CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

1.8. Motivation for the Gyro-Twystron

1.9. Outline of the Thesis

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1.1. Introduction

Ever since the invention of microwave sources, it has brought an unprecedented revolution in every sphere of human life. Despite of competitive incursion from solid-state devices, microwave tube has complete dominance in high power, high frequency regime [22]-[26]. It has different applications in various field, from beneath of the earth to deep in the space, from food to war, from diamond to weapon [1]-[5],[16]-[22]. Some of the important applications of the microwave tube in millimeter range are, remote sensing, space debris detection, weather monitoring, missile tracking, particle accelerators, plasma heating, material processing, and so on [27]-[33]. The invention of microwave tubes are highly motivated from the invention of the vacuum diode by John Ambrose Fleming in 1904 and the vacuum triode by Lee de Forest in 1906. However, as the frequency increased to the UHF range, the tube performance degrades due to the factors like the lead inductance, inter-electrode capacitance, finite transit time of electron flight between electrodes, power losses resulting from the skin effect, I^2R loss caused by capacitance-charging currents, dielectric loss, electromagnetic radiation, heating of electrodes, etc [17],[21]-[25]. The conventional vacuum electron device (VED) i.e. magnetron, klystron, travelling wave tube (TWT) were developed in early decade of nineties, based on Cherenkov and transition radiation, are used to generate and amplify the RF wave in the frequency range of 1-30 GHz. However, with increment in operating frequency, the realization/fabrication of conventional VED is difficult as the RF structure is in the order of wavelength. This dimensional limitation limits its power handling capability at millimeter (30-300 GHz) and submillimeter (> 300 GHz) frequency range.

Various important applications in the millimeter and submillimeter wave frequency range have motivate the research community to attempt to fill the technological gap between microwave and optical frequencies. Some of the major applications are: high range resolution radar for space debris detection, phase array, weather monitoring and for detecting the deep grounded materials, for the detection of aircraft, deep space and specialized satellite communication, advanced high gradient RF linear accelerators, material processing, ceramic sintering, laser pumping, power beaming and electron cyclotron resonance (ECR) heating of fusion plasmas [20]-[32]. The various applications, discussed above, require the high power in millimeter or submillimeter frequency range, but due to the technical research gap, there is many difficulties to obtained this requirement. There are two possibilities to fulfilling the high power requirement in high frequency. One, to increase the operating frequency of conventional VEDs to the millimeter or submillimeter frequency range. As transverse dimension of conventional VEDs are of the order of their operating wavelength. Hence, as the operating frequency of the devices moves toward the higher frequency band, the size of the device gets reduced. The narrow dimensions of the device decrease the power handling capability, which limits the utility of the device for the various millimeter and submillimeter applications. This decrement in power output is due to the 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. Also, alternatively, one can reduce the operating frequency of quantum optical mechanical devices, like, laser. A decrease in the operating frequency of a quantum optical device reduces the quantum energy and, therefore, also the available power, and reduces the population inversion stability, which is a major requirement for the operation of an optical device.

Different research efforts are being made to seal this gap in technical research for the development of high-power VEDs in the millimeter and submillimeter frequency bands. These efforts motivate the research community and lead to more research and development of unconventional VEDs that work in fast-wave regimes. Electron Cyclotron Resonance Maser (ECRM) instability [8],[34] is the key to the high power performance of fast wave VEDs in the high frequency range. This ECRM instability significantly increases the physical amplitude of the VED at high frequencies and makes the structure large enough that it can handle higher power levels at millimeter or submillimeter frequencies. The research community has delicately exploring the possibilities of various fast wave devices also known as gyro-devices to utilise their efficient performance in millimeter and sub millimeter wave range. Most of the present fast wave device's development is inspired by their slow wave counterparts, like, gyrotron [20]-[29] development is motivated by monotron, gyro-klystron , and gyro-TWT are inspired by klystron and travelling wave tube (TWT) , respectively, similarly, gyro-BWO oscillator [36] followed the backward wave oscillator (BWO). The basic principle of the VEDs is briefly discussed in next section.

1.2. Basic Physics of Microwave Tube

All Microwave tube defined as the devices that can generate and amplify the RF power in the frequency ranges of 1 GHz to 300 GHz. The basic block diagram (Figure1.1) of Microwave tube consists of particle source, interaction structure, input coupler, particle collector and RF window. Microwave tubes performance is mainly depending on the beam wave interaction or energy transformation. On the basis of energy conversion mechanism and electron bunching mechanism, there are different types of microwave tubes. Accordingly, one can place microwave tubes under the categories of the O-type (O standing for TPO — tubes à propagation des ondes) and M-types (tubes à propagation des onde à champs magnetique). The conventional microwave tube, like klystron, TWT are categorised as the O-type tube in which, the magnetic field constrains the electrons to move in the longitudinal direction and keep in interaction with the RF wave, during this interaction the kinetic energy of the electron beams transfer to the RF wave, therefore this category of the conventional tube is also known as the longitudinal beam wave interaction type or kinetic energy type or the slow-wave structure type tubes [15]-[22]. Similarly, the magnetron or the crossed-field amplifier (CFA), classified as the M-type tube, where the magnetic field is responsible for the interaction between the electron beam and slow electromagnetic waves and in this process the potential energy of the electrons is converted into electromagnetic energy as the electrons move in the region between the cathode and the anode-cum-slow-wave structure, and therefore this variant of tube is also known as the transverse beam wave interaction type or the electron potential energy conversion type tube [15]-[22].

The operation of the vacuum electron tube is based on the energy conversion or energy transformation of the energised electron beam to the electromagnetic radiation. Based on electromagnetic wave generation, microwave tubes are further classified into three categories, namely Cherenkov radiation, Transition radiation, and Bremsstrahlung radiation [25],[29]-[35]. When electrons pass across a boundary between two media with nonuniform refractive indices, or when the electrons' route through a medium is perturbed by a conducting grid or plate, transition radiation is produced [31]. The klystron having the short gap resonant cavities is a transition radiation-based slow-wave vacuum electron device. The schematic view of the transition radiation based klystron is presented in Figure 1.2.

When the electrons are travelling in medium of refractive index greater than unity and their velocity exceeds the phase velocity of a propagating electromagnetic wave, electromagnetic radiation results. Such electromagnetic radiation, which is essentially referred to as Cherenkov radiation [30], is typically produced in slow wave devices like travelling wave tubes (TWTs) and backward wave oscillators (BWOs).

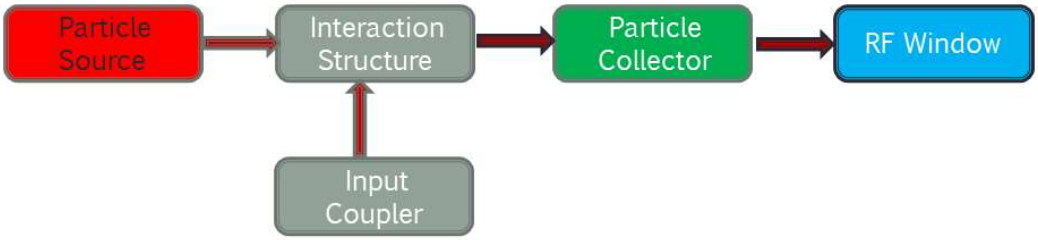

Figure 1. 1. Basic block diagram of microwave tube.

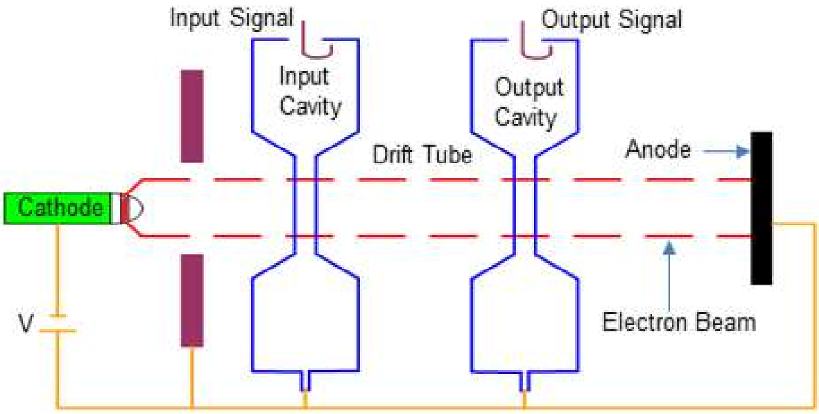

Figure 1. 2. Basic schematic diagram of a klystron amplifier.

The schematic view of the Cherenkov radiation based TWT and BWO is presented in Figure. 1.3. Since the electron beam velocity could not cross the velocity of light, therefore, a slow wave structures are introduced to obtain the synchronism between the electron beam and RF wave, in microwave tubes to bring the phase velocity of the EM wave down to the speed of light.

Bremsstrahlung radiation [34] is basically known as cyclotron resonance maser (CRM) principle, where the gyrating electrons accelerate or decelerate under a static axial magnetic field and interact with the electromagnetic wave, transmiting their kinetic energy to the wave and generate coherent EM radiation. The necessary condition for the effective beam wave interaction is $\omega - k_{\|} v_{\|} = s\Omega_c$, where, Ω_c is the electron cyclotron frequency, s is the harmonic number, $k_{\|}$, $v_{\|}$ and ω are the axial wavenumber, axial drift velocity of the electrons and wave angular frequency, respectively. Various Gyro devices like gyro-

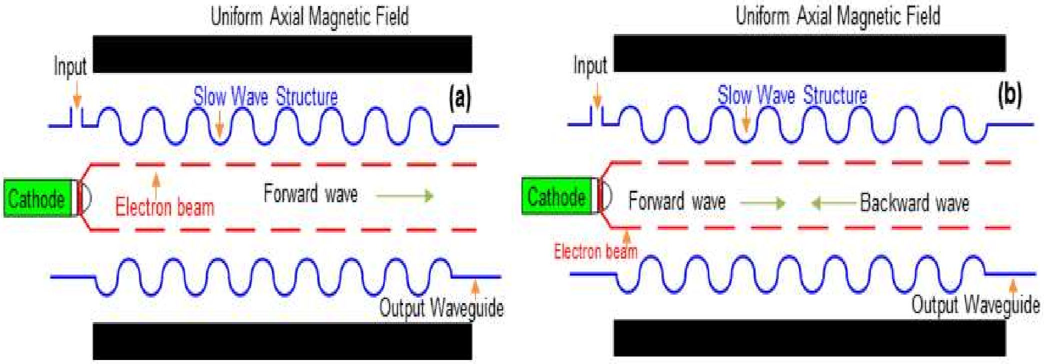

Figure 1. 3. Basic schematic diagram of a (a) TWT and (b) BWO.

