

CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

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1.1. Introduction

Microwaves are a form of electromagnetic radiation with frequencies between 300 MHz (0.3 GHz) and 300 GHz and wavelengths from one meter to one millimetre. Microwave and millimetre wave frequencies are now ubiquitous in almost every part of our lives, from microwave ovens in the kitchen to electronic warfare (EFW) systems on the battlefield. Microwaves have an unrivalled position in the electromagnetic spectrum; although these radiations are not visible, their impact on our society is immense. These radiations have many applications in communication, radar, electronic warfare, missile tracking and guidance, remote sensing, industrial heating, cooking, material processing, hyperthermia, waste remediation, direct energy weaponry (DEW) using high-power microwave (HPM), plasma Heating for controlled thermonuclear energy research, atmospheric purification of freons, ozone production, advanced electron accelerators in high energy physics research, satellite power station etc. [1], [2], [3], [4]. Since there are so many uses of millimetre and sub-millimetre waves, researchers are concentrating on creating new devices that can function in these frequency ranges. Solid-state devices can be used for several cost-effective microwave applications. However, they are unable to offer higher powers at frequencies above a particular threshold [4], [5]. However, there are a number of applications that need high powers in various microwave spectrum zones, such as industrial heating, plasma heating in experimental Tokamaks and Stellarators, millimetre wave radars, and spectroscopy [6].

Microwave tubes (also known as Vacuum Electron beam Devices (VED)) are the only option capable of delivering high power in microwave frequency ranges. Conventional microwave tubes such as klystron, TWT, and Magnetron are used for signal production and amplification at microwave and millimetre frequencies [6]. These devices can overcome the disadvantages of conventional electron tubes' high-frequency

performance caused by the effects of lead inductance, inter-electrode capacitance, electron transit time between electrodes, and gain-bandwidth product limit. Traditional microwave tubes, promising to supply a few hundred kilowatts of CW power at frequencies below 1 GHz, showed little promise for working at higher frequencies while providing higher powers. The primary limitation of these classic microwave tubes is the drastic reduction in interaction structure dimensions with increasing frequency. As a result, attempting to increase the operating frequency of standard microwave tubes to the millimeter and submillimeter wave frequencies, where intriguing phenomena and applications exist, limits the output power. Major power limiting factors are DC power dissipation, RF losses, attainable electron current density, heat transfer (restricting the average power capability), material breakdown (arcing) (limiting the peak power capability), and also technological constraints in fabricating the tiny parts. An alternative to reach the millimeter and submillimeter wave frequency range is to lower the operating frequency of quantum-mechanical optical devices [9]. However, any attempt to reduce the operating frequency of quantum optical devices, such as lasers, will not only reduce the energy of each quantum, but also reduce the power available from these devices, making the viability of population inversion difficult. Hence there is a technology gap in the generation and amplification of millimeter and submillimeter waves.

However, there are many applications in the millimeter and submillimeter wave frequency range that have led to interesting research and development activities over the past few decades in an attempt to bridge this technology gap between microwave and optical frequencies. Some of these applications are high resolution radar and high information density communication, deep space and satellite communication, advanced high gradient RF linear accelerators, plasma diagnostics, power beaming, and electron

cyclotron resonance (ECR) heating of fusion plasmas, radar and imaging in atmospheric and planetary science and spectroscopy. For instance, millimeter wave communication systems, like optical communication systems, benefit from features like better information density transmission with improved directivity and efficiency, removal of multipath effects, improvement in clutter rejection, and jamming resistance. In contrast to optical communication systems, millimeter wave communication systems do not experience the issues associated with power absorption by clouds, fog, rain, haze, or smoke. Because of this, millimeter wave devices will be in high demand for these communication systems. In particular, microwave tubes can offer high output power, which is important given that the attenuation coefficient of the atmosphere increases typically with frequency [7]-[13].

In an effort to bridge the technological gap in the implementation of high-power millimeter and sub-millimeter wave devices, microwave tube research activities have turned from the traditional slow wave regime to the fast wave regime. Due to the development of superconducting magnets capable of producing a few tens of Tesla of magnetic field and the efforts of earlier researchers on fundamentals, several fast wave devices have been created. In the mid-1960s, Russia developed the earliest prototype of the gyrotron based on ideas studied in the late 1950s on the generation of microwaves via electron cyclotron resonance maser instabilities. In the subsequent decades, fast wave gyro devices have gained momentum and developed analytically and experimentally [10], [11]. Fast wave devices use smooth waveguides or massive overmoded resonators as interaction structures, as contrast to slow wave tubes, which use spatially periodic interaction structures. The size of fast wave structures does not decrease with frequency as much as slow wave structures [13]. As a result, a fast wave tube typically has a substantially greater interaction volume than a slow wave tube,

