducting colliders, plasma diagnostics and chemistry, material processing, waste remediation, ceramic sintering, fusion plasma.

**Keywords:** Microwave devices, RF window, Beam wave interaction, Modes, Oscillations

**1.1 Introduction**

Microwave is serving today the in every house, sphere, house hold to communication, space sciences to future energy generation. Microwave tubes are basically microwave sources in the microwave frequency band providing high output power. These microwave devices are available with a long list; some popular devices are traveling wave tube (TWT), klystron, crossed-field devices, Gyro-TWT, Gyro-klystron, etc. as amplifiers; while backward wave oscillator (BWO), Gyrotrons. Vacuum devices are performing vital role leading towards creating quality life style as well as environment for human kind. The scenario of finding newer and newer applications using these devices for better world, today one cannot imagine the world without microwave tubes.

Microwave tube continues to be leader in high power, high frequency regime in spite of challenges continuously coming from solid state devices due to inherent capability of the former in terms of thermal management, reliability, life and cost too if estimated for the same power level, efficiency at the frequency range of application, as well as from EMI and EMC considerations. The applications of microwave tubes cover wide horizons, such as, communication, radar, electronic warfare, directed energy weaponry (DEW) using high power microwaves (HPM), industrial ovens, cooking, material sintering , hyperthermia, plasma heating for energy research, atmospheric sciences, satellite communication and so on [1]-[4]. It is now possible to construct finely grained ceramics of a more uniform microstructure yielding to the development of stronger and less brittle ceramics and new ceramic composite materials with the application of medium and high power millimetre waves generated from the microwave tubes, which gives the advantage of the volumetric and selective heating utilising the property that the absorptivity of a material increases with frequency and therefore, yielding faster and better ceramic sintering [5].

These devices are used for high resolution image mapping radars as well as for the ground probing radars, the latter for the detection of underground materials. Further, these devices are the heart of the impulse radar for the range resolution as well as for the detection of stealth aircraft, etc. and also for the cloud-radar used as a sensor in environmental research, it being believed that clouds can dominate the effect of greenhouse gases in global warming. In addition, it is to be noted that by the middle of the present century, high power microwave tubes in the millimetre-wave frequency range required for plasma heating would greatly contribute to electric power production using controlled thermonuclear fusion bypassing the fission that is associated with the problem of disposing a large quantity of radioactive waste. The first venture to address the technological and scientific tasks of finding alternative source of energy by exploring the fusion power through an ITER program is already in process [6].

Through the development and use of advanced design, materials and technology, the capability of conventional slow-wave microwave tubes, like, the travelling-wave tube (TWT), klystrons, magnetrons, etc. has been enhanced many fold. Moreover, it is interesting to mention here that the realisation of newer devices, such as, microwave power module and micro-fabricated vacuum electronic tubes has added new dimensions to the area of microwave tubes because these devices possess some inherent advantages of the both, solid-state as well as vacuum-electronic devices. Some other unconventional tubes, like, the VIRCATOR, the MILO, the relativistic backward-wave oscillator (BWO), the OROTRON, etc., provide HPM sources, which, for instance, can cater to the need of DEW Also, there are some other unconventional tubes, like, the gyromonotron or gyrotron the gyro-tystron and the gyro- travelling-wave tube (gyro-TWT) [7], based on CRM instability as well as the slow-wave cyclotron amplifier (SWCA) based on Weibel instability, and the cyclotron auto-resonance maser (CARM) based on both the CRM and Weibel instabilities, which can provide high powers in the microwave to terahertz frequency range.

Here, it is worthy to mention that the renewed interest in the gyrotron, lies with joining of the world community to create reactor machine through ITER program. High power gyrotrons at different frequencies such 120GHz, 140GHz and 170GHz would be required for ITER machine in this program.

**1.2 History of Microwave Tubes**

 Microwave tubes (e.g., helix TWTs) provide very wide bandwidths ~ 2-3 octaves required in electronic warfare (EW), electronic counter measure (ECM) and electronic counter counter measure (ECCM)) systems. Microwave tubes meet the requirement of the communication sector by way of providing moderate CW power, relatively narrower bandwidth as compared to the requirement of the EW sector, high gain, low group delay, low AM-to-PM conversion coefficient, good reliability, long life, high efficiency (for instance, for space applications), etc. For applications, such as, plasma heating and electron acceleration, the demand is for very high CW power ~ 250kW to 1MW as well as for very high pulsed power upto ~ multi megawatts. Microwave tubes are also in demand for industrial heating in various industries, like tea, paper, wood, leather, food grains, etc. Microwave tubes find applications in the medical sector as well, for instance, as applicators in hyperthermia for the treatment of cancer. Microwave tubes are based on the mechanism of conversion of EM radiation from individual electrons into coherent radiation by bunching the electrons in proper phase with respect to the RF wave by adjusting the electron beam. Accordingly, microwave tubes are classified in different possible ways, such as (i) O-type and M-type; (ii) slow-wave and fast-wave types; (iii) longitudinal space-charge wave, transverse space-charge wave, and cyclotron mode interaction types; (iv) kinetic and potential energy conversion types; and (v) Cerenkov, transition, and bremsstrahlung radiation types [9].