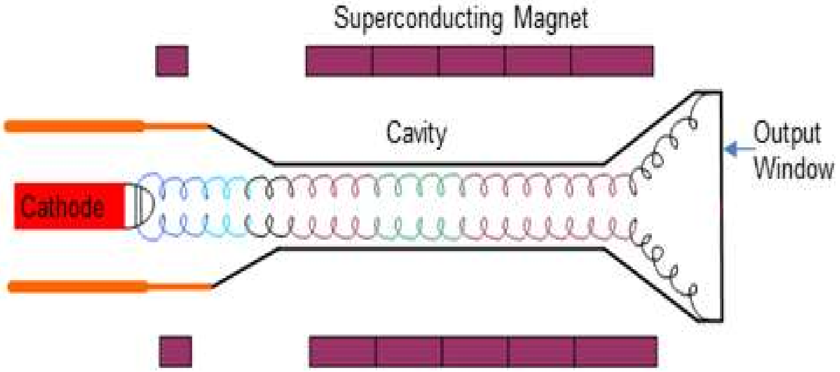

Figure 1. 4. Schematic diagram of a cyclotron resonance maser configuration.

monotrons, gyrotron traveling wave amplifiers (gyro-TWTs), the gyrotron backward wave oscillators (gyro-BWOs), gyro-klystrons, gyro- twystrons, cyclotron auto resonant masers (CARMs), free-electron lasers (FELs) are the examples of Bremsstrahlung radiation-based device or electron cyclotron maser devices.

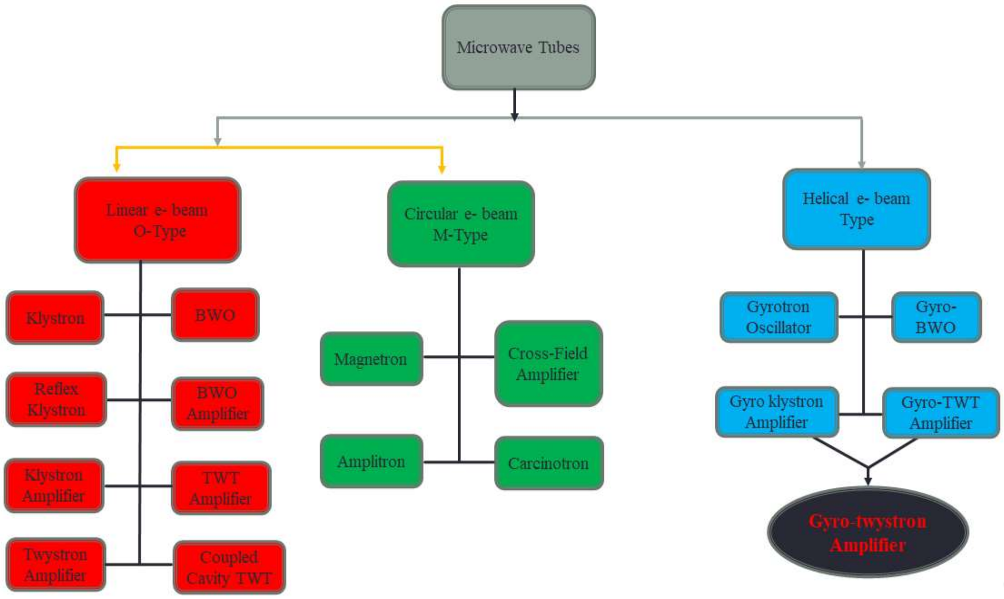

Figure 1. 5. Family tree of microwave tubes.

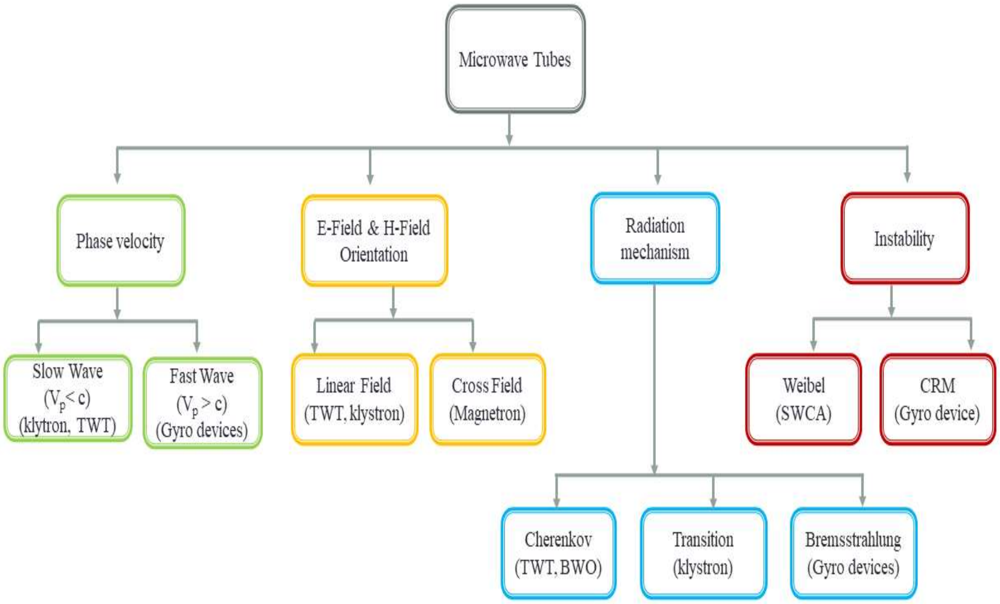

Figure 1. 6. Variant of microwave tube based on various mechanism.

The Schematic diagram of a cyclotron resonance maser configuration is presented in Figure. 1.7. The basic classification of the microwave tubes is concluded in Figure1.5, further on the basis of energy conversion, radiation mechanism, phase velocity and relativistic factor, classification of the tube is shown in Figure1.6. As the structure dimension of a conventional microwave tubes decreases with frequency to a greater extent and this limit the power handling capability of the tube. This limitation of the conventional tube is overcome with the help of fast wave microwave tubes or gyro devices. The working physics of the gyro devices are discussed in section 1.3.

1.3. Introduction of Gyro Devices

The prime motive of a microwave tube is to support electromagnetic waves for interaction with the electron beam in interaction region. This interaction structure should be larger in order to handle greater power devices. It is generally known that the transverse dimension of typical slow-wave microwave tubes such as klystron, TWT, and others scales inversely with increasing operating frequency. As a result, at millimeter and submillimeter wave frequencies, the power handling capabilities of these devices is dramatically reduced. As a result, as the working frequency of traditional microwave tubes increases, the RF output power decreases dramatically due to several limiting variables such as DC power dissipation, RF losses, electron current density, material breakdown, and so on. In response, researcher and scientists from all over the world have been vigorously looking for fast wave devices based on electron cyclotron resonance maser (ECRM)(discussed in section 1.3.1) instability based devices to fill the void in terms of perceptible power level in the millimeter and submillimeter wave regions [20],[28],[29] . The transverse dimension of the interaction structure of a gyro-device, such as the gyro klystron, gyro-TWT, gyro-twystron, reduces with frequency, like in slow-wave device, such as a klystron, TWT, twsytron. However, this diminution is not to the same extent as to the slow wave devices. The transverse dimension of a fast-wave device can be enlarged by operating it in higher-order modes, which correspond to a higher eigenvalue. Since the power loss density at the RF structure's walls is decreased, more power may be handled at higher frequencies. In addition, the gyrating electron beams employed in a fast wave device can be positioned farther away from the RF structure's walls in order to generate the larger field necessary for the precise beam-wave interaction. The operating mechanism of the gyro devices, ECRM is discussed in the next section.

1.3.1. Electron Cyclotron Resonance Maser (ECRM)

In fast wave devices or gyro devices, the beam wave interaction is governed by the CRM instability phenomena [8],[34]. In the gyro devices, based on CRM instability, the phase bunching occurs in cyclotron orbit due to the modulation in cyclotron frequency. and RF waves causes a change in the relativistic mass of gyrating electrons. This energy transformation and electron phase bunching is governed by the cyclotron frequency (Ω_c) and relativistic factor (γ) as:

$$\Omega_c = \frac{eB_o}{\gamma m_e} \qquad [1.1]$$

$$\gamma = 1 + \frac{eV}{m_e c^2} = 1 + \frac{V(kV)}{511} \qquad [1.2]$$

Where m_e, V and c are the effective mass of electron, beam voltage and speed of light , respectively. A cross section of the gyrating electron beams under the influence of DC magnetic field (B_0) is shown in Figure 1.7.(a), where gyrating electron beams are moving through a CRM system with TE_{0n} waveguide mode. The direction in which various particles are oriented with regard to the electric field (E_θ) is what generates the phase bunching in cyclotron orbit. The fundamental working mechanism of CRM interaction may be explained by examining the interaction of the electrons in a single beamlet like shown in Figure1.7. (b) with the electric field. Now, electron in position number 1 is moving opposite to the E field direction, hence they are accelerated causes an increase in the relativistic mass factor of the electron and hence an increase in its relativistic mass which in turn causes a decrease in the relativistic electron cyclotron frequency and hence an

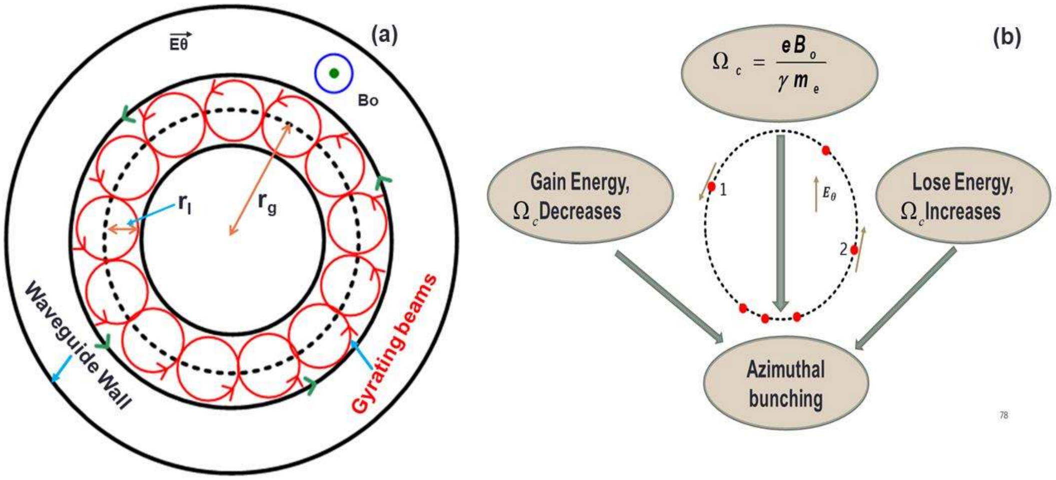

Figure 1. 7. Schamtic illustration of (a) TE_{0n} waveguide mode and electron beamlets in metallic waveguide and (b) electron phase bunching in RF electric field of TE wave.

increase in the time period of gyration of the electron. Electrons moving in perpendicular to the electric field, their mass and energy remain affected in cyclic movement. Electron in position number 2 is moving in the direction of the electric field, hence they are decelerated causes an reduction in the relativistic mass factor of the electron and hence an decrement in its relativistic mass which in turn causes a increment in the relativistic electron cyclotron frequency and hence an reduction in the time period of gyration of the electron. As the rate of rotation for some electrons are increased and at the same time for others it decreased, this process is repeated, resulting in an electron bunch in cyclotron phase space [34], which is referred to as "phase bunching”. This type of phase bunching introduces an AC component to the electron beam current, allowing for the generation of EM waves. In actuality, the movement of electrons in gyro devices can be interpreted in a direct manner by creating linkages to the orbit of the moon inside the solar system. In the Larmor circle, along the magnetic flux line, an electron (like 'moon') orbits the guiding center (like 'Earth'), while the guiding center itself revolves the cavity transverse center (like 'Sun').

