CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

1.1 Introduction

Now a day's microwave and millimeter wave frequencies are widely used in almost every field of our life ranging from electronic warfare systems (EW) in the battlefield to microwave ovens in the kitchens. Microwaves occupy a matchless position in the electromagnetic spectrum, although these radiations are not visible, but their impacts are enormous in our society. Applications of these radiations are numerous, from ground base to the deep-space communications, for civilian as well as defence requirements, space exploration, scientific researches to medical applications, strategic to industrial applications, generation of thermonuclear energy, and so on [Amboss *et al*. (1980), Andronov *et al*. (1978), Barker *et al*. (2001), Chu *et al*. (1978), Gandhi (1981), Gaponov *et al*. (1994), Gilmour (1986), Hirshfield *et al*. (1977), Singh *et al*. (2011)]. During the past few decades, continuous R&D efforts are being made to extend the frequency range of microwave devices to the millimeter and submillimeter wave range, for their use in the newer application systems, but the power available at these frequencies becomes limited. [Chatterjee (1999), Chu (2004), Edgcombe (1993), Felch *et al*. (1999), Gaponov *et al*. (1994), Nusinovich (2004)]. At these frequencies, vacuum electron beam devices, widely known as microwave tubes are capable to deliver high power and their solid-state counterpart devices are not able to compete [Chu (2004), Kartikeyan (2004), Liao (1988)].

Microwave tubes, like, magnetron, backward wave oscillator, klystron, traveling-wave tubes (TWT) are essentially vacuum based electron beam devices used for the generation or amplification of RF waves at microwave and millimeter wave frequencies. Basically, these devices are the transit-time devices which overcome the problem of impairment of the high-frequency performance of conventional electron tubes caused by the effects of transit-time of electron motion, and gain-bandwidth product. In a microwave tube, the interaction between the electrons and RF waves is supported by an electromagnetic structure such that the electron beam energy gets converted into the RF waves [Gandhi (1981), Chatterjee (1999), Liao (1985), Gilmour (1986)].

The power handling capability of these microwave tubes decreases with the increase of the operating frequency primarily due to consequent reduction of their physical dimension. This limits their use at millimeter and submillimeter wave frequencies. The major power-limiting factors are: DC power dissipation, RF losses, attainable electron current density, heat transfer (restricting the average power capability), material breakdown (arcing) (restricting the peak power capability), and also the technological constraints in fabricating the tiny parts. One way by which one can think of reaching to the millimeter and submillimeter wave frequency range is to decrease the operating frequency of the quantum-mechanical optical devices, like, lasers. Even though, if we try to decrease the operating frequency of the quantum-optical devices, the energy of each quantum, and hence the available power from these devices also decreases. Further, it makes difficult to sustain population inversion, which is necessary for the generation or amplification of RF waves through a quantum optical device. Therefore, there was a significant gap in the generation and amplification of millimeter and submillimeter waves [Gaponov *et al*. (1994), Grantstein *et al*. (1987), Edgcombe (1993), Gilmour (1986), Benford (1992)].

Numerous important applications in the millimeter and submillimeter wave frequency range have led to interesting research and development activities during the last few decades in an attempt to narrow down this technological gap between microwave and optical frequencies. Some of these applications are: high resolution radar and high information density communication, deep space and specialized satellite communication, advanced high gradient RF linear accelerators, plasma diagnostics and chemistry, material processing, waste remediation, ceramic sintering, laser pumping, power beaming and electron cyclotron resonance (ECR) heating of fusion plasmas, radar and imaging in atmospheric and planetary science, and nonlinear spectroscopy [Collin (1966), Barker *et al*. (2004), Benford (1992), Chu (2004), Feinstein *et al*. (1987), Flyagin *et al*. (1988), Gold *et al*. (1997), Grantstein *et al*. (1987), Nusinovich (2004), Sakmoto (2006), Singh *et al*. (2011), Thumm (2003)].

Vigorous research efforts to fill-up this technological gap for the realization of the high-power millimeter and submillimeter wave devices, microwave tube community have led to the fast-wave regime operation of the conventional slow-wave microwave tubes. Fast-wave devices utilize cylindrical smooth wall waveguides or cavities as the RF interaction structures and a periodic relativistic electron beam, unlike slow-wave devices, which use the spatial periodic RF interaction structures and a smooth cylindrical electron beam. The size of the fast-wave RF structures does not decrease as much with frequency as does that of the slow-wave structures due to the higher mode of operation, thereby can handle higher power operation. Fast-wave devices include gyromonotron, gyro-traveling-wave tube (gyro-TWT), gyro-klystron, gyro-BWO, and gyro-twystron [Chu (2004), Felch (1999), Nusinovich (2004)]. A typical comparison of the power delivered by different devices has been shown in Fig. 1.1 [Parker *et al.* (2002)].

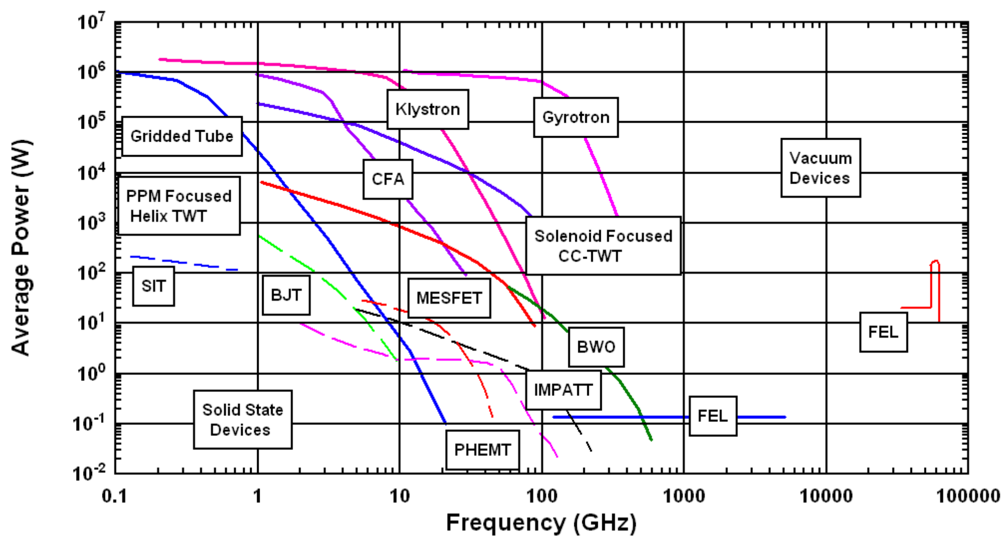


Fig. 1.1 Comparison of average power versus frequency for various types of devices [Parker *et al.* (2002)].

1.2 Classification of Microwave Tubes

Microwave tubes have been classified in the literature in various ways based on the mechanism of conversion of spontaneous radiation from individual electrons into coherent radiation by bunching the electrons in a proper phase with respect to RF wave by adjusting the beam, magnetic field and interaction structure parameters. In one of the basic approaches, they are classified as O-type and M-type tubes (O is the acronym of TPO standing for *tubes à propagation desondes*, and M is the acronym of TPOM standing for *tubes à propagation des ondes à champs magnetique*). O-type tubes are linear beam devices where electrons are allowed to move in a direction parallel to the applied DC magnetic field, the latter is not taking part in the interaction process. The electrons interact with the longitudinal RF electric field supported in the RF interaction structure. Here, the role of DC magnetic field is limited to focus the electron beam. In an M-type tube, the electrons are subject to transverse DC electric and magnetic fields, and hence the device is also known as crossed-field device. In these devices, the background DC magnetic field plays a direct role in the beam-wave interaction process. For example, traveling-wave tube (TWT) and klystron belong to O-type, and magnetron and crossed-filed amplifier (CFA) are M-type devices [Liao (1985), Gilmour (1986), Nusinovich (2004), Benford *et al*. (1992].

