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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 efficiency radar, data communication and specialized satellite communication, advanced high gradient linear accelerators, superconducting colliders and fusion plasma.

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 vacuum devices are TWT, klystron, crossed-field devices, Gyro-devices, 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 radar system. 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, v_p, 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:

Electric field is maximum in the interaction structure to have high coupling coefficients and for stable operation. The bunching mechanism done in the middle section of the cavity only. So the azimuthal electric field needs to be very high. One can design the cavity to suppress the back propagation towards gun and as well as electric field in the middle section is very high.

The interaction cavity for the gyro-oscillators consists of a simple cylinder with a down-taper at the cavity entrance and an up-taper at the cavity exit, as shown in Figure 1.1. Since, the gyro-oscillators (gyrotron) operate most efficiently close to the cut-off frequency of the desired TE mode in the cavity; this enables the mild tapers at the entrance and exit of the cavity to provide enough reflection to maintain a standing wave in the cavity. The frequency of the resulting resonance is set corresponding to the desired operating frequency, which in turn must satisfy the cyclotron resonance condition. The midsection provides the region for interaction of RF field and electron beam for the generation of microwave/ millimeter-wave power at the desired frequency. The input down-taper acts as a cut-off section, which prevents the back propagation of RF power to the magnetron injection gun. The up-taper connects the cavity with the output waveguide or the quasi-optical launcher. For the gyrotron under consideration, the axial RF output is planned and thus, requiring the nonlinear output-taper in this case.

In the three section linear tapered RF cavity interaction structure, another important consideration for the interaction structure design of gyrotron is the shape of the cavity. First, it is possible to enhance the saturated efficiency by profiling the RF field amplitude in the cavity. In general, this is achieved by a cavity where the fields increase along the electron beam, reaches its peak at the middle of the cavity, and then drop abruptly. The second design goal, which can be achieved by shaping the cavity, is to move the unused Eigen modes away from synchronism with the beam mode, so that only the desired mode is excited. This is an important consideration for gyrotron design because the cylindrical cavity does not provide sufficient mode separation inherently. Most gyro-oscillators are designed to operate with an axial mode number, q, of one, while the azimuthal mode number, m, and the radial mode number, p, can be quite large, though many early Gyrotrons utilized the circular-symmetric electric, family of modes.

The RF fields in this region interact with the orbital kinetic energy of the gyrating electron beam to get RF output. The electrons in the beam, therefore, must have a strong transverse velocity as well as the usual longitudinal beam velocity. The ratio of transverse to longitudinal velocity in

the interaction region is typically chosen between 1 and 2 for the practical gyrotron. In this device, relativistic operation has brought increased power through the use of stronger beam fields coupling within the interaction region.

The design of resonator for gyrotron requires the knowledge of the proper RF field known as the operating mode, RF field profile, proper excitation of RF field estimated through start oscillation current, Eigen frequency, quality factor, competing modes, efficient RF power growth, etc. Reflections at the tapers lead to the resonant behavior of the RF interaction structure, while quality factor is the measure of efficiency with which a wave is generated in the resonator. The eigen frequency and the quality factor are determined by boundary conditions at the interaction cavity output sections. The electric field pattern for a tapered interaction cavity is such that it should be at cut-off in the input taper section and propagation in the output tapered section. Further, the electric field attains its maximum value at the center of the cavity where the maximum interaction takes place.
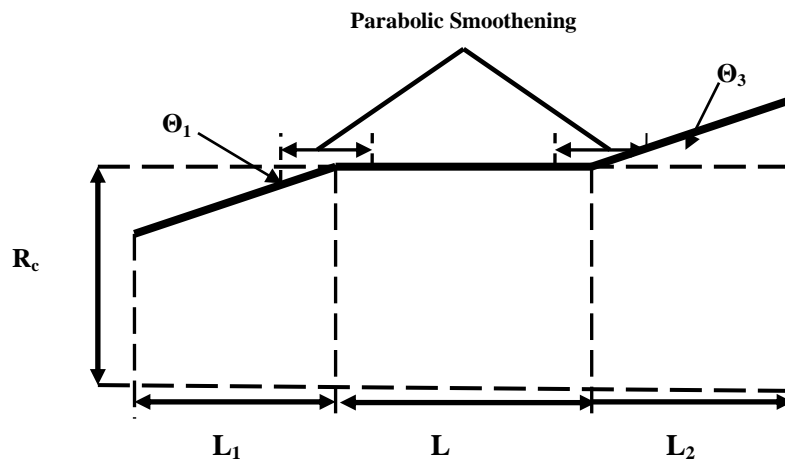