1.4. Classifications Gyro Devices

The Since the introduction of cyclotron-resonance maser (CRM) instability devices, a huge proportion of research has been conducted, and a number of gyro-devices have been developed. The gyrotron is undoubtedly the most widely used of these devices (alternatively known as gyro-monotron). The gyrotron backward-wave oscillator (gyro-BWO), gyro klystron amplifier, gyrotron travelling-wave tube amplifier (gyro-TWT), gyro-twystron are the other types of commercially available gyro-devices that find widespread use in in various applications. The interaction section of gyro devices can either be a cavity or a waveguide section.

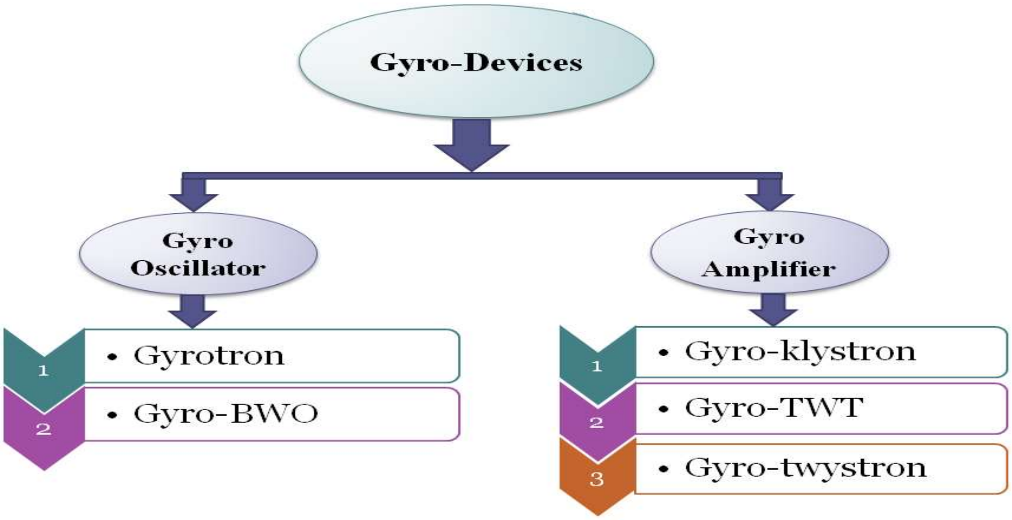

Figure 1. 8.Family tree diagram of gyro devices

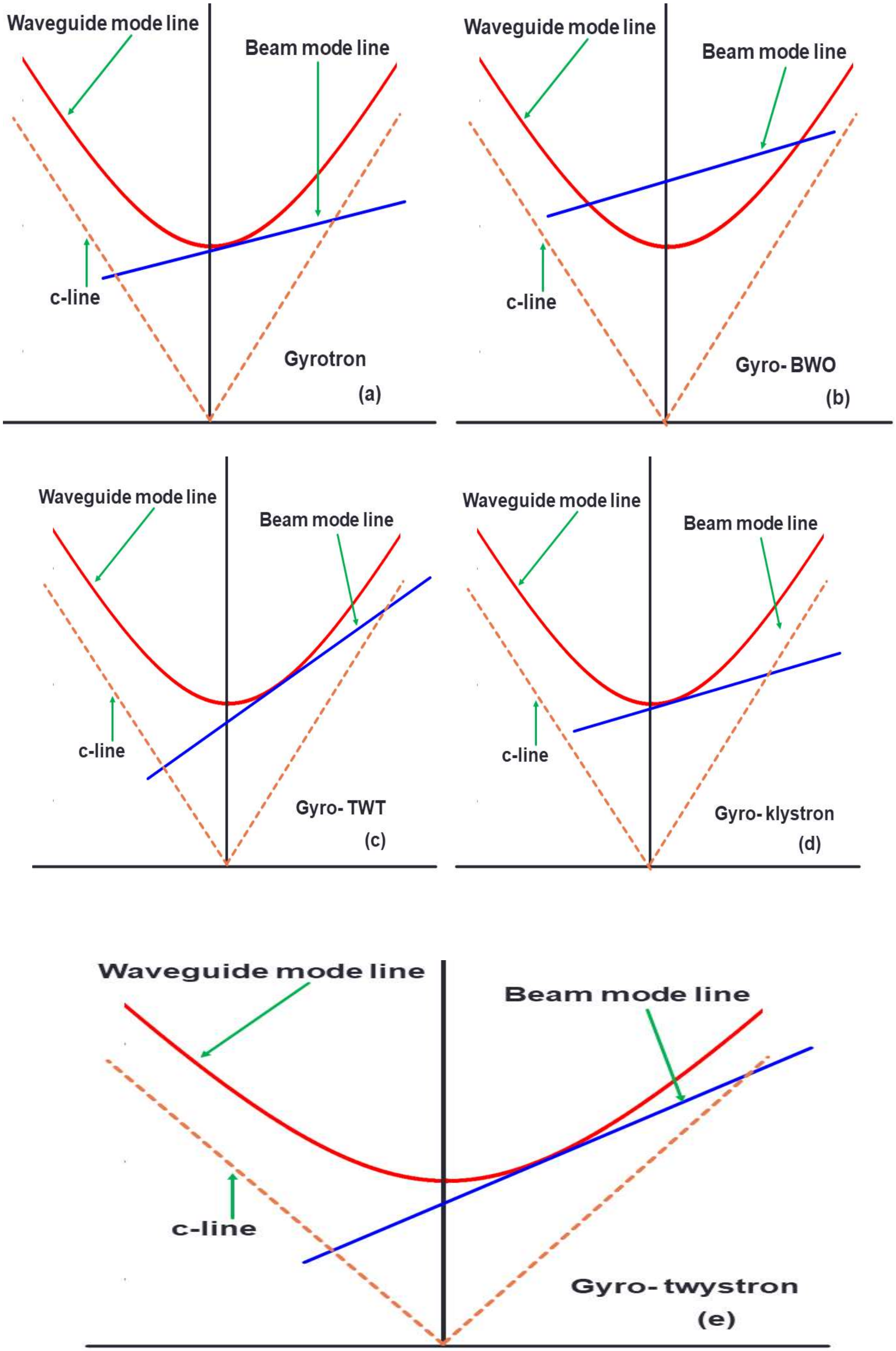

Figure 1. 9. Dispersion characteristics of (a) Gyrotron, (b) Gyro – BWO, (c) Gyro - TWT, (d) Gyro -klystron and (e) Gyro-Twystron.

In either case, this is the section where beam wave interaction occurs under the guidance of a DC magnetic field. As a result of this interaction, some of the kinetic energy of the electron beam is transferred to the electromagnetic signal. The amplified microwave signal is extracted via the microwave window, while the spent electrons are gathered on the collector wall. The complete family of gyro-device is mainly classified as gyro oscillators and gyro amplifiers, as shown in gyro devices family tree in Figure1.8.

The important gyrotron oscillators, in which electromagnetic radiation is generated through either the self-excited oscillations or the noise signal, are gyrotron and gyro-BWO, while the gyrotron amplifiers, in which some external microwave signal is required in order for the electromagnetic radiation to be amplified, are gyro-klystron, gyro-TWT and gyro-twystron. Also, each gyro device is differing by its wave-particle interaction, defined as the point of grazing interaction in dispersion diagram, where the two curves just touch, shown in Figure1.9.

1.4.1. Gyro Oscillators

Devices such as the gyro-monotron and the gyrotron backward wave oscillator are variants of what are known as gyrotron oscillators. They are able to produce the electromagnetic radiation by utilizing the localized interaction or local cavity interaction. The gyrotrons find application as high-power millimetre wave sources, for instance, in plasma heating for controlled thermonuclear reactor and in material processing. The gyrotron is a fixed-frequency oscillator that interacts with the electron beam by maintaining electromagnetic energy in the waveguide resonator cavity at a group velocity close to zero. Using self-excited oscillations, it produces electromagnetic radiation. When the gyrotron is run close to its cut-off frequency, the wave and particle interaction is strong, the power is stable, and the efficiency is high. At the gyrotron's operational point, the axial phase propagation constant of the RF wave is small enough to mitigate the impact of electron beam velocity spread on an inhomogeneous broadening of the cyclotron resonance band. A small beam-mode mismatch, and thus a small frequency mismatch for a small Doppler shift, assures coherent phasing and keeps the electron bunches in the retarding phase of the waveguide resonator. In a gyrotron (Figure1.10.a), an electron beam is injected into a region with a strong axial magnetic field and transmitted through a cylindrical cavity or waveguide region carrying an electromagnetic wave with an azimuthal component of electric field. The gyrotron has seen the most technological advancement compare to other member of the gyrotron family. The applications of gyrotrons have been extended from microwave wave to low THz wave technology. The different gyrotrons have been developed at different operating frequency for the various application, like as nonlethal active denial weapon to serve for crowd control and anti-terrorist activities [37],[38], for nuclear fusion experiments i.e., International Thermonuclear Experimental Reactor (ITER) [39],[40]. The gyrotron backward-wave oscillator, or gyro-BWO, is a new circuit

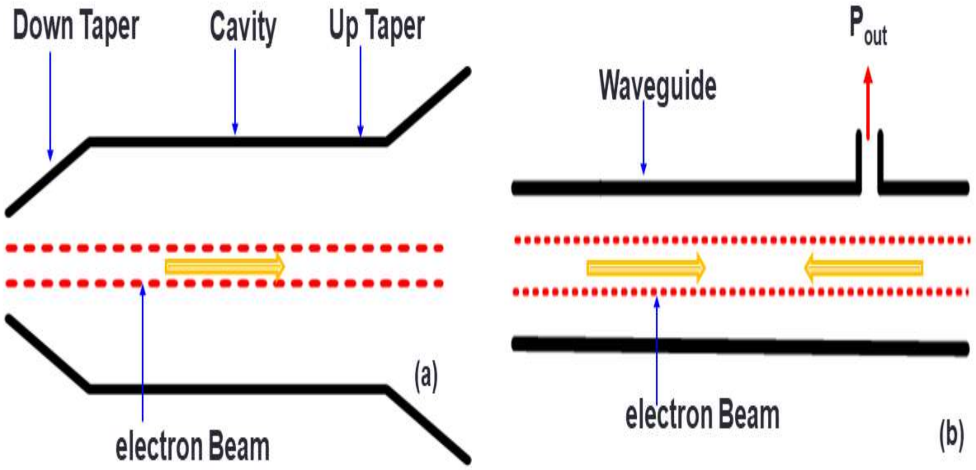

Figure 1. 10. Schematics of (a) Gyrotron, (b) Gyro-BWO

configuration that can give a constantly adjustable signal. The smooth wall waveguide would replace the resonant cavity of gyrotron (Figure1.10.b), and oscillation would emerge from interaction between the forward-propagating beam mode line and the negative propagating waveguide mode line. Therefore, gyro-BWO [36] operates at a point corresponding to the negative values of both the phase and group velocities of the RF waves. The gyro- BWO is frequency tune able over a wide range of frequency by adjusting either the beam voltage or the magnetic field. With the change in the beam voltage, it is possible to modify the axial beam velocity, which, in turn, would cause the slope of the beam-mode dispersion characteristics to change, which would change the operating point of the device or interaction of beam mode line and waveguide mode line. Similarly, by varying the magnetic flux density, the beam-mode dispersion line can be moved parallel to itself, changing the -intercept of the beam-mode dispersion characteristics and hence the working point of the device.