In another approach, microwave tubes may be classified as Cherenkov radiation, transition radiation, and bremsstrahlung radiation types. In the Cherenkov radiation type, the electrons travel in a medium with a speed greater than the phase velocity of electromagnetic waves in the medium. The TWT belongs to this type. In case of transition radiation type, the electrons cross the boundary between two media of different refractive indices or pass through perturbations in a medium involving conducting grids and a gap between these conducting surfaces. Klystron is one of the examples of this kind. In the bremsstrahlung radiation type, radiation occurs when electrons undergo an acceleration or deceleration in an electric or magnetic field. Typically, these electronic motions can be oscillatory. The electrons radiate coherently when the Doppler-shifted frequency of the RF wave coincides with the oscillation frequency of the electrons or with one of its harmonics. The examples of bremsstrahlung radiation type are: gyrotron, gyroklystron, ubitron, peniotron, and vircator. In a fast-wave electron beam device, like, gyrotron, the electron beam, rather than the interaction structure as in a helix TWT, is made periodic in its cyclotron motion under the effect of the background DC magnetic field. In an ubitron, the electrons are undulated with a wiggler magnetic field. Hence, microwave tubes can be classified based on the various aspects; however, it often becomes difficult to make discrimination between the types. Such as a transition radiation device, like, klystron may be looked upon as a Cherenkov device. Similarly, a bremsstrahlung device, like, a slow-wave cyclotron amplifier (SWCA), can be considered as a Cherenkov device [Carter (1990), Chatterjee (1999), Gandhi (1981), Gilmour (1986), Liao (1988), Gold *et al*. (1997)].

1.3 Fast-Wave Gyro-Devices

The basic purpose of the RF interaction structure in a microwave tube is to support electromagnetic waves for interaction with the electron beam. In order to handle higher power device, this interaction structure should be of larger size. It is well known that the transverse dimension of the conventional slow-wave microwave tubes, like, klystron, TWT etc. scale inversely with the increase in their operating frequencies. Due to this reason, the power handling capability of these devices reduces significantly at the millimeter and submillimeter wave frequencies. Hence, with the increase in the operating frequency of conventional microwave tubes, the RF output power decreases drastically due to the various limiting factors, like, DC power dissipation, RF losses, electron current density, material breakdown, etc. This has motivated the researchers across the globe to search for the electron beam devices that fulfill the gap in terms of appreciable power level in the millimeter and submillimeter wave regions, for instance, fast-wave devices, like, the cyclotron resonance maser (CRM) instability based device gyrotron, which were used in the 1960's for the fusion plasma heating experiments. In a fast-wave device, an electron beam moving in helical trajectories interacts with the azimuthal RF electric field in a cylindrical waveguiding structure [Baird (1979), Barker (2001), Edgcombe (1993), Felch *et al*. (1999), Gilmour (1986), Nusinovich (2004)].

The transverse dimension of the interaction structure of a gyro-device, like, the gyroklystron decreases with frequency but not upto that extent as compared to a slow-wave device, like, klystron. Further, the fast–wave device can be operated at the higher-order modes, corresponding to higher eigenvalue, due to this reason the transverse dimension of a fast-wave device can be increased. It allows handling a larger power at the higher frequencies due to a reduction in the power loss density at the walls of the RF structure. Further, the electron beam in a fast-wave device can be placed away from the walls of the RF structure to realize the larger field necessary for the proper beam-wave interaction. This also reduces the problem of beam interception at the wall of the metallic RF structure. However, operating a device at the higher-order mode causes the problem of mode competition and decrease in the interaction efficiency [Jain *et al.* (1994), Liu (2000), Kartikeyan (2004), Gaponov *et al*. (1994), Thumm (2012), Grantstein *et al*. (1987), Curie (1989)].

In gyro-devices, beam-wave interaction takes place between a cyclotron mode supported by the helically gyrating electron beam and a waveguide mode. These devices are based on CRM instability, and the bunching of electrons occur in azimuthal direction due to the relativistic dependence of mass of a gyrating electron beam. In order to get coherent radiation from these relativistic gyrating electrons, it is necessary that the significant contributions from electrons strengthen the initially emitted radiation, if the device is an oscillator, or enhance the input signal, if the device is designed to work as an amplifier. This criterion for coherent radiation can be satisfied; if the wavelength of the imposed RF signal is comparable to the sizes of electron density variations caused by the bunched electron beam [Thumm (2012)]. In a fast-wave device, like gyrotron, bunching is achieved because, as an electron gains energy, its relativistic mass increases, and it thus moves slower whereas the electron which loses energy, its relativistic mass decreases, and as a result it moves faster. Hence, electrons get bunched in gyration phase. These electron bunches are allowed to remain most of the time in the decelerating phase of the alternating field of the operating mode. It makes them to lose their most of the energy to the RF field instead of gaining energy from the RF wave. This can be achieved by slightly detuning the cyclotron resonance condition as in the case of a gyrotron, the cyclotron frequency is slightly detuned to a lower value in comparison to operating frequency [Edgcombe (1993), Gilmour (1986), Nusinovich (2004), Singh *et al*. (2011)].

The fast-wave gyro-devices R&D activities have grown up during the past few decades. Moreover, the frequencies of these devices have been extended to further higher level by making use of some of the novel interaction structures, like, coaxial, photonic band gap (PBG) structures, etc.

1.3.1 Dispersion relation

Depending on the nature of the RF interaction structure, an electron beam can support a space-charge mode, and different RF operating modes. The coupling between electron beam mode and electromagnetic modes can be easily studied using dispersion diagrams. Dispersion diagram, variation of the phase velocity of the RF wave with frequency, is also known as $\omega - k_{\|}$ plot, or Brillouin diagram which describes the operational characteristic of the device, also the device synchronism condition between an RF mode and a fast electron cyclotron mode (fundamental or harmonic) can be obtained at the grazing intersection between the beam mode and waveguide mode dispersion curve. Based on the nature of interaction of fast waveguide mode with electron beam, a device could either an oscillator or an amplifier. For examples, gyrotron and gyro-BWO are being used as the oscillators whereas gyro-TWT and gyroklystron work as amplifiers. In a fast-wave device, like, gyrotron, the condition of synchronism between the transverse electronic motion and RF waves, can be used to derive the following beam-mode dispersion relation [Chu (2004), Edgcombe (1993), Gaponov *et al*. (1994), Gilmour (1986), Kartikeyan *et al*. (2004), Nusinovich (2004), Thumm (2012)].

1.3.1.a Beam-mode dispersion relation

The beam mode dispersion relation, $\omega - k_{\|} v_{\|} - s\omega_c / \gamma = 0$, for a gyro-device can be easily derived by using the concept that over a complete electron cycle (cyclotron motion), one or more RF cycles are completed [Edgcombe (1993)]. Here, ω is the angular frequency of the RF wave, $k_{\|}$ is the axial propagation constant, s the harmonic number, γ the relativistic mass factor, and $v_{\|}$ is the axial electron beam velocity. Let us take the case of a gyrating electron beam that completes its one cyclotron motion in time T_c. The RF phase of the electric field component can be written as $\omega t - k_{\parallel} z$. After one complete cycle, the initial phase of the electrons will change and can be expressed as $\omega(t+T_c) - k_{\parallel}\left(z + v_{\parallel} T_c\right) = \omega t + \omega T_c - k_{\parallel} z - k_{\parallel} v_{\parallel} T_c$. Now, putting $s(2\pi) = (\omega - k_{\parallel} v_{\parallel}) T_c$, the initial phase change can be written as $\omega t - k_{\parallel} z + s(2\pi)$. Considering,

$$s(2\pi) = (\omega - k_{\parallel} v_{\parallel}) T_c \quad , \tag{1.1}$$

$$\Rightarrow s(2\pi)/T_c = \omega - k_{\parallel} v_{\parallel} \; . \tag{1.2}$$

The angular cyclotron frequency $\omega_c = 2\pi/T_c$, and equation (1.2) can be written as:

$$s\,\omega_c = \omega - k_{\parallel} v_{\parallel} \tag{1.3}$$

$$\Rightarrow \omega - k_{\parallel} v_{\parallel} - s\,\omega_c = 0 \quad , \tag{1.4}$$

where, $\omega_c = eB_0 / m_e$. (1.5)

B_0 is the axial magnetic field, e and m_e are the magnitude of electron charge and mass at the rest, respectively. Since, gyro-devices are relativistic devices, so by taking into account the relativistic mass factor (γ), the above equation (1.4), modified to:

$$\omega - k_{\parallel} v_{\parallel} - s\,\omega_c/\gamma = 0 \quad . \tag{1.6}$$

The equation (1.6) is the beam-mode dispersion equation and it represents a straight line of slope equal to $v_{\parallel}$, with $s\omega_c / \gamma$ as the intercept on the ω- axis.