In an O-type microwave tube, a DC axial magnetic field constrains the electrons to move in the interaction structure as a linear beam. The device is hence also called a linear beam tube. In such a type of tube, the magnetic field does not take part in the beam-wave interaction process; the longitudinal space-charge wave interaction takes place; the axial kinetic energy of the electron beam is converted into electromagnetic waves; and a slow wave mode is destabilised. On the other hand, in an M-type tube, a DC magnetic field, applied perpendicular to the electric field, takes active role in the beam wave interaction process. In this type, the transverse space-charge wave interaction takes place and the potential energy of the electron beam is converted into electromagnetic waves. while those like magnetron and CFA belong to the M-type. In the devices, like, gyrotron, a fast cyclotron wave interacts with a fast waveguide mode, and the magnetic field takes a dominant role in the cyclotron resonance instability mechanism of the device. The TWT may also be classified as a Cerenkov radiation type of microwave tube in which the electron beam velocity is synchronised with the phase velocity of electromagnetic waves in the interaction medium. Similarly, one may have a class of microwave tubes belonging to bremsstrahlung radiation type, in which the electrons bremsstrahlung, that is, move with an acceleration or deceleration in an electric field, as in a virtual cathode oscillator (VIRCATOR), or in a magnetic field, as in a gyrotron.

The magnetrons, which belong to the M-type, are most extensively used as oscillators in early radars, usually as pulsed power sources, and are available from 0.5GHz to 50GHz operating frequencies with reported power upto 5GW. In the simplest configuration, the magnetron has a cylindrical cathode surrounded by a cylindrical thick anode with resonator slots, which open towards the cathode. In other configurations, they are available as the coaxial, inverted, and rising-sun magnetrons. A typical millimetre-wave rising-sun magnetron has reportedly delivered 100kW at 48GHz. The CFA is another useful M-type tube. The tube is highly efficient though at a low gain value, and enjoys the attractive features, such as low operating voltage, small size, light weight, and moderate bandwidth making them suitable for transportable and airborne applications. The S-band CFAs have been developed giving typically 1MW peak and 20kW average powers, with efficiency as high as 80% with a nominal gain of 30dB. The CFAs are often preferred to the TWTs in certain applications, such as, in the final amplifier stage of a radar transmitter. It is however felt that, as the operating frequency is increased to the millimetre wave range, the beam interception as well as RF losses at the anode-cum-slow-wave structure makes a CFA less competitive, with respect to the average power capability than an O-type tube, such as, klystron or TWT.

 The klystrons belonging to the family of the O-type tubes find wide applications in communication systems and accelerators, have been built at frequencies from 0.5 to 35GHz, yielding CW power over 1MW and pulsed power over 100MW with gain values ranging from 10dB to 70dB. The multi-megawatt, multi-beam klystrons have also been built yielding several tens of kilowatts or megawatts of power at several hundreds of megahertz frequency, for the linear accelerators and synchrotrons for the study of high-energy physics.

The TWT is similar to the klystron in that it belongs to the family of O-type in one of the different ways of classifying microwave tubes already discussed. However, in another way of classifying microwave tubes, the TWT belongs to the Cerenkov radiation type of tubes, unlike the klystron that belongs to the transition radiation type. The power capabilities of TWTs range from few watts to the ~ megawatts, and they are available at lower microwave frequencies as well as at millimetre waves. The two types of TWTs are most extensively used in numerous applications. They are, the coupled-cavity and the helix TWTs, the former using a coupled cavity and the latter a helix as the slow-wave interaction structure. Unlike a helix TWT, which uses a non-resonant helix interaction structure that has a wideband potential, a coupled-cavity TWT has a limited bandwidth, as it uses, a stack of resonant cavities with suitable coupling between adjacent cavities, as the interaction structure. Coupled-cavity TWTs, however, have a higher power capability than a helix TWT, and they are used in surface and airborne radars, as well as in high power, millimetre-wave communication systems.