1.4.2. Gyro Amplifiers

The terms "gyro-klystron," " gyro-TWT," and "gyro-twystron" are all examples of devices that can be classified as "gyrotron amplifiers." In order to excite the electromagnetic radiation, these devices require an external input signal. The configuration of the several types of gyrotron amplifiers is quite similar to that of traditional linear beam vacuum tube amplifiers; however, these amplifiers have the advantage of having a fast wave structure, that handles high power at high frequency.

The gyro-klystron (Figure1.11. a) is a device that functions is analogous to that of a traditional klystron and utilize the standing waves in single cavity or multi cavity structure. It consists of several different sub-assemblies, i.e., an input cavity, one or more intermediate cavities, drift tube, an output cavity, a beam collector, and an output window. An RF signal is fed to the input cavity, where the velocity modulation of the electron beam takes place and these modulated beams interact with the RF wave in output cavity section to transmit their energy to the wave. The gyro-klystron produces high power, but due to the resonant interaction structure, it also has a bandwidth constraint [41]. The major application of gyro-klystron includes the linear accelerator and space radar system. Researchers at the Institute of Applied Physics (IAP) and the Naval Research Laboratory (NRL) conducted a significant amount of work on gyro klystron amplifiers for a variety of radar applications using frequency windows of 35 GHz and 94 GHz.

Although the gyrotrons and the gyro-klystrons have been developed commercially, the development of the gyro-TWTs, which have potential applications in millimetre-wave communication and radar, are development in various laboratories.

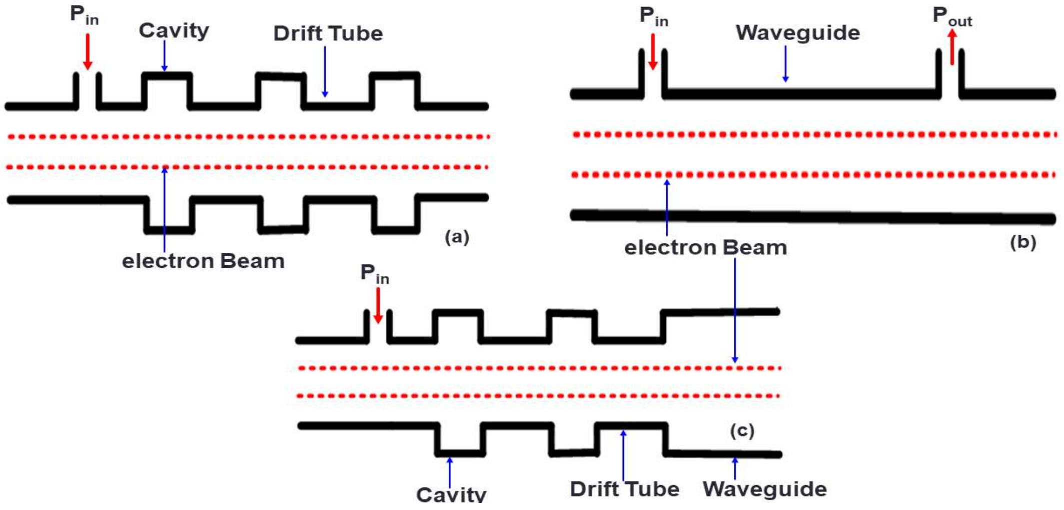

Figure 1. 11. Schematics of (a) gyro - klystron, (b) gyro -TWT and (c) gyro-twystron.

The gyro-TWT using a non-resonant waveguide supporting propagating waves enjoys a wider bandwidth potential than the gyro-klystron supporting stationary waves using a system of resonant cavities. The resonant cavity of the gyro klystron is replaced with a smooth-wall waveguide in gyro-TWT (Figure1.11. b). Electron phase bunching and EM wave amplitude both develop exponentially along the entire interaction section and generate amplified saturated output signal. Since the traveling waves can interact with an electron beam over a wide range of frequencies, the bandwidth is very large. Since gyro-TWT emits high-power electromagnetic radiation over a broad range it becomes the most promising source for a high-resolution remote-imaging radar system and in millimeter wave defense applications. The gyro-TWT has the capability of amplifying RF wave of one order of magnitude larger than what is possible in a conventional TWT and also offers a high spectral quality. The broadband coalescence in gyro-TWT can be achieved by adjusting the dc magnetic field for grazing point interception *i.e.* the group speed of the RF wave equal to the axial beam velocity. There are various waveguide dispersion shaping techniques such as metallic vane loading, helical corrugation, dielectric loading of the waveguide [42], etc. for broad- banding of the device but at the mean time reduction in gain also observed. This is because of the smaller interaction sections that become effective for amplifying other competing modes of the device. There are many ways to both widen the device's bandwidth and keep its gain high, such as loading the device with metallic vane, helical corrugation, dielectric loading of the waveguide, etc. However, the method of dielectric loading the waveguide for broad banding a gyro-TWT entails the risk of dielectric charging and heating the dielectric if it is lossy, a problem that has to be alleviated by the application of a thin metal coating on the dielectric,[43]-[47].

The gyro-klystron and gyro-TWT are effective amplifiers at high frequencies. However, they still suffer from various limitations, such as the microwave breakdown problem in gyro-klystron due to the output cavity section and mode competition constraints in gyro - TWT due to the short output waveguide section. A hybrid amplifier known as a gyro – twystron [48] is introduced to address these problems and combine the benefits of the two devices into one. The developed gyro- twystron (Figure1.11.c), analogous to a conventional twystron is constituting one or more input cavities followed by an output waveguide section, provides a significant gain-bandwidth improvement over other gyro amplifier. In multistage gyro-twystron the electron beam is modulated at the input stage and pre-bunching occurs in the drift section that separates the output stage from the input stage before being inserted into the output waveguide. The gyro-twystron merging the merits of two gyro amplifiers (gyro klystron, gyro – TWT), it has aroused considerable research interest in widening the bandwidth with sufficient power level for applications such as in high-resolution radar and high information density communication systems in the millimetre-wave frequency band.The theoretical as well as experimental research on this hybrid amplifier was started at Massachusetts Institute of Technology (MIT), Naval Research Laboratory (NRL), University of Maryland. The working principal and physical detail of gyro-twystron is discuss in next section.

1.5. Gyro-Twystron Amplifier: Physics and Sub-Assemblies

1.5.1. Gyro-Twystron Physics

The gyro-twystron amplifier is a high-power, microwave and millimeter wave coherent radiation amplifier that operates on the cyclotron resonance maser (CRM) instability. As discussed in section 1.3.1 the dependence of relativistic cyclotron frequency on electron energy is caused by CRM instability. In gyro-twystron several transverse electric modes are supported by the RF interaction structure, which interact with a gyrating electron beam under a static magnetic field. The relativistic cyclotron frequency changes as a result of the phase of the electric field and the movement of electrons, resulting in phase bunching. The characteristic of a gyro-twystron is mostly governed by the effectiveness of beam wave interaction in the interaction region. The dispersion relation, which governs the intersection of the beam mode and the waveguide mode, $\omega - k_{\parallel}$ relation of waveguide mode line [34] is defined as

$$\omega^2 - k_{\|}^2 c^2 - \omega_{cut}^2 = 0 \qquad [1.3]$$

while $\omega - k_{\|}$ relation of beam mode line [34] is defined as,

$$\omega - k_{\|} v_{\|} - \frac{s\omega_c}{\gamma} = 0 \qquad [1.4]$$

where ω and $k_{\|}$ are the angular frequency and the axial phase propagation constant of RF waves supported by the waveguide (resonant structure, say for a gyrotron and propagating structure for a gyro-TWT), respectively and c is the speed of light and ω_{cut} is the cutoff angular frequency of the waveguide. ω_c is the non-relativistic angular cyclotron frequency, ω_c/γ represents the relativistic angular cyclotron frequency, $v_{\|}$ is the axial beam velocity of the gyrating electrons and s is the beam-harmonic mode number. By considering the small Doppler-shift frequency term ($k_{\|} v_{\|}$), ω_c may be expressed, in terms of the background axial magnetic flux density B_0, as:

$$\omega_c = \frac{|e|B_0}{m_0\gamma} \qquad [1.5]$$

where e and m_0 are the electronic charge and rest mass, respectively. The small Doppler shift frequency value makes the angular frequency harmonic dependent, and the operating frequency of the device at the beam harmonic would be reduced by a factor s for the operation of the device at the s^{th} beam harmonic. The dispersion relation for any gyro devices is derived from the wave guide mode line (1.3) and beam mode line (1.4). The wave guide mode line follow the hyperbolic pattern and intersect the angular frequency axis at ω_{cut} , similarly beam mode line follow the straight line with the slop of $v_{\|}$ and cross the angular frequency axis at $s\omega_c/\gamma$.

The dispersion diagram of gyro-twystron is illustrated in Figure1.12, determines the device's operating point or the grazing interaction point or intersection between the beam-mode and the waveguide-mode dispersion characteristics. The gyro-twystron can operate with wideband coalescence between the beam-mode and waveguide-mode dispersion characteristics. However, since the CRM is essentially a Doppler-shift (βv_z) device, corresponding to a larger value of βv_z, it is prone to inhomogeneous broadening of the cyclotron resonance band due to beam velocity spread. To mitigate the effect of electron beam velocity spread on inhomogeneous broadening of the cyclotron resonance band, the Doppler shift kept small. A smaller Doppler shift (βv_z) results in a small frequency mismatch ($\omega_c \overset{\sim}{<} s\omega/\gamma$), which ensures the effective beam wave synchronism during the beam wave interaction process.