1.3.1.b Waveguide-mode dispersion relation

Waveguide-mode dispersion relation can be obtained by considering a cylindrical waveguide excited in the transverse-electric (*TE*) mode forwarding in positive *z*-direction. The axial component of electric field intensity is zero for a *TE* mode. The axial component of magnetic field intensity H_z may be derived from the solution of the beam-absent wave equation and can be expressed as [Liao (1988), Kartikeyan *et al*. (2004)]:

$$H_z = C_{mn} J_m(k_{\perp} r) \exp\left\{ j(\omega t - k_{\parallel} z - m\theta) \right\} \; . \tag{1.7}$$

Here, r, θ, z are cylindrical polar coordinates, m and n are the azimuthal and radial indices of the mode, $k_\perp$ is the transverse propagation constant, J_m is the m^{th} order Bessel function of first kind. C_{mn} is the field constant defined as:

$$C_{mn} = \frac{1}{J_m(v_{mn})\sqrt{\pi(v_{mn}^2 - m^2)}} \tag{1.8}$$

and

$$k_\perp = \left(k_0^2 - k_\parallel^2\right)^{1/2} = \left(\omega^2 / c^2 - k_\parallel^2\right)^{1/2} = v_{mn} / r_w \ , \tag{1.9}$$

where, $k_0 = \omega(\mu_0 \varepsilon_0)^{1/2} = \omega/c$ is the free-space propagation constant; c is velocity of light in free space, μ_0 and ε_0 are permeability and permittivity of the vacuum, respectively. Now, considering the axial magnetic field intensity H_{z0} at axis of the guide, i.e., r = 0. For the azimuthally symmetric mode ($m = 0$), $J_0(0) = 1$. Consequently,

$$H_z\big|_{r=0} = C_{mn} = H_{zo} \quad . \tag{1.10}$$

Therefore, (1.7) can be written as:

$$H_z = H_{z0} J_m(k_\perp r) \exp\left\{j(\omega t - k_\parallel z - m\theta)\right\} \quad . \tag{1.11}$$

The azimuthal component of electrical field intensity can be written as:

$$E_\theta = \left(\frac{j\,\omega\mu_0}{k_\perp}\right) H_{z0}\, J'_m(k_\perp\ r)\ \exp j\left(\omega t - k_\parallel\, z - m\,\theta\right) \quad . \tag{1.12}$$

At the perfect conductor, the electric field becomes null. Hence, at the waveguide wall ($r = r_W$), substituting (1.12) $E_\theta\{r = r_W\} = 0$, one may immediately gets

$$J'_m(k_\perp\ r_W) = 0 \quad . \tag{1.13}$$

The above equation has infinite roots. The n^{th} root (eigenvalue) of equation (1.13) may be put as

$$k_\perp r_W = v_{mn} . \tag{1.14}$$

Combining (1.9) and (1.14), one gets

$$\omega^2 - k_\parallel^2 c^2 - k_\perp^2 c^2 = 0 . \tag{1.15}$$

Here one can easily recognize $k_\perp$ as the cutoff wave number $k_c (= \omega_{\text{cut}} / c)$, where ω_{cut} is the cutoff angular frequency, that is the angular frequency corresponding to $k_\parallel = 0$. In other words, we can write

$$k_{\perp} = k_c \,. \tag{1.16}$$

Thus in view of the equation (1.16), one can re-write the eigenvalue equation given by (1.14) as:

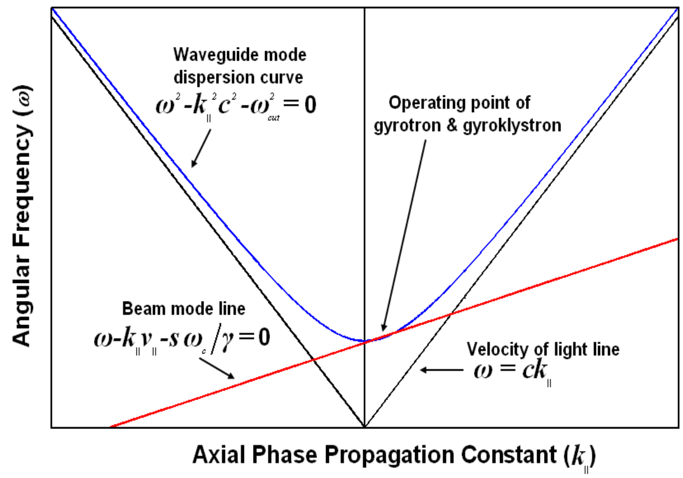
$$k_c r_W = \nu_{mn} \,. \tag{1.17}$$

In the light of above equation, one can re-write the equation (1.15) to obtain the waveguide-mode dispersion relation as:

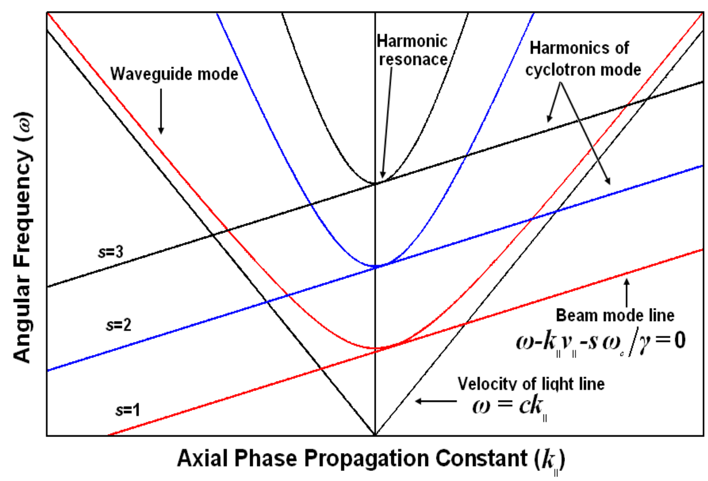
$$\omega^2 - k_{\parallel}^{\,2} c^2 - \omega_{cut}^2 = 0 \,. \tag{1.18}$$

The equation (1.18) is known as the waveguide mode dispersion relation, and it represents a hyperbola, with cutoff frequency (ω_{cut}) of the waveguide as the intercept on the ω- axis. The waveguide-mode dispersion hyperbola intersects the beam-mode dispersion line, in general, at two points, giving two possible operating points of a gyro device. At the point of intersection of these two curves the phase velocity of the beam mode and the RF wave are equal. It thus, describes the synchronism condition for a strong beam-wave interaction process in a gyro-device.

The general dispersion diagrams for gyrotron oscillators and gyroklystron amplifiers for the fundamental harmonic as well as for the higher harmonic interaction between the beam mode and waveguide modes are shown in Figs. 1.2(a) and 1.2(b), respectively. Both the devices operate near to the waveguide cutoff frequency (phase velocity, $v_{ph} (= \omega / k_{\parallel}) >> c$), i.e., at around zero group velocity. The frequency mismatch $(= \omega - s\omega_c / \gamma)$ is small but positive in order to achieve the correct phasing to keep electron bunches in the retarding phase. Harmonic operation ($\omega \cong s\omega_c / \gamma$) reduces ω_c and hence the required background DC magnetic field B_0 by a factor of *s*. The three beam lines in Fig. 1.2(b) correspond to the fundamental, second and third harmonics of the cyclotron mode. The intersection of the fundamental beam mode line and the waveguide mode represents the fundamental resonance. Similarly, the intersection of the second harmonic beam line and the waveguide mode represents the second harmonic resonance [Gilmour (1986), Jain *et al*. (1994), Kartikeyan *et al*. (2004)], Symons *et al*. (1986)].



(a)



(b)

Fig. 1.2 Dispersion diagrams for the gyrotron oscillator and gyroklystron amplifier **(a)** fundamental resonance, and **(b)** harmonic resonance.

1.3.2 Cyclotron resonance maser (CRM) instability

In order to understand, how generation or amplification of RF signal takes place in a gyro-device, one should have the knowledge of the interaction process in the device. The interaction process in the microwave tubes is explained with the help of the instabilities developed during the beam-wave interaction process. The interaction in a fast-wave device, like, gyro-device, can be understood with the help of the cyclotron resonance maser (CRM) instability. The interaction of a helically gyrating relativistic electron beam with an RF wave in the background of static magnetic field leads to the extraction of the transverse kinetic energy of the interacting particles, i.e., electrons. This interaction is defined as the CRM instability [Chu (2004)].

The typical arrangement of CRM interaction is shown in Fig. 1.3. Let us take the case of an annular gyrating electron beam traveling through a waveguide supporting *TE* mode immersed in a background axial DC magnetic field B_0 [Kartikeyan *et al*. (2004)].