This limits the power capability of these tubes at high frequencies, specially, in the millimetre-wave frequency range. In sixties, gyrotrons used for heating fusion plasma, which are based on the principle of cyclotron resonance maser instability (CRM), came into being. The sizes of these devices do not shrink as much as do those of the conventional slow wave microwave tubes. Subsequently, other gyro-devices (CRM instability based devices), like, gyro-klystron and gyro-TWT, etc. were also developed. Gyrotron is basically a fast wave device, which uses a smooth wall circular waveguide (large resonator) in which no attempt is made to reduce the velocity of the wave, so here the phase velocity, *vp*,is more than the velocity of light, *c*. Here, the electron beam is injected into the electromagnetic field in a manner such that sustained beam wave interaction takes place.There is intense interest in these fast wave devices at present time. It stems from the simplicity of the RF structure and the fact that the electron beam is normally placed well away from the RF structure. The result is that the size limitation is significantly relaxed. With larger dimension, the power handling capacity is also significantly increased.

**1.3 Analysis of Microwave Tubes:**

Interaction structure is a very important component of microwave device for RF generation. In the microwave devices, the beam-wave interaction takes place in the interaction structure, also called as cavity due to its resonant behavior.

 In Gyrotron, simple cylindrical resonator cavity is the widely used as the interaction structure due to its simple structure and low loss. The simple cylindrical interaction cavity is a three section structure with an input taper, a uniform middle section and an output taper. The input taper is a cut-off section, which prevents the propagation of RF power towards the electron gun. The cold cavity analysis and beam wave interaction takes place at the uniform middle section where the RF field exits in the form of standing wave. The output taper section converts the standing wave into the traveling wave. The reducing radius of the input taper section provides higher cut-off frequency region to the signal resonating in the middle section and thus the resonating signal is reflected back. The output taper section is also a tapered cylindrical waveguide of increasing radius. This section behaves like a cylindrical horn antenna and the RF resonating at the middle section can propagate through this section as a travelling wave. The tapered angle of the input section is decided in such a way that 100 % RF reflection can occur. Similarly, the output taper angle is decided on the basis of partial reflection around 25-35%. The reflections on both the sides of middle section are very necessary to make a standing wave so that the oscillator operation of the gyrotron can take place. The efficiency and the output power performance are considered as the main goals in the optimization of the cavity parameters.

The Gyrotron interaction cavity consisting of three parts, the down-taper (*L1*), the middle section (*L*), and the up-taper (*L2*) is shown in Fig. 1.1, where  is down-taper angle,  is up-taper angle and *Rc* is cavity radius. The interaction structure or cavity is made as an open resonator (both sides are open) to minimize the mode density and thus the mode competition. The reflected RF on each of the ends of mid-section makes a standing wave in Gaussian profile. This kind of profile is very useful because the ohmic wall loss is minimum for this case. The length of the middle section is decided by the diffractive quality factor. So the cylindrical cavity shown in Fig. 1.1 fulfills the entire desired requirement like a particular value of the diffractive quality factor (in terms of standing wave), the minimum mode competition and the minimum ohmic wall loss. Parabolic smoothing is sometimes used at the both ends of middle section to improve the efficiency of the structure, which is not included in the study and analysis here for the sake of convenience. The overall performance of the Gyrotron tube including the interaction cavity performance highly depends on the operating mode. A particular operating mode is selected on the basis of power and frequency requirement of a Gyrotron. As the power and frequency of a Gyrotron increase, the high order TE modes become more important

Design of gyrotron interaction structure is utmost important, since it serves as the region for the actual RF power required for the device under the optimum condition. To fulfill this condition, the dimension and shape of the gyrotron cavity should be such that it provides (i) high efficiency of the energy exchange from the beam to the RF wave, (ii) High Axial Field Profile, (iii) Suppress the Competitive modes, (iv) High Diffractive Quality Factor, etc. These all criteria affect the shape of the geometry and the last criteria depend upon both the geometry and the material including its surface roughness. In addition, the first taper (joining the beam tunnel on the electron side) should have opening below the cut-off diameter of RF mode, so that the RF wave is totally reflected from this end. The diameter of the middle section (interaction zone) is near cut-off, so that even small changes lead to the strong reflections, which result in an increase in stored energy in the middle part, that is, the resonator. The diameter of third section is such that, there is no reflection and the wave should propagate further

**Parabolic Smoothening**

**Rc**

**L1**

**L**

**L2**

**Θ1**

**Θ3**

**Fig. 1.1:** Gyrotron structure with uniform middle section and linearly tapered end

The main initial design parameters of interaction cavity are output power, frequency, operating mode and efficiency. The power growth in the interaction cavity critically depends on the operating mode which in turn depends on various parameters related to operating frequency, electron beam radius, cavity radius, cavity material, magnetic field at cavity center, start oscillation current, coupling coefficient, etc. This can be easily accomplished through the study of operating mode index, quality factor, ohmic loss, space charge effect, etc. in relation to the ratio between cavity and beam radii.