The gyro-twystron amplifier has the potential to generate high powers over a wide range of frequencies in the millimeter and sub-millimeter wave band offers a viable solution for many millimeter wave radar systems. As shown in Figure1.13, the gyro-twystron is made up of several sub-assemblies. This includes a magnetron injection gun (MIG) that generates a gyrating beam, an RF input cavity, a drift tube, an interaction region under a strong superconducting magnet, a particle collector, and an output window. The gyrating electron beam emitted from the MIG is phase modulated inside this cavity, and this causes an azimuthal bunching of the electrons as they move through a certain drift length.

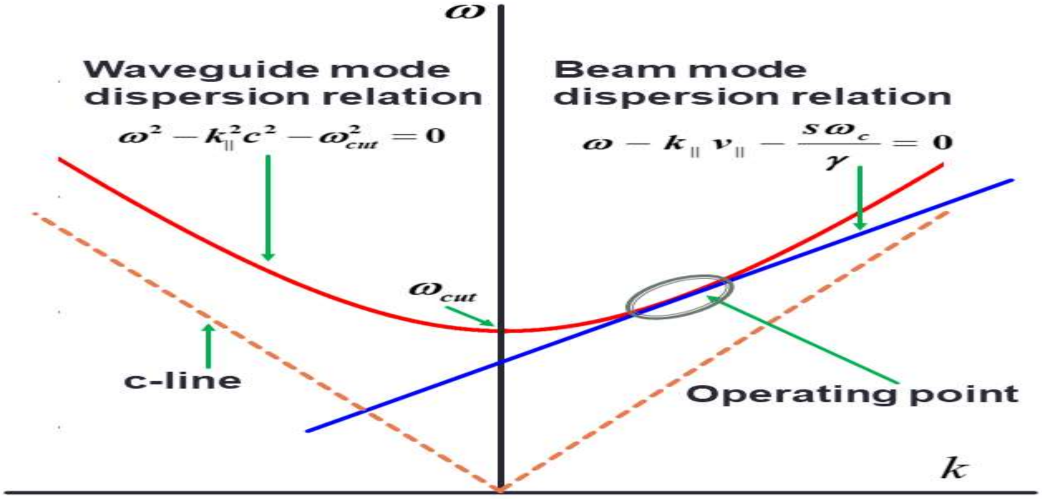

Figure 1. 12. Dispersion diagram of gyro-twystron.

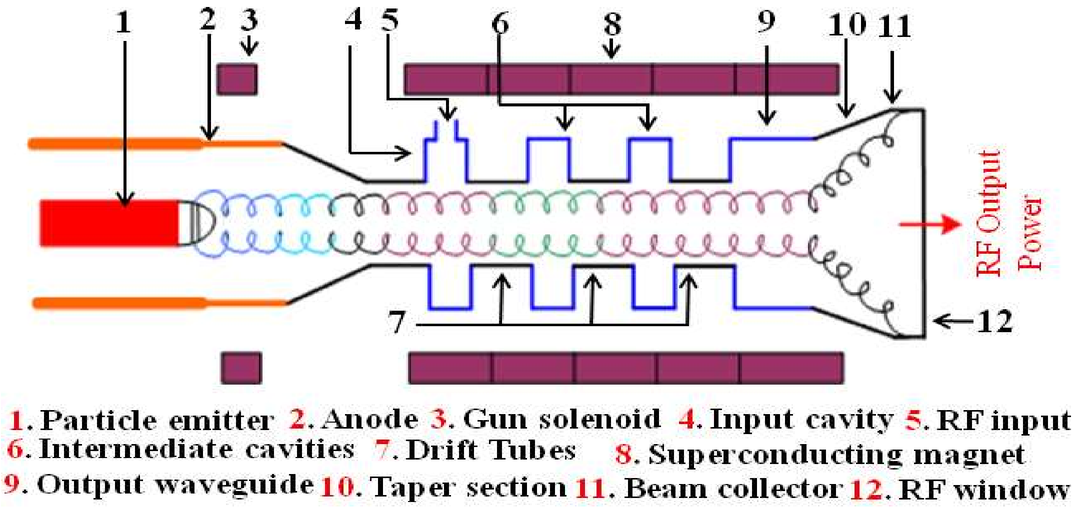

Figure 1. 13. Schematic of gyro-twystron amplifier

After transmitting its energy to the RF wave, the spent electron beam exits the waveguide section and is collected in the collector to extract the remaining energy. The RF power in the *TE* mode is coupled out axially with the help of an output RF window.

1.5.2. Magnetron Injection Gun (MIG)

A magnetron injection gun (MIG) [20], [49],[50], so-named as it resembles a magnetron [20], forms a hollow beam of electrons in helical trajectories in the device. electrons are emitted from an annular strip on the lateral face of the convex thermionic dispenser cathode and are drawn off the cathode at an angle with the tube axis by the potential on the first anode of the MIG into crossed electric and magnetic fields imparting a small rotation of electrons; the non-emitting portion of the cathode of the MIG serves as a focusing electrode. A DC magnetic field, produced by the gun solenoid, is required for focusing the emitted electrons. The second anode of MIG delivers a significant amount of axial energy to the beam. Finally, the beam is subjected to a slowly growing magnetic field or adiabatic compression region, which converts a significant percentage of the beam's axial energy into rotational energy. As the emitted electrons approach the end of the cathode-anode boundary, the electric field lines oriented parallel to the magnetic field lines. Consequently, electrons possess both orbital and axial velocity components. Under the influence of electric and magnetic fields, the emitted electron beams spiral around a fixed guiding center with the guiding radius of r_g and Larmor radius of r_l , Since the larmor radius is small in comparison to the beam radius, the movement of the beam remains annular. The helical beam generated by the MIG is launched into the interaction section under the guidance of a rising magnetic field, where it interacts with the specified TE waveguide mode and transfers its kinetic energy to the RF energy. For the efficient energy tranformation, electron beam gyration should synchronize with RF wave propagation as well as meet the phsysical design expectations of interaction circuit. Various mechnical and electrical parameters such as Larmor radius , guiding centre radius, beam voltage, beam current, pitch factor and velocity spread are optimized accordingly to get the maximum beam-wave interaction efficiency. Various parameters, such as the magnetic compression ratio, down taper dimensions, cathode angle, and cathode-anode gap, are carefully optimised to achieve synchronism between the MIG parameters and the design of the RF interaction section. The schematic diagram of MIG is shown in Fig.1.14. The spent electron beam exits the waveguide section after transmitting its energy to the RF wave and is collected in the collector to extract the remaining energy.

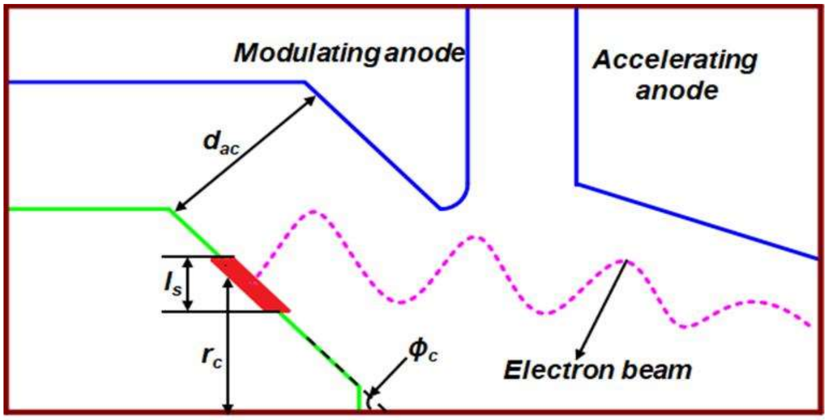

Figure 1. 14. Schematic of Electron Beam Source

1.5.3. RF Interaction Section

The emitted electron enters the RF interaction region of the gyro-twystron amplifier, comprising one or more cavities and an output waveguide. Cavities and waveguides are physically separated by field-free drift areas, providing isolation between the adjacent sections. The gyro-twystron is made up of multi cavities, depending on the design, gain, and output power needs, all of which have different functions. The first cavity is the so-called input cavity, in which a low power RF signal is introduced and interacts with the electron beam through an external driver and after interacting with this mode, the electron beam is phase modulated inside this cavity and these modulated beam experience azimuthal bunching. The physical dimensions of these cavities are depends on the operating mode and resonating frequency and a ring of lossy material is also inserted inside the cavity to reduce its quality factor. The modulated electron beams pass over a specific drift length. The length and the radius of the drift tube is optimized to achieve a sufficient isolation between intermediate cavities as well in between outer cavity and output waveguide. Increasing the number of RF cavities in a in multi cavity gyro- twystron improves bunching and, consequently, device gain. The drift tube is used not only for isolation but also to provide the ballistically bunched electrons at the entrance of the output waveguide section, where the beam wave interaction takes place and the amplified output is extracted. The physical dimensions of the output waveguide section is depends on the operating mode, start oscillation current (SOC) and start oscillation length (SOL).

1.5.4. Beam Collector

After the beam wave interaction, the spent electron beam proceeds to the collector, where a depressed collector system allows some of the remaining energy from the electron beam to be recovered, enhancing total device efficiency. In collector, after the beam wave interaction the kinetic energy of the spent beam is converted into electrical energy [51]. Depending on the required output and the applied voltage, two types of collectors, the undepressed collector and the depressed collector, are employed at the output section to extract the residual energy from the spent electron beam. The undepressed collector, preferred in the axial extraction, is simply a cylindrical waveguide to collect the spent electron beam with collector's potential equal to the body potential of the tube and the energy of these spent electron beams are recovered efficiently in the heat form. In the depressed collector, the beam is collected on a surface where potential is reduced relative to the cathode potential. The remaining kinetic energy of the spent electron beam in the depressed collector is converted into electrical energy, thereby reducing the power consumption of the tube, which would otherwise heat the surface of the collector. In any collector type, the collector design is optimized for the maximum beam collection at the collector wall, and the maximum collector efficiency, as well as loading on the collector surface, is adjusted within limits to avoid the failure of the collector due to metal fatigue. The collector wall can be damaged if there is an excessive amount of heat dissipation on the collector wall; in order to prevent this damage, the dimensions of the collector as well as its heat transfer

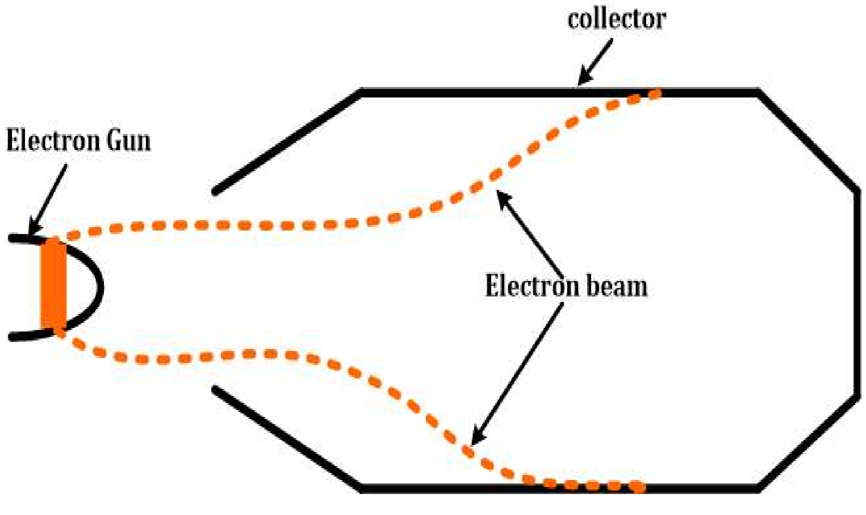

Figure 1. 15. Schematic of Beam Collector System

coefficient is increased. In order to ensure that the collector has a long service life, it is important that it be designed with materials that have a high temperature coefficient and a high fatigue life time. Usually, oxygen-free high conductivity (OFHC) copper is chosen for the gyrotron collector due to its high thermal conductivity. Fig. 1.15 shows the beam collector system.