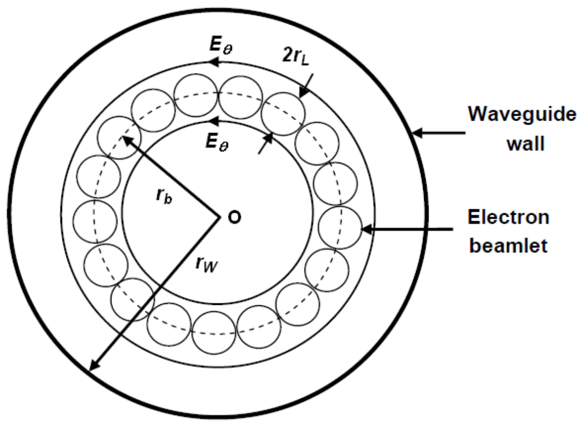


Fig. 1.3 TE_{0n} mode RF electric field in a waveguide with the electron beamlets.

In Fig. 1.3, r_w is the cylindrical waveguide radius and r_b is the guiding center radius or beam radius. This type of beam is generally produced with the help of a magnetron injection gun (MIG) by launching a hollow annular electron beam at an angle to the DC axial magnetic field to encourage gyrations in the trajectory of each electron. The field orientation of a TE_{0n} mode is also shown in the Fig. 1.3. The thickness of the gyrating beam is equal to twice of the Larmor radius (r_L) defined as

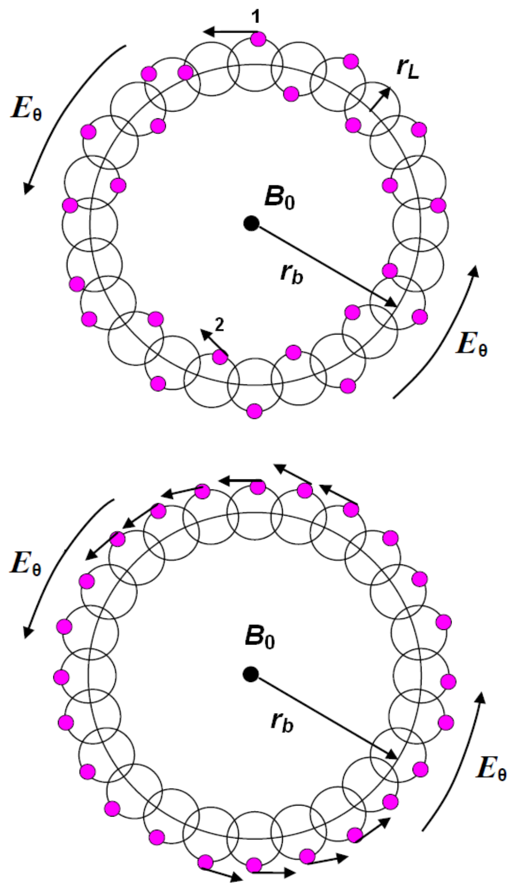
$$r_L = c\, v_\perp / \omega_c \quad , \tag{1.19}$$

where, $v_\perp$ is the perpendicular velocity of the electrons. The relativistic mass factor (γ) in terms of parallel velocity ($v_\parallel$) and transverse velocity ($v_\perp$) of the electron beam is defined as:

$$\gamma = \left(1 - \left(v_\perp^2 + v_\parallel^2\right)/c^2\right)^{-1/2} \quad . \tag{1.20}$$

The relativistic angular frequency of the circularly moving electrons in the absence of any electric field can be expressed as:

$$\omega_c = e B_0 / \left(\gamma m_e\right) \quad . \tag{1.21}$$



(a) **(b)**

Fig. 1.4 Illustrations of phase bunching phenomenon in an annular electron beam **(a)** random distribution, and **(b)** phase bunched electrons in their cyclotron orbits.

In the presence of azimuthal electric field (E_θ), the electrons moving in the cyclotron motion experience an additional force *qE,* which allow some electrons to accelerate and others to decelerate depending on the relative phase of the electric field. This causes the phase velocity modulation of the electrons. As a consequence of this relativistic cyclotron frequency of electrons is altered due to the change in their relativistic mass factor. The relativistic mass factor of the electrons increases or decreases, depending on condition, whether the electrons are getting accelerated or decelerated, respectively. Due to this process, the electrons get bunched in phase in their cyclotron orbits as shown in Fig. 1.4 (b) (front view) and Fig. 1.5 (b) (side view) [Chu (2004), Gilmour (1986)]. Figures 1.4(a) and 1.5(a) show the random distribution of the electrons in the transverse and axial directions, respectively.

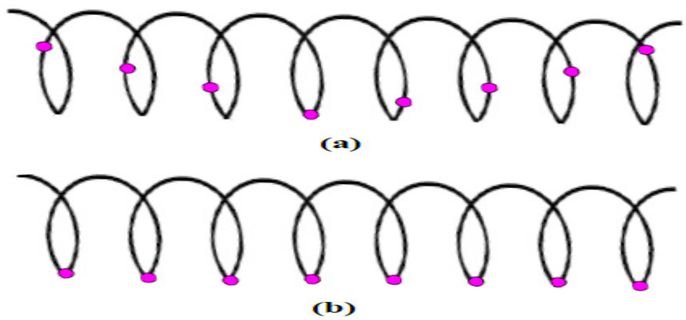


Fig. 1.5 Side view of the annular electron beam **(a)** electrons in random phase, and **(b)** electrons in bunched phase.

1.3.2.a Phase bunching

To understand the phase bunching process, let us consider one orbit case with electrons having zero axial velocity ($v_{\parallel} = 0$). The snapshot of the electrons moving in a single orbit before interaction is shown in Fig 1.6.

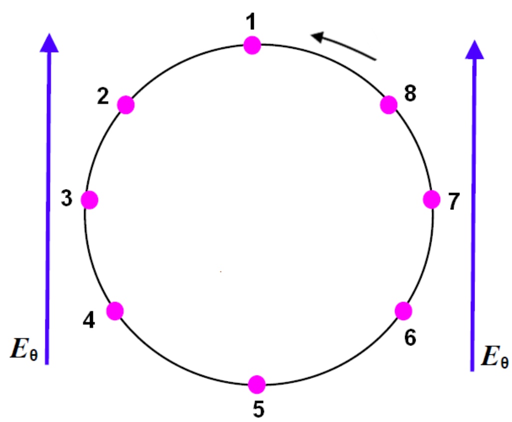


Fig. 1.6 Cross-sectional view of a single orbit before electron bunching.

In Fig. 1.6, the electrons are equally distributed in the circular orbit all over the phase (0, 2π) with radii equal to Larmor radius r_L, typically $r_L << r_b$ for a small orbit case. Further, it is assumed that the electrons are moving in counter-clockwise direction. The electrons will be accelerated or decelerated, due to the presence of the transverse RF field inside the RF interaction cavity in the *TE* mode. After interaction of the electrons with the azimuthal RF field (E_θ), electrons 2, 3, and 4 are accelerated, while electrons 6, 7, and 8 are decelerated due to the electric force *eE* exerted by electric field on these electrons. The electrons 1 and 5 remain undisturbed, due to vanishing electric force on these electrons. As, the cyclotron frequency is inversely proportional to the relativistic mass factor (γ), the angular frequency will decrease for accelerated electrons and increase for decelerated electrons. After a few cycles of cyclotron motion, the electrons that gained energy lag in phase and the electrons that lose energy go forward in phase, resulting in phase bunching. If the interacting mode frequency is exactly equal to the electron cyclotron frequency, this bunching process will continue until the whole electrons are bunched at a zero-field phase point. One can draw energy from these bunched electrons, only when they are bunched at the point of maximum field. This can be achieved by slightly lowering the cyclotron frequency than the RF frequency with the help of detuning of the axial static magnetic field. When this condition is satisfied, then bunches start moving in phase with the RF electric field and transfers their transverse kinetic energy to the interacting *TE* mode RF wave [Gilmour (1986), Chu (2004), Kartikeyan (2004), Symons *et al*. (1986)].

1.4 Gyrotron Amplifier

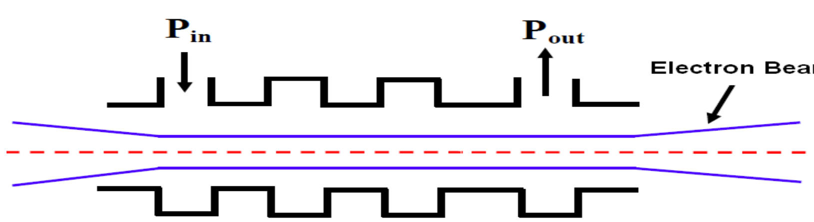
The gyro-device family may be divided in two groups, one oscillator and the other amplifier. The gyromonotron (gyrotron) and gyro-BWO are the key members of the oscillator group of this family. Devices like the gyroklystron, gyro-TWT, and gyro-twystron come under the amplifier group of this family. These devices are analogous to their corresponding slow-wave counterpart's klystron, TWT, and twystron.