allowing for higher power operation. Furthermore, in slow wave tubes, an electron beam must be placed close to the interaction structure, whereas in fast wave devices, the beam can be placed further from where the field is focused. This alleviates the problem of high-power electron beam interception by the interaction structure in fast wave devices [9]-[13]. The majority of current fast wave device development is inspired by their slow wave counterparts, such as gyrotron development being inspired by monotron, gyro-klystron, and gyro-TWT being motivated by klystron and travelling wave tube (TWT), respectively, and gyro-BWO oscillator being inspired by backward wave oscillator (BWO). The basic principle of VEDs is briefly explored in the next section.

1.2. Classification of Microwave Tube

The basic working principle of all microwave tubes or VEDs is to convert electron kinetic energy into electromagnetic wave energy. Generally, microwave tubes comprise the following essential components: an electron gun, input coupler, RF interaction circuit, collector, and RF output window. An electron gun is intended for the generation of a high-quality electron beam, which traverses through an RF interaction circuit, where the electromagnetic wave interacts with an electron beam. A highly pressurized vacuum environment is maintained in the interaction circuit so that the motion of electrons is not disturbed by the ionized charge particles. During the interaction process, the electron beam gives its energy to the RF wave, and the spent electron beam is collected by the collector. The design of the collector is crucial since it is directly related to efficiency. Depressed collector techniques of single-stage and multi-stage are developed to increase the overall efficiency of the tube. The generalized schematic of the microwave tube is shown in Fig. 1.1

In the literature, microwave tubes have been categorized in various ways based on the mechanism of converting spontaneous radiation from individual electrons into coherent radiation by bunching the electrons in the proper phase concerning the RF wave by adjusting the beam, magnetic field, and interaction structure parameters.

1.2. (a) O-type Tubes (Linear beam devices) and M-type tubes (Cross field devices)

In O-type tubes (O is the acronym of TPO standing for *tubes à propagation des-ondes*) motion of the electron beam is parallel to the direction of the external DC magnetic field. This external DC magnetic field is responsible only for focusing of the electron beam and it won't involve in beam wave interaction. Before entering into the interaction circuit the electron receives its potential energy from the applied DC potential and this potential energy is converted to the kinetic energy once the electron beam starts to travel along the interaction circuit. RF electric field which is supported by the interaction circuit interacts with the electron beam and modulates its velocity. In this type of devices kinetic energy of the electron beam is converted to the RF energy. Conventional klystron, TWT belongs to this category [3], [4] [7].

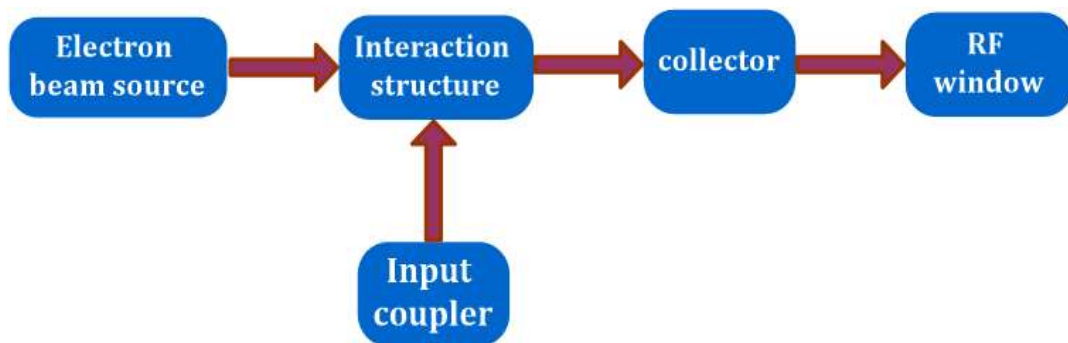


Fig. 1. 1. Basic block diagram of microwave tube.

In M- type tubes (M is the acronym of TPOM standing for *tubes à propagation des ondes à champs magnetique*) electron beam traverses in the direction perpendicular to

both DC electric and magnetic field. In these devices applied DC magnetic field involves in the beam wave interaction mechanism. In this type of devices potential energy of the electron beam is converted to the RF energy. M-Type devices are comparatively more efficient than O-Type devices. Magnetron, Cross Field Amplifiers (CFA'S) are the some examples of M-type tubes [3], [4] [7].