1.5.5. RF Window

The RF output is coupled out from a region further down the axis of the tube beyond an output window that is vacuum-sealed to the tube [52]. It should withstand the high power, mechanical and thermal stresses, be leak tight, the high thermal conductivity. Microwave windows can be made from a variety of materials, however the material selection is primarily determined by the material's dielectric properties (loss factor or loss tangent). The low loss material is stable over a wide temperature range, allowing the window to perform consistently over a wide temperature range. Ceramics are the most common due to their low losses and great strength. Some of the shortcomings of ceramic materials, such as local impurities and defects, can cause power absorption and breakdown due to thermal stress, limiting their applications. Now

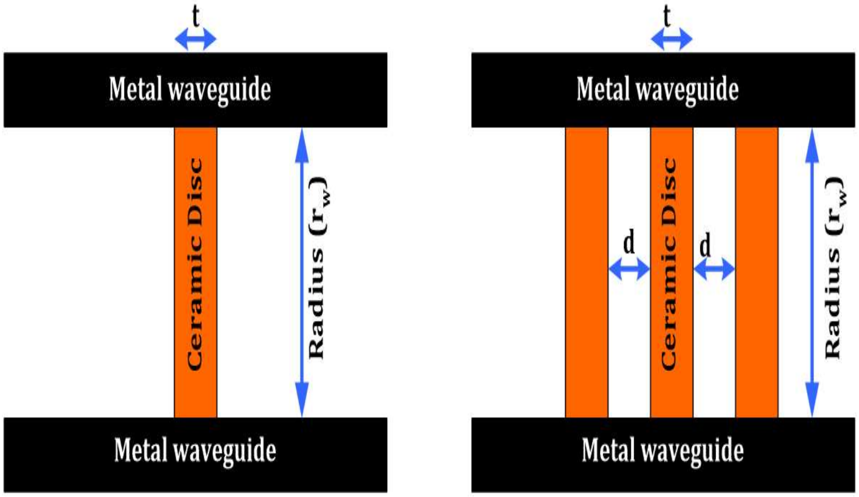

Figure 1. 16. Schematic of single disc and multi disc window.

days CVD diamond windows are found more suitable for higher power applications, but they are costly. The dielectric properties of the window materials, the loss factor ($\tan\delta$), and the relative permittivity (ε_r) are critical features of high power window development since they directly affect power absorption and reflection. The thickness of the dielectric disc (in single disc window) and the separation between the discs (in multidisc window) are optimized for the significant power transmission and least reflection. In multidisc window the separation between the discs are the multiple of half wavelength. In wide band operation, the multidisc window is preferred; however, due to the face cooling mechanism of the multidisc window, there is power loss in the various discs. When power losses are the primary concern, edge-cooled single-disc windows are recommended.

1.6. Advantages and Applications of Gyro-Twystron

The concept of gyro-twystron is mainly derived from its slow wave counterpart *i.e.*, twystron. In twystron an arrangement of cavity and waveguide section is motivated to achieve the optimum performance between klystron and TWT.

1.6.1. Advantages of Gyro-Twystron

Being a hybrid device, twystron have the advantages of both the parent device and thereby possess the unique property of high power-bandwidth product and gain-bandwidth product [53],[54]. The interaction region of the gyro-twystron consists of an RF cavity, then there is a drift region which is followed by a slightly tapered output waveguide. This arrangement mitigates the one the major problem associated with gyro-klystron i.e., breakdown at high powers. For megawatt-class operation, the energy of the RF field localized in the output waveguide of a gyro-twystron may be significantly lower than the microwave energy stored in the high-Q output cavity of a gyro-klystron.

Granatstein et al. proposed that gyro-twystron is suitable for megawatt-class operation [55]. The short output waveguide section, gyro-twystron not only reduces the parasitic instabilities and spurious oscillations but also reduces the deleterious effect of velocity spread as compared to the gyro-TWT. The output waveguide length is critical for the stable operation of a gyro-twystron since the starting current typically scales inversely with the cube of the waveguide length. Similar to gyro-klystron, more than one cavity can be used for bunching which increases device efficiency and gain. Another benefit of the multi-cavity structure is enhanced bandwidth, which is accomplished by tuning various cavities to different resonance frequencies, i.e. stagger tuning. Bandwidth can also be improved by replacing the intermediate cavities with cluster cavities, with the minimum compromise of the gain. The potential need of gyro-twystron research can be understood from the fact it has been successfully developed at Communication & Power Industries (CPI) for the Haystack Ultra wideband Satellite Imaging Radar (HUSIR) Transmitter for U.S. Space Surveillance Network as the highest-resolution space-object-imaging radar in the world [56],[57]. Its principal mission is to collect space-object identification and characterization data in support of space situational awareness. The HUSIR consists of several gyro-twystron (as a high power amplifier), each of which has produced at least 55 kW peak output power at 10% duty factor with a bandwidth in excess of 1.6 GHz [56]. Interestingly, a wide-bandwidth gyro-traveling-wave-tube (TWT) amplifier (as a driver to feed the high power amplifiers) has also been used as the driver for an array of these higher-power gyro-twystron amplifiers. Which clearly states that there is no competition between these two devices and neither of them can be replaced by others, rather they can be used together for such interesting applications.

1.6.2. Applications of Gyro-Twystron

The gyro-twystron hybrid amplifier combines the benefits of gyro-klystron and gyro-TWT into a single device, making it a promising contender for millimeter wave radar applications such as space debris detection, weather monitoring, and asteroid tracking. Furthermore, by reducing the microwave breakdown problem, the gyro-twystron amplifier become a more suitable candidate for particle accelerator applications [55]. However, gyro-twystron also has great potential too, but it received very few research attentions during the past decades, and its claims are limited to RADAR and particle accelerators, which are discussed in detail in next section.

1.6.2.1. Millimeter Wave Radar

Millimeter wave radars are typically designed to target atmospheric windows at 35 GHz and 94 GHz [58]-[60]. Millimeter wave radar is smaller, lighter, and has a narrow beam width, excellent resolution, multipath effects, and anti-jamming capabilities. In addition to high output and broad operating bandwidth, the characteristics of high gain, high efficiency, low noise figure, compactness, and light weight are extremely desirable for a high-performance radar. In 1960s, various conventional twystron tube were developed by Varian for RADAR applications and were successfully commissioned in US AIR force RADAR. A W-band WARLOC radar system [61] was developed at NRL, USA, consisting of a 94 GHz gyro-klystron transmitter that delivered 80 kW of RF power and was used as a research radar to investigate cloud physics in the millimeter wave band. The Italian Space Agency (ASI) have investigated the feasibility of using W-band amplifier for telecommunications experiments under their major projects DAVID (DAta and Video Interactive Distribution), Wave (W-band Analysis and Verification) [62],[63]. In 2006, the National Aeronautics and Space Administration (NASA) also started a mission

‘CloudSat’ to carry a space-ready high-power W-band amplifier operating at 94 GHz to measure the vertical structure of clouds [64]. Space has become increasingly crowded with satellites over the past 50 years of advancements in space technology; as a result, the Haystack Ultra-wideband Satellite Imaging Radar (HUSIR) system was developed to collect space-object identification and characterization data in support of space situational awareness. A 94 GHz gyro-twystron employed in HUSIR system which delivers 50 kW of RF power with the significant power-bandwidth. It is an improvement of 46 kW-GHz [56].

1.6.2.2. Particle Accelerator

To accelerate particles in RF structures, high RF power is required. The RF energy of VEDs is transmitted to particles in particle accelerators, as opposed to the beam-wave interaction process of VEDs, where the beam energy is transferred to the RF wave [55]. Particle accelerators and their variants are used in particle and nuclear physics, material research, and industrial material processing [58]. After CERN's successful large hadron collider (LHC) experiment, the high energy physics community is investigating a super collider electron–positron collision experiment to explore the subatomic universe. The cost of the collider is defined by the number of gyro-amplifiers, and the performance of the gyro-amplifiers is determined by the accelerating gradient, total efficiency, and voltage required to operate the gyro-amplifiers [65]. The University of Maryland created a series of X- and Ku-band gyro-amplifiers to minimize the collider's length and cost. Two different configurations of the gyro-klystron in the fundamental TE_{01} mode and at ~10 GHz provide 24 MW and 27 MW of RF power for the two and three cavity configurations, respectively. Since the output cavity of gyro klystron is susceptible to the microwave breakdown, therefore gyro-twystron amplifier is preferred for Megawatt class operation. Gyro-twystron amplifier operating in TE_{01}

mode delivered 22 MW of RF power at 9.88 GHz and its second harmonic counterpart operating in TE_{02} mode delivers 12 MW of RF power at 19.76 GHz [66], [67]. In 2001, Wilson from University of Maryland, developed a gyro- klystron operating at 91.4 GHz for the 15 TeV-collider which delivered 10 kW RF power with 57 dB gain [68]. A three cavity gyro-klystron operating in Ka band was developed by Wang *et al*., which produces 1.5 MW of RF power with efficiency and gain of 40 % and 35 dB, respectively [69]. According to the literature discussed above, a megawatt class gyro-twystron is a suitable contender for the particle accelerator application and competes with other gyrotron amplifiers.