It is true that, among all the gyro-devices, most advances have been made in developing gyrotrons and most of the concepts of the other gyro-devices are basically derived from those of gyrotrons. However, it is not suitable for applications in information carrying systems, due to its poor signal coherence and spectral quality. For communication system applications, amplifiers like gyroklystron, gyro-TWT or gyro-twystron are used. The RF interaction structures of used for these gyro-amplifiers are shown in Fig. 1.7.

The resonant cavity arrangement in a gyroklystron consists of a series of RF cavities separated by the drift sections (Fig. 1.7(a)). This arrangement is similar to that in a conventional klystron for localized and intensified beam-wave interaction to produce high powers with larger gain and efficiencies. The input cavity is excited with the help of an external driver. An RF signal injected into the input cavity is then amplified in the each RF cavities, and finally, the amplified signal is extracted from the output cavity [Tran *et al.* (1986), Nusinovich (2004)].

The gyro-TWT uses a non-resonant interaction structure, i.e., a smooth-wall cylindrical waveguide to support a traveling wave for the growing-wave interaction (Fig. 1.7(b)). Gyro-TWT is a broadband amplification capability than the gyroklystron due to close matching of the waveguide mode and cyclotron mode. They are capable of producing high power and efficiencies because in gyro-TWTs the group velocity of waveguide mode is nearly equal to the axial velocity of the electrons. However, gyro-TWT often suffers from problems of self-oscillations due to backward wave oscillations arising from long interaction structure and velocity spread effects [Gilmour (1986), Nusinovich (2004)].

Gyrotwystron, like a conventional twystron is a hybrid device, consists of a gyroklystron section followed by a gyro-TWT section. It is a device that is basically derived from the gyroklystron by extending the length of the drift section and replacing the output cavity by a smooth wall waveguide structure as in a gyro-TWT. The RF interaction structure of a gyrotwystron is shown in Fig. 1.7(c). The combination of series of RF cavities and the output waveguide make gyrotwystrons attractive as wideband high efficiency, high gain amplifiers. Moreover, the problems of RF breakdown arising from high power operation of a gyroklystron are also alleviated in the gyrotwystron, since the power density in the output waveguide is much smaller than in the output cavity [Kou *et al.* (1997), Nusinovich *et al.* (1998), Gilmour (1986)].



(a)

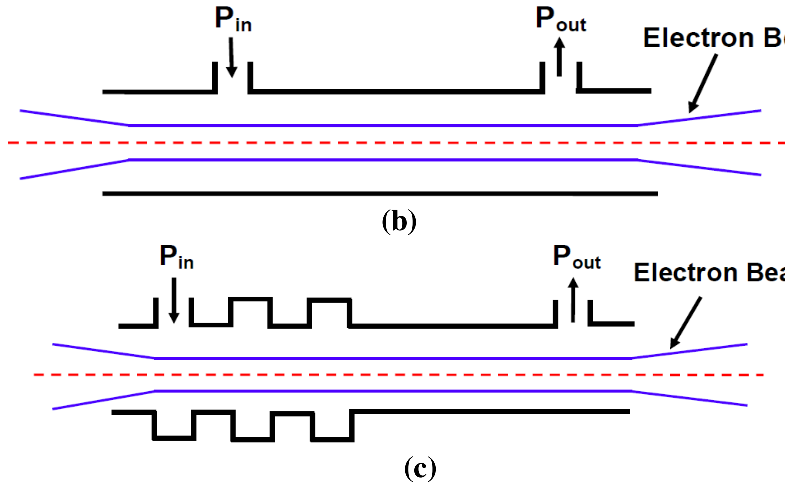


Fig. 1.7 Interaction structures of different gyro-amplifiers **(a)** gyroklystron, **(b)** gyro-TWT, and (c) gyro-twystron.

1.5 Gyroklystron Amplifier

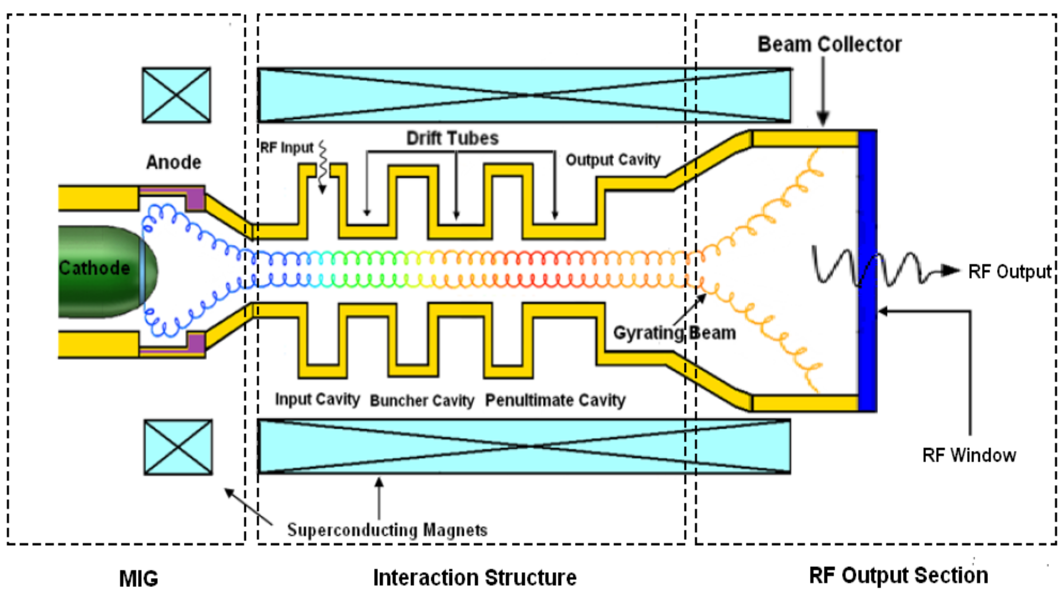


Fig. 1.8 Schematic arrangement of a gyroklystron amplifier with axial output.

Gyroklystron amplifier is an efficient high power millimeter wave amplifier based on CRM instability. A schematic of a gyroklystron amplifier is shown in Fig. 1.8. The gyroklystron consists of a magnetron injection gun (MIG), superconducting magnets, RF interaction structure which consists of few isolated RF cavities, and an RF output section. The external magnetic field produced by a superconducting magnet causes the electrons to gyrate emitted from the MIG. The RF interaction section of a gyroklystron consists of a series of cavities, i.e., input cavity, output cavity and in between few more buncher cavities each separated by drift tubes, which are at cutoff to the operating mode. In the input cavity, the desired *TE* mode is excited with the help of a driver. The gyrating electron beam emitted from the MIG is phase modulated inside this cavity after its interaction with this mode due to CRM instability process. This causes azimuthal bunching of the electrons as they move through a certain drift length. Adding more RF cavities in gyroklystron enhances the bunching process and hence the device gain. In the output cavity, the azimuthally bunched beam is continuously decelerated, and it thus transfers its energy to the desired operating *TE* mode. In case of the axial output coupling device, the spent electron beam is collected at the uniform output waveguide section known as a collector and the RF power in the *TE* mode is coupled out axially with the help of an output RF window (Fig. 1.8). The other type of gyroklystron is the quasi-optical type, where the RF window is perpendicular to the gyroklystron axis for RF output [Choi (1998), Granatstein *et al*. (1996), Gold *et al*. (1997), Shou (2012), Nusinovich (2000), Fischer (1997)].

1.5.1 Sub-assemblies

The major sub-assemblies of a gyroklystron are (i) magnetron injection gun (MIG), (ii) RF interaction structure (iii) collector, and (iv) output window.

1.5.1.a Magnetron injection gun (MIG)

Electron gun is an important sub-assembly of all the microwave tubes and provides suitable beam of electrons for the beam-wave interaction. For designing an electron gun, the beam parameters such as beam radius, beam density, beam velocity, etc. are taken into consideration. Typically, a high power gyroklystron uses a MIG, which produces an annular electron beam with the desired beam parameter in which electrons execute small cyclotron orbits at a frequency required for cyclotron resonance interaction in a gyroklystron. The magnetron injection gun is so named because of the appearance of its cathode assembly similar to that of a magnetron [Choi (1999), Singh *et al*. (2010)].