Fig. 1.1: Gyrotron structure with uniform middle section and linearly tapered

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 input and output taper angle gives the enough reflection for the standing waves. So selecting the taper angles depend on the requirement of Diffractive Quality factor of the mode. From the figure shown that how the quality factor varied with the input taper angle and output taper angle. 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/ cm^2), etc. are also finalized. The radial position of the first maxima of TE$_{22,6}$ mode position equals to the beam radius (R_b) and this value is used. For the maximum interaction efficiency and the minimum ohmic wall loss, a Gaussian type standing wave profile required.
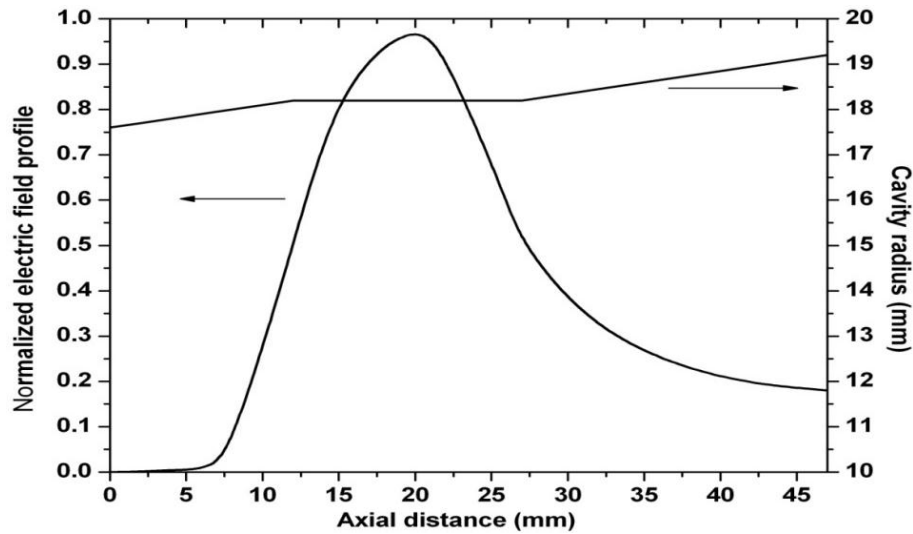
Fig. 1.2: Electric field profile of the cavity.

The output taper mouth is closed by a port for the observation of power, frequency and other parameters. 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.

Other important component which affects the beam wave interaction is electron beam source or MIG. The electron beam is mainly affected by some parameters like compression ratio, cathode slant length, cathode slant angle, cathode radius at cathode and cavity. After analyzing all the parameters, the range of parameter values have been selected so that the beam quality is not degraded.

References

[1]   O. Dumbrajs, "Kinetic theory of electron cyclotron resonance masers with asymmetry of the electron beam in a cavity", *IEEE Tr. Plasma Science*, vol. 20, pp. 126, 1992.

[2]   O. P. Gandhi, *Microwave Engineering and Applications*, New York: Pergamon Press, 1981.

[3]   M. Thumm, "State-of-the-Art of High Power Gyro-Devices and Free-Electron Masers: Update 1955," FZKA Report 5728, Institut f ü r Technische Physik, Karlsruhe, 1996.

[4]   M. A. Henderson, S. Alberti, P. Benin, T. Bonicelli, R. Chavan, *et al*., "EU developments of the ITER ECRH system", *Fusion Eng. & Design,* vol. 82, pp 454–462, 2007.

[5]   T. Omoria, M. A. Hendersona, F. Albajarb, S. Albertic, U. Baruahd, *et al*., "Overview of the ITER EC H&CD system and its capabilities", *Fusion Eng. and Design*, vol. 86, pp. 951-954, 2011.

[6]   A. A. Andronov, V. A. Flyagin, A. V. Gaponov, A. L. Goldenberg, M. I. Petelin, V. G. Usov and V. K. Yulpatov, "The Gyrotron: high power sources of millimeter and sub millimeter waves," *Infrared Physics*, vol. 18, pp. 385-393, 1978.

[7]   M. Thumm, "MW gyrotron development for fusion plasma applications," *Plasma Phys. Control. Fusion*, vol. 45, pp. A143–A161, 2003.

[8]   A. V. Gaponov- Grekhov and V. L. Granatstein, Application of High Power Microwaves, Norwood: Artech House, 1994.

[9]   G. Dammertz, "High-power Gyrotron development at forschungszentrum Karlsruhe for fusion applications", *International Conference on Plasma Science*, 2005, Monterey, CA

[10]   R. Chatterjee, *Microwave, Millimetre-Wave and Submillimetre-Wave: Vacuum Electron Devices*, New Delhi: Affiliated East-West Press, 1999.