1.7. Literature Review

1.7.1. Gyro Devices

The discovery of the electron cyclotron resonance maser (ECRM) instability [34] mechanism has encouraged the research community to initiate work on developing a fast wave device based on this principle. Various scientists, including Gaponov [71] from the Russian Academy of Sciences, USSR, Twiss [70] from MIT, USA, Schneider [72] from Duke University, North Carolina, and Zheleznyakov [73] from the Russian Academy of Sciences, USSR, began research on CRM-based devices in the mid-twentieth century and developed the theoretical concepts related to CRM mechanism. A.V. Gapanov et.al. performed an experiment of CRM monotron at Radiophysics Research Institute and generate ~ 190 W RF power in TE_{02} mode with efficiency of 15 % [74] and enhance the efficiency up to 50 % in fundamental mode and 20 % in second harmonics [75]. The International Thermonuclear Experimental Reactor (ITER), one of the world's largest active projects, is aimed at developing a reactor capable of carrying out controlled nuclear fusion, where gyrotrons play a vital role as an RF source with high output power and efficiency. Alikaev et al. have successfully demonstrated the gyrotron as an efficient RF source for plasma heating, which is required in electron cyclotron resonance heating (ECRH) applications [76]. The gyrotron operates in higher order modes having a large transverse dimension, producing high power at high frequency, but this high order mode operation also suffered mode competitions [17],[26]. Waveguide and taper design stimulate spurious mode for long pulse operation, limiting RF power conversion into Gaussian mode. Radial RF power extraction using quasi-optical mode converters avoids spurious mode generation after the interaction cavity [26]. The high power at high frequency level makes the gyro devices (gyro klystron, gyro-TWT, gyro-twystron) an prominent candidate for radar and particle accelerator application [24]-[29]. In 1994, using a two-cavity gyro-klystron operating in the X-band, I. I. Antakov et al. experimental generated 700 kW of RF output power and investigated the impact of cavity length on device efficiency [77]. A two cavity gyro-klystron operating in TE_{02} mode, delivered ~ 260 kW RF power at 35 GHz with the efficiency and gain of 18% and 17 dB, respectively [78]. At NRL a C-band gyro klystron was developed employed the three rectangular cavity and produce the RF output power of ~ 52 kW with the efficiency of 30% and measured bandwidth is 0.4 % [79]. The two cavity gyro klystron operating in Ka band, delivered ~210 kW RF power with the efficiency of 37 % and gain of ~ 24 dB [80], while a three cavity gyro klystron delivered power of 225 kW with 30.3 dB saturated gain and 32% efficiency [81]. Further addition of intermediate cavity enhances the device output and delivered the output power of 208 kW with the saturated gain of 53 dB and efficiency of 33 % [82]. 1999, Blank *et.al.* performed the experimental demonstration of 94 GHz gyro klystron for radar application and obtained 10 kW avg. output power with efficiency and bandwidth of 33 % and 420 MHz [83]. At University of Maryland, a X band gyro klystron was developed for particle accelerator application delivered the 20 MW power with 26 dB gain [84] and the addition of one more intermediate cavity in existing structure can enhance the power to 27 MW with the gain of 34 dB [85].

The gyro-amplifiers required for radar applications must usually be capable of high average power and bandwidth this urge for exploring the various configuration of gyro amplifiers. CRM counterpart of conventional TWT with travelling wave interaction section provided large bandwidth and became a suitable amplifier for RADAR applications [58]. In the early 1970s, the National Research Laboratory (NRL) initiated research on Gyrotron Traveling Wave Tube (Gyro-TWT) amplifiers to explore their ability as a source for various radar applications. At NRL Barnett *et.al.* performed an experiment study of 35 GHz gyro- TWT and obtained 10 kW power with 30 dB gain at 9 A current [86]. In 1981, Varian Associates tested a gyro-TWT using three different sized and configured interaction structures, and obtained 50 kW of RF power with an efficiency of 17% and 6% saturable bandwidth for a loaded waveguide segment [87]. Continuous beam wave interaction in a metallic waveguide induces the operating mode as well as various parasitic modes. Mode competition and instability result from the emergence of these modes. The waveguide's RF propagation engineering has been done to reduce mode competition and increase stability. Various approaches are discussed in order to optimize the interaction structure, reduce the mode competition problem, and increase stability. Several new types of interaction structures have been investigated and classified as mode control, mode filter, and dispersion control technologies [42]. C.H. Du and P.K. Liu, reported that for high-power operation periodic dielectric loading (PDL) is more suitable than uniform dielectric loading (UDL) whereas for low-power applications photonic band gap (PBG) structures are used as a mode filter [82]. It is an oscillation observed in RF power output at high current, and for eliminating this oscillation a distributed loss technique [88] was employed in interaction section to achieve stability, but this technique enhances the bandwidth on the cost of efficiency. As the operating point of the gyro – TWTs are far from the cut off point, its bandwidth is limited by velocity spread also. Denisov *et al.* suggested a novel approach, a helically corrugated waveguide section, and reported an output of ~ 1MW with 20 % efficiency in X band. This novel approach enhances the amplifier's bandwidth by reducing the effect of velocity spread [89]. The losses are distributed over the linear section of the RF interaction circuit as the sever is used in conventional TWT as a lossy section to cut-off the path of the reflective feedback, which suppresses the spurious oscillation and improves the gyro -TWT performance [90]. K.R. Chu, introduced a distributed loss in the interaction structure and obtained 93 kW of RF output power with the bandwidth of 3 GHz, and the efficiency and gain are ~27 % and 30 dB, respectively [44]. A Ka-band gyro-TWT using PDL was developed at NRL by Calame *et al.* that delivered ~ 137 kW of RF output power with the gain of 49 dB and band width of 1.1 GHz [91]. At University of Electronic Science and Technology of China (UESTC), China, Wang *et. al.* experimentally achieved 153 kW RF output power with the bandwidth and gain of 2.3 GHz and 41 dB, respectively in Ku-band, using PDL gyro -TWT [92]. In 2014, Ran *et al.* have introduced the nonuniform dielectric loaded W-band gyro-TWT and obtained the RF output power of 112 kW with the gain and efficiency of ~ 70 dB and ~ 23 % [93]. In 2017, Yong Xu *et.al.* used an additional cutoff waveguide section with the interaction section in Ka band gyro – TWT and reported 20 kW avg. output power with the band width and gain of 3.2 GHz and 52 dB, respectively [94]. A W band gyro -TWT with the optimized electron gun generated the RF output power of ~ 36 kW with the 3 dB bandwidth of 5 GHz [95]. Shou-Xi Xu with his team designed a W band gyro -TWT that generate 100 kW peak RF power with the efficiency of 28 % and band width of 3.2

% [96]. Recently, Liu *et. al.* performed an experiment on W-band dielectric loaded gyro -TWT, and reported the peak power ~160 kW with an efficiency of 16 %. The reported gain and bandwidth are 75 dB and 8.5 GHz, respectively [97]. Furthermore, the research evolution and progress of hybrid amplifier, gyro-twystron amplifier is discussed below.

1.7.2. Gyro-Twystron

A hybrid amplifier was introduced to incorporate the benefits of conventional amplifiers (klystron and TWT) in a single device. It consists of the input cavity section of the klystron and the output waveguide section of the TWT amplifier. In 1962, at University of California, Lichtenberg and his team developed a hybrid tube, i.e. twystron and find an significant enhancement in efficiency, from 20 % to over 35 % [48]. When it comes to improving the performance of the tube, Varian Inc. has put in a lot of research and development. In S-band TWT, a coupled cavity was introduced as a pre-bunching section to provide a well-bunched electron beam for the interaction section (VA-125B). As a result of Varian Inc.'s advancements in tube technology, several linear beam twystron tubes have been developed, and the AN/TPS RADAR of the United States Air Force uses a refined version of this hybrid vacuum amplifier [98]. In 1969, VA-145 series of S-band twystron delivered 2-7 MW of RF power with the bandwidth of 8 % [53] , and VA-146A series of twystron with stagger tuned cavities delivered 5 MW of RF power with a bandwidth of 10 % and efficiency of 40% [54]. In the early 1970s, after seeing the impressive results of the hybrid tube, i.e. twystron, scientists and academicians were very impressed and decided to extend this unique feature to gyro devices and began research on gyro-twistrons. Theoretical studies done by Bratman *et al.* [99] and Moiseev *et.al.* [100] suggested that gyro-twystron with tapered input and output section is an efficient amplifier with some with some restraint. Moreover, studies also suggested that amplification band of CRM-twystron is dependent on the difference between the operating and cut-off frequencies of the output waveguide section [99]],[100]. The first analytical studies of gyro-twystron was made in 1985 by Tran *et al.* by introducing a waveguide section in pre-existing gyro klystron and extend the formalism related to the gyro klystron to the gyro – twystron and developed a self-consistent analytical calculations of field profile and transverse efficiency in a small signal regime [101],[102]. At the University of Maryland, Nusinovich and Li developed the analytical approach for the gyro travelling-wave amplifier (gyro-TWA) [103] and was extended over the generalized theory of relativistic gyro-twystron to study the energy modulation of relativistic electrons in the input cavity and their phase bunching in the drift space [104]. Nusinovich and Li demonstrated the large-signal operation of the gyro-twystron in the output waveguide section for the first and second harmonics to achieve high efficiency. Energy extraction from both the axial and transverse components of electron motion is increased by optimizing the recoil parameter in a gyro-twystron [105]. With the advent of theoretical research, an experimental effort on gyro-twystron was made in 1990s for particle accelerator and RADAR applications at the University of Maryland and NRL, USA, respectively. In 1994, Latham et.al. conducted the first-ever experiment on gyro – twystron, operating in X band, at University of Maryland [66]. The stability of the gyro-twistron is greatly deteriorated due to the occurrence of oscillations in the interaction region [105] and due the spread in gyrating electron beam motion [106]. The deleterious effects of velocity spread on the amplifiers performance is increased for Doppler up shifted operation, and this effect is offset by a large beam current [66]. The first-ever experiment of gyro-twystron with single cavity operating in TE_{01} mode generated 21 MW of RF output power with 22 % conversion efficiency, and 24 dB gain [66]. Further research on experimental gyro-twystron was conducted in order to optimise performance metrics and investigate the effects of parasitic modes and velocity spread. The performance of the gryro-twystron is depends on various parameter like, beam voltage, beam current, applied magnetic field, spread in electron beam, ratio of the beam velocity components, length of the interaction circuit, and beam bunching, to obtain the maximum output these parameters need optimization [107]. With the introduction of advanced electron beam sources, such as MIG, which generate gyrating beams with low velocity dispersion, resulting in an effective beam-wave interaction, as well as reducing reflections from the window due to the high pitch factor, which allows for a reduction in oscillations and an increase in amplifier efficiency [108]. The harmonic version of X-band gyro-twystron , operating in TE_{02} mode is suffered with spurious oscillation delivered ~12 MW power with 11% efficiency and 21 dB gain [109]. Malouf *et al.* discussed the design methodology of C-band gyro-twystron for the radar applications and analytically obtained an output power of 60 kW with an efficiency and gain of 22.5 % and 22 dB, respectively [110]. Parametric analysis of C-band gyro-twystron has been suggested that the bandwidth is independent of the length of the drift tube; however, the efficiency and gain are increased with the length of the drift tube [110]. In 1994, Nusinovich *et al.* have developed the mathematical model of beam-wave interaction in mixed geometry three stage gyro-twystron and reported an output power of 55 kW with the gain of 26 dB and a bandwidth of 6 %. [111] The analytical performance of this mixed geometry gyro-twystron is confirmed with the experiment that delivered 46 kW of RF output power with an efficiency of 23 % and a gain of 37 dB [112]. These analytical studies of the gyro-twystron predicted the significant improvement in the gain-bandwidth product as well as predicted transverse efficiency of gyro-twystron is close to the gyro-klystron near/below unity pitch factor [113]. In 1998, Perry M. Malouf and G. S. Nusinovich have patented the crosspolarized mixed geometry gyro-twystron amplifier, consist of tunable rectangular cavities followed by cylindrical output section [113]. At NRL, Blank et al. used the time-dependent MAGYKL code to investigate three different configurations of the three-stage gyro-twystron, and this analytical finding was also experimentally validated. For a beam parameter of $I_b = 1A$ and $V_b = 16$ kV, this experiment generates 4.4 kW of RF output power with 1.6% bandwidth [114]. The quality factor of the output waveguide limits one of the amplifier's major outputs, bandwidth. However, in the case of high velocity propagation, the bandwidth is primarily limited by the beam quality [114]. The development of high power gyrotron amplifiers at 35 GHz and 94 GHz is encouraged by the relatively low attenuation in these frequency ranges, which opens up a window for communications. The theoretical studies of multi-cavity gyro-twystron, operating in 35 GHz band, is focused on the stability analysis at a high value of the beam velocity pitch factor [115]. The analytical study of three stage Ka band gyro-twystron operating in TE11 delivered 90 kW with a gain of 55 dB. The stagger tuned cavities used in the multi-cavity Ka band give the 0.7 GHz bandwidth, and the magnetic tapering enhances the efficiency from 33 % to 43 % [115].