In MIG, electrons are emitted from an axially symmetric conical cathode, which operates in the temperature-limited region rather than in the space-charge-limited region to minimize the velocity spread in the beam. Electron emission resulting from the heating of the cathode surface is known as thermionic emission, and it is strongly dependent on temperature and work function of the cathode emitting surface. Therefore, emitting surfaces in such a type of the cathodes are heated up to a temperature from where electrons can easily overcome the work function and escape from the surface. The most commonly used thermionic emitters are tungsten cathode, LaB_6 cathode, oxide cathode, dispenser cathode, scandate cathode and thorium-based cathode. Now-a-days, dispenser types of cathodes are more popular and widely used than others due to their better emission density, life and reliability [Edgcombe (1993), Baird (1986)].

1.5.1.b RF interaction structure

The RF interaction structure simply known as the RF structure of a gyroklystron is the region where the electron beam interacts with the RF wave and transfers its energy to the RF field. It mainly consists of series of RF cavities separated by the drift sections, which are at cutoff to the operating mode. Drift tube is the space between two successive cavities. The drift tubes are designed such that no RF field is excited at the frequency of operation to isolate the various cavities of the circuit. In the drift length, electrons group into bunches after undergoing a change in velocity while passing through the cavity. The choice of proper drift length is necessary for obtaining optimum bunching effect [Nusinovich (2004), Tran *et al.* (1986)].

The gyroklystron consist of probably two to five resonant cavities depends on the design, gain and output power requirements, each of which has been varying functions. The first cavity is the so-called input cavity where a low power RF signal is injected with the help of an external driver, and interacts with the electron beam. The electron beam is deformed by this interaction and begins to bunch azimuthally due to CRM instability process. This bunching process is significantly enhances as the electron beam advances through the cavities and drift tubes. In the output cavity, grown RF field, caused due to extracting energy from the electrons, is extracted out through diffractive coupling with the help of an up-taper [Gilmour (1986), Choi (1998)].

1.5.1.c Collector

The role of the collector is to collect the unspent electron beam after interaction with the RF field. The collector must be able to handle the heat loading of a weakly relativistic electron beam and must be properly designed to avoid incurring any hot spots, which leads to a phenomenon that can effectively poison the operation. To avoid wall loading on the surface of a collector its diameter must be chosen sufficiently large. In order to estimate the wall loading on the surface of a collector it would be helpful if one may know the current flowing through the collector. For this purpose usually the collector in high power gyroklystrons is insulated from the gyroklystron main body. Thus, the thermal design of the collector in high power gyroklystron plays a crucial role in the overall device efficiency. Also, the total efficiency of a device can be significantly increased by the addition of an energy recovery system, like, a depressed collector. A depressed collector scheme allows reusing the residual energy of the electrons remains after the beam-wave interaction process. It can be a single stage or multistage, depending on the number of electrodes it has at different potentials for selectively collecting the electrons of various energy levels [Nguyen *et al.* (1998), Saraph *et al.* (1998), Granatstein *et al.* (1995)].

1.5.1.d RF window

RF window is an important component of the output system of the gyroklystron. It serves as a barrier between the vacuum side of the gyroklystron and the output transmission line. It should withstand the high power, mechanical and thermal stresses, be leak tight. It must be fabricated from a low-loss material, like, alumina, beryllia, sapphire. Now days CVD diamond windows are found more suitable for higher power applications, but they are costly. Because of the high power, the thermal management of the RF window becomes an important issue and must be taken into consideration during the designing phase of RF window. Therefore, the working temperature of the window has to be carefully chosen [Yong Xu *et al.* (2007), Gilmour (1986)].

1.5.1.e Output taper

A nonlinear output taper is placed between RF interaction structure and collector of the gyroklystron. The main role of the output taper is to convert the standing wave developed in the output cavity into traveling wave. It also separates the microwave energy from the electron beam as there is no RF interaction in this nonlinear tapered section. In a conventional gyroklystron, having an axial arrangement for extracting RF wave, the output taper is a nonlinear tapered waveguide, i.e., a continuously varying special radial contour designed to provide the mode purity in transfer of RF mode from the output cavity to the window. In the quasi optical gyroklystron, it basically consists of a number of parabolic mirrors, so that RF is collected through the gyroklystron window at right angle to the electron beam transmission [Lawson (1990), Nagarkoti *et al*. (2012)].

Lastly, an important sub-assembly in the gyroklystron is the magnet system, it provides the right magnetic field on the electron beam, and so that the electron beam gyrates properly and is effective for interaction with RF wave. The magnets used in a gyroklystron are superconducting magnets placed around the RF interaction structure [Hazelton *et al.* (1998), Edgcombe (1993)].

1.5.2 Applications

Gyroklystrons can be used for a variety of applications, such as drivers for linear colliders, millimeter wave radar applications, plasma heating and spectroscopic applications. Furthermore, the high power millimeter wave gyroklystrons can be used for the technological possibilities for the different kinds of atmospheric diagnosis, like, cloud monitoring, humidity measurement, and turbulence structure determination. These millimeter wave amplifiers are the foremost candidates for providing microwave power in the space-debris removal and the phased-array mapping radars as well as for the ground probing radars used in the various military applications, like detection of underground materials buried in bunkers, mines, pipes, voids, etc. Some of the applications of gyroklystrons are briefly discussed below.

1.5.2.a Millimeter wave radars

As the attenuation coefficient of the atmosphere increases with frequency, the existing communication system is required to be enhanced and changed to meet the future demand of the high information density communication systems, and provide high powers for the millimeter wave radars for their enhanced range and resolution. The millimeter wave radars enjoy the advantages of both the microwave radar and laser radar. Compared to the microwave wave radar, millimeter wave radar has advantages such as narrow beam width, high resolution, multipath effects and anti-jamming capability, smaller size and light weight. It can more effectively work in the rain, fog, and battlefield smoke work environment, compared with infrared and optical radars. Research in this area is mainly focused at frequencies of about 35 GHz and 94 GHz, due to availability of the two atmospheric windows at these frequencies. The gyro-amplifiers, like gyroklystron are ready to serve, for these specific purposes. U.S. and Russia are using the gyroklystron amplifiers in their military radars. A 120-element phased-array 34 GHz radar system using two 500 kW gyroklystrons with 50 MHz bandwidth, 100 μs pulse duration and 0.01 duty factor is operating in Russia. In US a W-band radar system using a 92 kW, 94 GHz gyroklystron with 420 MHz bandwidth and a duty factor of 0.11 (10 kW average power) has been built [Nusinovich (2004), Kasatkin *et al.* (2008), Granatstein *et al.* (1997), Gold *et al.* (1997), Gilmour (1986), Thumm (2001)].

1.5.2.b Particle accelerators

After the successful large hadron collider (LHC) experiment at CERN, the high energy physics community is eyeing towards an electron–positron collision experiment through the linear accelerator (super collider) for probing the depths of the subatomic world. The accelerating gradient for such an accelerator should be more than 100 MeV/m to keep the accelerator length to a reasonable size. In order to achieve such an accelerating gradient at minimum cost one must use the RF drivers both at higher values of power and frequency. The cost of such a super collider will depend both on the number and cost of each microwave amplifier required as drivers [Granatstein *et al.* (1988)].

Klystrons are the current state-of-the-art as microwave drivers for particle accelerators but being a conventional slow-wave microwave amplifier it cannot handle both high power and frequency simultaneously due to decrease in transverse dimension with frequency. The klystron development programs can serve for linear colliders in the energy range up to 1 TeV. However, for energy gradient more than 1 TeV, i.e., supercolliders experiments, the drivers producing greater than 100 MW peak power of 1 μs pulse length at around 34 GHz are required. The gyroklystron can be used for such type of applications due to their capabilities to provide high power at millimeter wave frequencies.

University of Maryland has been working for more than last two decades to develop gyroklystrons for the linear collider applications. The experimental work of University of Maryland, mostly concentrated in developing the X and Ku-band both conventional and coaxial types of relativistic gyroklystrons. As an example of gyroklystrons developed at University of Maryland for particle accelerator, a two cavity gyroklystron produces 32 MW power at frequency 19.76 GHz with a gain 27 dB and an efficiency of 29% by utilizing an electron beam of 457 kV, 244 A. At present the developments of gyroklystrons for accelerators are aimed at increasing the pulsed power to 100 MW at frequency 17–18 GHz. The achievement of such a power level is quite impossible with the conventional type of gyroklystrons. Therefore, coaxial cavity gyroklystrons are being developed at the University of Maryland for this purpose. One of their coaxial cavity X-band gyroklystron experiments produces peak power of 85 MW, at a pulse length of 2 μs with efficiency 32%, and gain 30 dB [Granatstein *et al.* (1996), Nusinovich (2004), Kasatkin *et al.* (2008)].