The criteria for selection of operating mode with respect to different parameters such as voltage depression (> 10% of operating beam voltage), limiting current (~ > 200% of operating beam current), wall loss (< 1 kW/ cm2), etc. are also finalized. The operating beam voltage and beam current are taken as 80 kV and 40 A, respectively. The indigenous mode selection code is used for the mode finalization for a typical high power gyrotron namely 1 MW, 120 GHz Gyrotron. The RF power is very high for 120 GHz Gyrotron compared to the low power Gyrotron and thus the ohmic wall loss factor is very critical. To reduce the ohmic wall loading, high volume cavity is required for the high power Gyrotron.

The electrical design of RF interaction cavity for 120 GHz, 1MW Gyrotron is completed through eigen mode analysis, beam-wave interaction analysis and parametric analysis, etc. Eigen mode analysis has been carried out using CST Microwave studio and Ansoft HFSS. Particle-in-cell (PIC) electromagnetic simulation code MAGIC is used for beam-wave interaction analysis and sensitivity analysis. The design of interaction cavity for Gyrotron requires the knowledge of the RF field profile, the resonator eigen frequency, and the quality factor Q. The need for high power, high frequency Gyrotron for Electron Cyclotron Resonance Heating (ECRH) in magnetically confined plasma requires tens of megawatt of electromagnetic power at high frequency. The device can generate several MW’s of electromagnetic power by the efficient interaction of the gyrating electron beam of very high electron beam power with RF in the interaction cavity. A cylindrical interaction cavity is quite practical for 1 MW output power at 120 GHz operating frequency due to its easy fabrication and thus used for the study and analysis.

In eigenmode analysis the resonance frequency of the structure has been obtained by applying different boundary conditions and studying the electric field patterns for different modes. Eigen mode analysis confirms the excitation of the operating modes in the cavity of the Gyrotron. As mentioned above the eigenmode analysis of the cylindrical cavity has been carried out using commercially available software HFSS and CST Microwave Studio (CST-MS), which are 3D electromagnetic simulators. For high frequency (>100 GHz) and above frequency it is necessary to assign the mesh refine operation in HFSS software.

The asymmetric mode TE22,6 is selected as the operating mode for 120 GHz, 1 MW Gyrotron after going through different mode selection process . The interaction cavity radius, the beam radius and the middle section length calculated for the operating mode.

For the simulation, a complete three section interaction cavity having input taper, uniform mid-section and output taper is considered. The input taper angle and output taper angle are optimized between the ranges of 2.8° to 3° with various lengths of all the three sections for getting the optimized results for eigen mode and eigen frequency. Table 1.1 shows the optimized interaction cavity geometry for the operating frequency 120.0 GHz. The *Q* value shown in Table 1.1 is calculated for the optimized interaction cavity geometry and the selected operating mode. The calculated *Q* value for 120 GHz interaction cavity is 706.

The radial position of the first maxima of TE22,6 mode position equals to the beam radius (*Rb*) and this value is used as the electron beam launching for better beam-wave coupling. For the maximum interaction efficiency and the minimum ohmic wall loss, a Gaussian type standing wave profile at the middle section of interaction cavity is required.

**Table 1.1:** Optimized cold cavity parameters for 120 GHz, 1 MW Gyrotron.

|  |  |
| --- | --- |
| **Parameter**  | **Value**  |
| Middle section length (*L*) | 15 mm |
| Input taper length (*L1*) | 12 mm |
| Output taper length (*L2*) | 20 mm |
| Cavity radius (*Rc*) | 18.1 mm |
| Input taper angle (*θ1*) | 2.8° |
| Output taper angle (*θ3*) | 2.8° |
| Quality factor (*Q*)  | 706 |

The normalized electric field profile for the cavity geometry summarized in Table 1.1 is presented in Fig. 1.2, which shows a cut-off region at the input taper side and a travelling wave region at the output taper side. Fig. 1.2 clearly shows the required profile as a Gaussian profile with the peak electric field value at the center of the middle section. The cold cavity analysis is carried out to verify the oscillation of desired operating mode and axial electric field profile in cold condition (without the electron beam).



**Fig. 1.2:** Normalized axial electric field profile.

The final design goal of any gyrotron interaction cavity is its output power and frequency performance according to the requirement and thus small changes in the geometrical parameters can be made during beam-wave interaction simulations for the optimization of output power. The completely closed interaction cavity except the output taper mouth is made of fully conducting wall for the beam-wave interaction simulations. The output taper mouth is closed by a port for the observation of power, frequency and other parameters. The electron beam emitted from the magnetron injection gun (MIG) is launched at the input taper entrance. The electron beam properties like beam radius, larmor radius and velocity ratio are defined at the input taper section entrance. The same electron beam moves across the interaction cavity and interacts with the insignificant electric field of the operating mode in the middle section. The bunching process takes place in the gyrating electron beam due to the relativistic effect and a coherent radiation emission mechanism starts in the electrons, which amplifies the weak operating mode signal in the resonant cavity.

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