The gyro-amplifiers required for radar applications must usually be capable of high average power and bandwidth. This urge for wide bandwidth led to exploring various methods to improve the device output performance. Thus, considerable research is being conducted on developing various approaches for increasing the device's bandwidth. There are two basic strategies used for bandwidth enhancement. The first way is stagger tuning [116] and the other one is cluster cavity [117]. These band width enhancement methods are commonly used in cavity-based gyro amplifiers to increase bandwidth at the expense of gain decrement. The effect of stagger tuning on the various design of GKL was carried out University of Maryland and Naval Research Laboratory

(NRL) [116],[117],[118]. Nusinovich and Chen et al. have explored the linear and nonlinear theories associated with staggered tuned gyro-twystron, and have observed a substantial improvement in bandwidth and gain-bandwidth product in contrast to synchronous tuning [118], [119]. The nonlinear formalism that was developed using the point gap model suggested that the bandwidth in the two cavity pre-bunching section is 1.65 times larger than that in the case of one pre-bunching section. Additionally, it was observed that the bandwidth is decreased above the optimal value of the bunching parameter [118],[119]. At NRL, Blank et al. conducted an experimental study of a W band stagger tuned multi cavity gyro-twystron. With a bandwidth of 925 MHz, this multi-cavity gyro-twystron produced 50 kW of RF output power. The electronic efficiency and gain for a beam parameter of 57 kV, 6 A, and velocity propagation of 9.0% are 17.5% and 30 dB, respectively [120]. The analytical calculations of the W-band gyro-twistron predicted 80 kW RF power with a bandwidth of 1.4 GHz with an optimised MIG of 4% velocity spread [121]. In 2002, Blank et al. published a review on gyrotron amplifiers and for the five cavity stagger tuned gyro-twystron, analytically obtained ~ 50 kW RF power with the bandwidth of ~ 1.8 GHz [122]. Ngogang et al. investigated the effect of large amplitude signal on relativistic electron beam for gyro-twystron and gyro-TWT amplifiers and found cyclotron resonance overlapping at different harmonics [123]. This study observed that the pre-bunched electron beam excited the waves at the output waveguide section, which carries signal frequency harmonics, making gyro-twystron operation more susceptible to cyclotron harmonic overlap.

1.8. Motivation for Gyro-Twystron

An urge to fill up the millimetre-wave technology gap in the high-power regime, where a large number of civilian and military applications exist, has led to extensive research and development activities in fast-wave gyro-sources and amplifiers. Although some gyro-amplifiers, namely, the gyro klystron and gyro -TWT is available for applications such as in mm-wave radars, communications, and plasma heating applications. Efforts have been made to improve the performance of gyro-klystron and gyro-TWT amplifiers, and this has led to the current state of the gyro-twystron, which is the result of a structural reformation that forms a trade-off between the two types of amplifiers. In comparison to gyro-klystron, the short output waveguide section of gyro-twystron increases the bandwidth and mitigates the microwave breakdown problem. This short interaction section, when compared to the gyro-TWT, also reduces parasitic instabilities and spurious oscillations. It also mitigates the deleterious repercussions of velocity spread. Despite its potential advantages over gyro-klystron and gyro-TWT, research on gyro-twystron is limited, leaving many issues unaddressed. The gyro-twystron solved the microwave breakdown problem of the gyro klystron by replacing an output cavity with a travelling wave section, but it also inherited the parasitic instability and backward wave oscillation problems of the gyro-TWT. Backward wave oscillation is generated by a number of distinct feedback mechanisms, and it is also caused by an absolute instability when the waveguide length cross the start oscillation length (SOL). Overlapping of neighbouring cyclotron harmonics in the RF output power occurs due to the large drive power causing the generation of sporous oscillations. Gyro-twystron is a strong choice for various radar applications that necessitate a wide bandwidth. This urge for increased device bandwidth led to the investigation of various methods, including the stagger tuning technique and the cluster cavity approach. Since the gyro-twystron is a hybrid device that utilizes both cavities and waveguide, the two methods of increasing the device's bandwidth; stagger tunning and cluster cavity, are perfectly applicable to it.

However, the gyro-twystron has excellent potential. it is observed that it is the least investigated (theoretically and experimentally) member of the gyrotron family. Most of the reported literature on gyro-twystron is focused on experimental results, and various design issues of gyro-twystron remain unanswered. Thus, theoretical studies, such as the design and simulation of gyro-twystron amplifier, are necessary to reach its full potential.

1.9. Outline of the Thesis

In this study, we employ nonlinear theories and the 3D PIC simulation code CST studio suite to design and simulate the millimeter-wave gyro-twystron amplifier. The dimensions of the interaction structure and the beam parameters of the gyro-twystron are established through a systematic design methodology. Stagger tuning and the cluster cavity approach have been studied in depth as methods for increasing the bandwidth. The 3D RF wave propagation study validates the design calculation. Subassemblies like the electron beam source (MIG), beam collector, and RF window are designed, modelled, and simulated to solve the problem of integration with the interaction structure.

The present thesis is structured into six chapters and chapter organization is given, as follows.

Chapter 1 is an introduction of the fundamentals of microwave tubes and the classification of the microwave tubes. The development and limitations of conventional tubes, along with the fast-wave microwave tubes, have been reviewed, and their applications have been discussed. The evolution of gyro devices, such as gyro oscillators and gyro amplifiers, is discussed, as well as their scope and limitations. A detailed literature review is conducted on the principles and development of various gyro amplifiers. As a result, the gyro-twystron amplifier outperforms other gyro-amplifiers as a superior RF source for RADARs and particle accelerators. The problems that exist in the current state-of-the-art gyro-twystron amplifier are studied, in addition to the solutions to those problems.

Chapter 2 contains an explanation of the theory related to the stagger-tuned gyro-twystron. The methodology for the design of conventional gyro-twystron has been developed, and a comprehensive study of the stagger tuning approach, which use the self-consistent nonlinear theory, has been carried out. The nonlinear theory of the gyro-twystron is used for the beam-wave interaction study, and the electrical and physical parameters of the device are decided based on that. A generalized analytical approach for stagger-tuned gyro-twystron is developed and successfully implemented for its bandwidth enhancement as well as for an analysis of the trade-off in between in gain bandwidth that resulted from changes in a different parameter. The analytical results obtained in this chapter are validated through PIC simulation results.

Chapter 3 is discussed about the beam-wave interaction behaviour of a millimetre wave stagger tuned gyro-twystron, using a 3D Particle In Cell (PIC) simulation. The individual sub-assemblies of gyro-twystron like single anode MIG, Collector and output window are also designed and simulated to ensure the favorable propagation. To illustrate the physics of beam-wave interaction in a hybrid RF structure, the PIC solver evaluates the RF power, efficiency, gain, operating frequency, and other parameters. The 3D simulation results of RF propagation characteristics are validated against the available published results and the results obtained with analytical theory discussed in chapter 2.

Chapter 4 discusses the design and simulation of a periodic dielectric loaded gyro-twystron to eliminate the sporous oscillation in interaction section. Self-consistent, nonlinear, multimode theory is used to analyse the beam wave interaction**.** The procedure for designing a periodic dielectric waveguide that operates in the desired mode and frequency is presented. The design of the MIG has been improved to triode (double anode) MIG, which allow more parameter space to control the velocity ratio and velocity spread in the electron beam. A single-stage depressed collector is also designed to recover the spent beam energy which in turns increases the efficiency of the gyro-twystron. A double-disk window is designed and simulated for the wideband transmission of the output signal.

In chapter 5, the performance of a W-band gyro-twystron amplifier is improved in terms of bandwidth using the device configuration known as a clustered-cavity. Firstly, a generalized analytical approach for clustered-cavity gyro-twystron is developed and successfully implemented on the three-cavity gyro-twystron amplifier for its bandwidth enhancement. The analytical results obtained are also validated through PIC simulation results.

In Chapter 6, a conclusion is structured based on the works done in previous chapters. The limitations of the present study are discussed to bring out the possibilities for future work. The technical contribution of the present thesis would fill the research gap in gyro-twystron and address the operational issue of gyro-twystron development at a higher frequency.

1.10. Conclusion

In the present chapter, the work embodied in the present thesis is outlined. The finding of the present chapter is as following:

- Basics of conventional microwave tubes, along with the gyrotron devices like gyro oscillators and gyro amplifiers, have been briefly discussed.
- Available Literature of the gyro-twystron amplifier is reviewed rigorously with its scope, limitations, and performance enhancement schemes.

- The physics and design methodology of gyro-twystron have been studied with the subassemblies and critical elements.
- Different configurations of the device for its performance improvement are also highlighted.
- The advantages of this hybrid gyro-amplifier have been discussed, which leads to the various applications, and gyro-twystron is an attractive VED amplifier for RADAR and particle accelerator.
- The problems identified on going through the literature survey are taken into consideration as a research objective in the present work.