1.5.3 Types of gyroklystron

1.5.3.a Cylindrical cavity gyroklystron

These are the simplest type of gyroklystrons and are more popular due to their easy designing and fabrication techniques as compared to other gyroklystrons. These gyroklystrons mainly work in small orbit operation and provide large gain, good linearity within a small half power bandwidth. The magnetic field requirements for these devices are more for fundamental harmonic operation, and also, due to overmoded drift sections, they are not suitable for higher mode of operation.

1.5.3.b Coaxial cavity gyroklystron

To operate the gyroklystron at higher power levels to meet the high power requirements, the necessity is to increase the beam voltage and beam current but the beam voltage cannot be increased after a certain value due to practical and safety reasons, therefore, we have to increase the beam current. This requires a larger beam radius, as a consequence the drift tubes would be significantly more overloaded. In order to overcome this problem cylindrical cavity in gyroklystron is replaced by coaxial cavity. The coaxial cavity gyroklystron uses an additional central conductor in the waveguide resonator. The introduction of the coaxial insert close to the electron beam solves the problem of voltage depression and a corresponding degradation of electronic efficiency. The coaxial cavity gyroklystrons mainly operated in large orbit operation as a result of which the beam size can be easily enlarged, and the introduction of the center conductor helps us to have control on the eigenfrequency and quality factor of the desired mode. This helps us to overcome the problem of overmoded drift section and RF cavity. As, use of coaxial cavities has been suggested in the various literatures for rarefying the mode spectrum and reducing the competing action of neighboring modes, enabling stable operation of the device [Lawson *et al*. (1998), Castle *et al.* (1999), Nusinovich (2004)].

1.5.3.c Frequency multiplying gyroklystron

Development of the gyroklystron at submillimeter frequencies is limited due to the non availability of the drivers of the desired power level. Moreover, the magnetic field requirement for such a gyroklystron is very high. In order to reduce the magnetic field requirement at higher frequencies one may choose a higher harmonic operating device. However, the efficiency and output power in such a device decreases drastically due to the weakening of the beam-wave interaction at the higher cyclotron harmonics. The frequency multiplying gyroklystrons or multistage gyroklystrons are developed to alleviate this problem by reducing the magnetic field requirement, and also they provide an easier choice of input drivers at lower frequency. In frequency multiplying gyroklystrons the successive multiplication of frequency takes place in each stage; this scheme provides a significant improvement of the electron bunching, which generally decreases as the device is operated at cyclotron harmonics. Moreover, the operation of the input cavity at lower frequency makes the input cavity dimension larger, which allows one to increase the beam diameter and correspondingly beam current. Thus, the maximum efficiency from output cavity operating at higher harmonics can be taken at larger beam currents, producing high output power. These gyroklystrons are of nonlinear nature due to this reason they are unsuitable for communication purposes but can be successively used for radars and particle accelerator applications [Walter *et al.* (2000), Savilov *et al*. (2007), Di-Wei *et al.* (2009)].

1.5.3.d Clustered cavity gyroklystron

The use of the gyroklystron for communication purpose is limited due to their limited bandwidth. The bandwidth of a gyroklystron can be increased by using a technique called stagger-tuning in which each cavity of the gyroklystron is tuned at different frequencies. This arrangement enhances device bandwidth at the cost of its gain. In order to increase the bandwidth of the gyroklystron without affecting its gain, one may go for cluster cavity gyroklystron. In case of a clustered cavity gyroklystron, each cavity is replaced by a bunch of two or more cavities and the quality factor of the cavity reduces to one-half or one-third as the number of cavities used in a bunch but the overall dimension of the tube remains same. This technique helps us to increase the bandwidth of the device without affecting the gain and efficiency of the device. Therefore, the clustered cavity gyroklystrons are capable of providing high gain and efficiency over a wide bandwidth. The difficulty arises in the practical fabrication of the device as the clustered cavity increases the complexity in the actual realization of the device [Nusinovich *et al.* (2002)].

1.5.3.e Photonic band gap (PBG) cavity gyroklystron

The higher frequency operation of the conventional cylindrical cavity gyroklystron is quite complex due to reduction in its dimension and mode competition. This dimension reduction limits the power handling capability of the device. Gyroklystron operation at the higher order mode can alleviate this problem but a dense mode spectrum in the RF cavities of the gyroklystron results in the problem of mode competition. The presence of parasitic modes not only reduces the efficiency of the device, but it also spoils the frequency spectrum of the device. All these problems can be resolved by using a mode selective structure, like photonic band gap (PBG) cavity structure. The use of PBG cavities in gyroklystron reduces the mode competition problem in the cavity due to its mode selective property. It also provides a novel method for adjusting the quality factor in a cavity without the use of lossy dielectrics or ceramics [Joo *et al.* (2006), Sirigiri *et al.* (2001), Ashutosh *et al.* (2012)].

1.5.3.f Multibeam gyroklystron

The concept of multibeam is not new to the field of klystron. For the conventional klystron, it has been successfully used for producing high power and larger bandwidths at lower beam voltages. The same multi-beam concept in gyroklystrons can be used to achieve high gain-bandwidth product at low beam voltages like multi-beam klystrons. This requires an increase in the beam preveance. In a multibeam gyroklystron between cavities, the individual beams are allowed to travel through separate beam-tunnels to reduce space-charge effects. This allows the total beam preveance to be high, while individual beam perveances are low. Due to the low beam preveance of individual beamlets, the gain and efficiency of the device is higher, also due to the increase in the overall beam current the device can be operated for higher RF output power operation. The use of multibeam configuration also reduces the overall size of the device to a greater extent due to its low beam voltage operation [Nusinovich *et al.* (1998), Kirshner *et al.* (2003)].

1.6 Gyroklystron — A Review

Historically, the first gyroklystron operation was reported in the literature in the year 1978. An experimental result of an X-band gyroklystron developed in the Russia in the year 1967 has been reported. The attractive feature of this experiment was that its efficiency, as high as 70%. This high efficiency is believed due to use of a low perveance electron beam in the experiment [Andronov *et al.* (1978)]. Later, in the year 1977 Jory *et al.* at Varian published the first gyroklystron research report. In this work, they discussed the experimental results of a 28 GHz three cavity gyroklystron which produces an output power of 65 kW with 10% efficiency. However, this tube was initially designed for 200 kW output power. The desired power level was not achieved due to the excitation of spurious modes [Jory *et al*. (1977), Nusinovich (2004)]. In another experiment in the year 1981, they demonstrated the second harmonic operation of an X-band gyroklystron. They achieve an output power of 20 kW with 8.2% efficiency from this experimental gyroklystron [Symons and Jory (1981)]. Afterwards, the research at the Naval Research Laboratory of United States started for the development of gyroklystrons for radar applications. In their first experiment, they were able to produce an output power of more than 50 kW with 25% efficiency using three cavities at 4.5 GHz [Bollen *et al.* (1985)]. Later, in the 1990s, a detailed study of 200 kW two-cavity, three-cavity and four-cavity Ka-band gyroklystrons for millimeter wave radars was carried out at NRL [Choi *et al.* (1998), Calame *et al.* (1999), Garven *et al.* (2000)].

The first experiments in W-band regime were successfully demonstrated at the Institute of Applied Physics, Russia for the four cavity gyroklystrons operating in pulsed and CW regimes. In pulsed mode, a peak output power of 65 kW with 34% efficiency and a gain of 33 dB with 280 MHz bandwidth were achieved. In the CW operation, the maximum output power of 2.5 kW was produced with an efficiency of 25%. The reported gain and bandwidth for this gyroklystron were equal to 30 dB and 0.35% respectively [Nusinovich (2004)]. After that, a four-cavity W-band gyroklystron amplifier producing 100 kW peak power and 10 kW average power at center frequency around 94 GHz with a bandwidth 700 MHz has been developed at the Naval Research Laboratory, US for new high power radar named WARLOC [Blank *et al.* (2002)]. Recently, Zasypkin *et al.* at the Institute of Applied Physics, Russia reported the experimental results of a 93.2 GHz gyroklystron amplifier operating in TE_{021} mode. In this experiment, a peak output power of 340 kW with 27% efficiency, 23 dB saturated gain, and 0.41% (380 MHz) bandwidth was obtained with a 75 kV, 17 A electron beam [Zasypkin *et al.* (2012)].

The gyroklystron could be a good choice as an amplifier because the gyroklystron utilizes a series of cavities, which can provide high gain at higher power levels. These cavities can also be tuned to different resonant frequencies to widen the bandwidth at the expense of amplifier gain, a method known as stagger-tuning, similar to the method used in conventional klystrons [Nusinovich *et al.* (1997)]. The cluster cavity technique can be used for widen the bandwidth without losing gain [Nusinovich *et al.* (2002)]. Some recent gyroklystron design advances and variations include a third-harmonic gyroklystron, a dual-cavity coaxial gyroklystron, and submillimeter second-harmonic designs [McNally *et al.* (1994), Xu *et al.* (1998), Nusinovich *et al.* (2000)]. In addition, many advances have been reported in the theory of gyroklystrons, such as the optimization of gyroklystron efficiency [Tran *et al.* (1986)], AC space charge analysis [Latham 1990], the effects of penultimate cavity position and tuning [Zasypkin *et al.* (1995)]; the theory of multibeam stagger-tuned and frequency quadrupling gyroklystron amplifiers [Nusinovich *et al.* (1998), Savilov *et al.* (2007)].

1.7 Motivation and Objective

The motivation for research and development of a device is related to its applications where it can be successfully utilized. During the last few years, gyroklystron has emerged as a potential device for the amplification of high power millimeter and submillimeter waves among the various devices of its class for the use in supercolliders, mm-wave radars, plasma heating experiments, communications, nonlinear spectroscopy and many other applications [Felch (1999), Nusinovich (2004), Thumm (2012)].

Significant works, both in theory and experiments, have been carried out during the past for the performance improvement of the gyroklystrons. But still at present the designing of a gyroklystron remains a critical issue for its developers. This is because of the fact that the design of a gyroklystron amplifier is more complex than it's oscillator counterpart, gyrotron, as the device must be kept stable in the absence of a drive signal, requires overmoded coupler to inject the drive signal, and also the performance parameters such as gain, bandwidth, noise and phase stability, which are not applicable to oscillators become crucial factors of importance here. Gyroklystrons are capable of high-gain and high efficiency amplification of electromagnetic waves but like their slow-wave counterpart klystrons in a relatively narrow bandwidth. These performances related issues along with the criticality in the design of gyroklystron have motivated the author of the present thesis to take up the analysis, design and simulation studies of a gyroklystron amplifier as his research problem.

The aim of this research is to present a more comprehensive and generalized approach for designing a gyroklystron. For doing so, it is important to explore the large signal behaviour of a gyroklystron, since the nonlinear analysis is capable of predicting the saturated gain, bandwidth, efficiency, and RF output power as well as the phenomenon of electron bunching and over bunching thereby providing better understanding of the beam-wave interaction mechanism and device performance.

The effect of various beam and device parameters, like, beam voltage, beam current, magnetic field, quality factor and electron beam pitch factor in the overall performance of a gyroklystron are investigated in order to make the present study of more practical use. An attempt is also made to increase the bandwidth of the device by making use of a technique known as stagger-tuning as compared to the device without stagger-tuning. So, it has been felt, that there has been a need to establish the full nonlinear behaviour of the interaction mechanism of a gyroklystron in order to fully explore the performance and capabilities of the device.

1.8 Plan and Scope

Gyroklystron has proved its credibility as a stable, high-gain high-power millimeter and submillimeter wave amplifier. This device is yet to be fully matured to become a device in the manufacturer product catalogue as the other device in this gyro-family, gyrotron. The need of high-power gyroklystron amplifiers for various applications, like, millimeter wave radars, linear colliders, spectroscopy etc., have motivated the author of the present thesis to take up the beam-wave interaction behavior study of the gyroklystron amplifier in the present thesis. In the present work, a detailed insight of the design, analysis and simulation of gyroklystron amplifier, including the nonlinear beam-wave interaction description, as well as performance improvement of the gyroklystrons have been presented. The work embodied in the present thesis is organized into six chapters, as follows.

In Chapter 1, which is an introduction to the work embodied in this thesis, the fundamentals of the conventional microwave tubes along with the fast-wave microwave tubes, and their applications have been talked about. An overview and literature survey of the principles and status and development of gyroklystron amplifiers have been presented. The conventional gyroklystrons as well as various advancements in gyroklystrons have been reviewed and found gyroklystron amplifier as an attractive device for millimeter and submillimeter waves amplification. Basic principle, working, advantages of the device are reviewed with their scope and limitations. A detailed literature review is made for the gyroklystron device development, present status, issues and limitations along with the different gyroklystron types for its performance improvement. The plan and scope of the present thesis are also described in this Chapter, Chapter 1.

In Chapter 2, generalized linear and nonlinear theories for gyro-devices based on the contour plots are presented to explore the beam-wave interaction behaviour of a gyroklystron amplifier. The single mode time independent approach has been used for this purpose. Further, the generalized nonlinear analysis is tailored to analyze the gyroklystron amplifiers and further extended so that the contour plots based decision making and optimization can be made in terms of computer friendly mathematical model. The numerical code based on the developed nonlinear analysis is developed to study the gyroklystron device beam wave interaction mechanism. The developed codes for the gyroklystron analyses are benchmarked against the published experimental results of reported two-cavity and four-cavity Ka-band gyroklystron amplifiers. The effects of the various device parameters, such as, variations in the beam current, quality factor, beam voltage, and velocity spread on the device electronic efficiency, bandwidth and RF output power are explored. The analysis developed here is used further in the subsequent work for the device design and performance exploration.

PIC simulation is an important tool to explore the device/system behavior and supplements the analytical results as well as reduces the development time/efforts. Gyroklystrons have also been investigated through PIC simulations in the past but mostly in-house custom built codes were used which are usually not available in public domain. Also, detailed of PIC results are not reported in the literature. In the present work reported in this chapter, Chapter 3, a commercially available particle-in-cell code 'MAGIC' has been used for 3D simulation of gyroklystron amplifier. 3D PIC simulation has been performed both for the beam absent (cold condition) and beam present (hot condition) cases using this commercial code. The simulation procedure and beam-wave interaction investigation have been thoroughly described. A flow chart for the gyroklystron simulation procedure in MAGIC has been given along with the code basic concept, and command checklist. The device simulation presented here covers the modeling of the RF interaction structure, creation of hollow electron beam similar to gyrotron, frequency of operation, RF output power, efficiency, and most important calculation of device gain, and bandwidth. The PIC simulation results obtained in this chapter are also benchmarked with the available published results and the analytical results obtained in Chapter 2.

Chapter 4 covers the nonlinear analysis, comprehensive design methodology, and 3D PIC simulation of a gyroklystron amplifier using analysis and PIC simulation techniques developed in the previous chapters. A comprehensive design methodology for designing a gyroklystron amplifier is developed and discussed herewith. Based on the developed approach, typically selected 200kW, Ka-band, four-cavity gyroklystron amplifier case, a device is designed. Various important design constraints and their role in selecting the design parameters are also illustrated. This conceptual device design is validated through performance estimation of the device in terms of RF output power, efficiency, gain and bandwidth, etc., using developed nonlinear analysis as well as 3D PIC simulation. During assembling of the various components of the gyroklystron amplifier some misalignment can occur. A practical case of the misalignment of the cavities axis, drift tube axis and both the axes is also investigated to study the effect of these misalignments on device performance.

In Chapter 5, the gyroklystron amplifier is explored further for its performance improvement using the stagger-tuning technique. In this technique, the resonant frequencies of different RF interaction cavities of a gyroklystron amplifier are slightly detuned, due to which the enhancement in bandwidth of the device occurs, but at the cost of its gain. Therefore, a study for trade-off in gain-bandwidth product for the device is carried out. First, a generalized analytical approach for stagger-tuned gyroklystron is developed and successfully implemented on the gyroklystron amplifier for its bandwidth enhancement. The analytical results obtained in this chapter are validated through PIC simulation results.

Finally, in Chapter 6, the works embodied in the present thesis are summarized, and the significant conclusions are drawn from the major findings. In addition to this, the limitations of the present study are also discussed, pointing out the scope for future work.

1.9 Conclusion

In the present chapter, the work embodied in the present thesis is outlined. The basics of conventional microwave tubes along with the gyrotron oscillators and gyrotron amplifiers have been briefly discussed. The major applications of gyro-devices, with a peered literature review of the gyroklystron amplifier have been presented. Brief outlines of the state-of-the-art, improvement and advancement of the gyroklystron amplifier, its limitations, and scope for the further performance improvement have been given. An overview with the discussions regarding the need, motivation, plan and scope of the present research work is also presented.