1.2. (b) Slow wave and Fast wave devices

In slow wave devices phase velocity of the RF which is supported by the external interaction circuit is approximately equal to the velocity of the electron beam. Since the phase velocity of RF signal in a two wire transmission line is approximately equal to the speed of the light we need slow wave structures like reentrant cavities, helical structures to slow down the phase velocity of the RF signal. Dimensions of these slow wave structures are highly dependent on the frequency of RF signal. This poses the severe drawback on the slow wave devices when they are aimed to use at higher ranges of frequency and power. Klystron, TWT, Magnetron, CFA's belong to this category.

Fast wave devices were developed in order to overcome the draw backs of the slow wave devices. In these devices interaction mechanism is such that it allows phase velocity of RF to be near to the speed of light. So there is no effort needed to slow down the phase velocity of RF signal. Over moded structures like smooth cylindrical waveguide or cavity are used as the interaction circuit in fast wave devices. The main advantage of this is that the size of the interaction circuit is feasible even for high frequencies, which is not possible in slow wave devices. Due to this the power handling capability of the device also increases. The basic fast-wave devices include- ubitron, peniotron, free electron laser and gyro-devices. Gyro devices work on the principle of Cyclotron Resonance Maser (CRM) instability. Among all fast wave devices gyro devices have a considerable interest and development due to its high efficiency and

simplicity in structure. In ubitron, an electron beam is undulated by a periodic magnetic field and is passed through a waveguide containing a TE- mode electromagnetic wave. If the beam velocity is adjusted so that beam is synchronous with the wave, the beam can give up energy to the wave and produce amplification. In peniotron, a thin hollow electron beam is immersed in an axial magnetic field and that travels through a waveguide structure having ridges to concentrate the electric field near electron orbits. Free Electron Laser (FEL) is involved with the principle of stimulated emissions of photons by free electrons in wiggler. It uses a relativistic electron beam which moves freely through a magnetic circuit and hence produces the coherent radiation. Researchers are not interested in FEL due to its very poor efficiency (less than 5%), more over for the operation of FEL we need a high quality electron beam which is very difficult to manufacture [2]-[8].

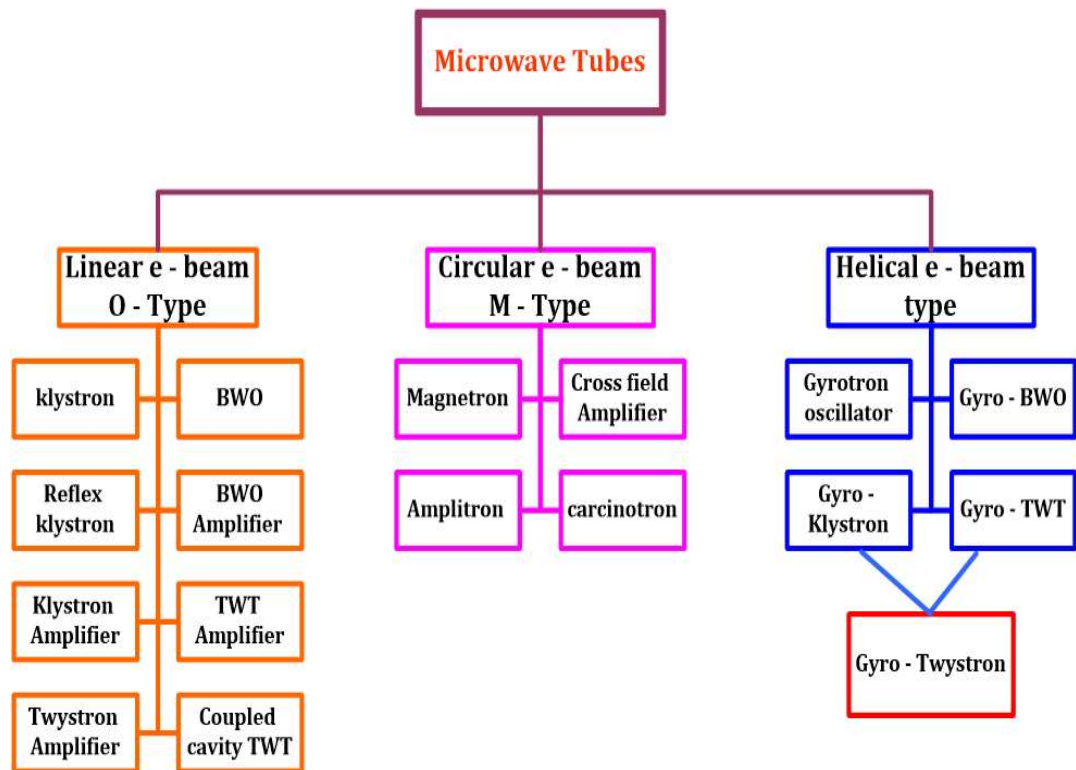


Fig. 1. 2. Clasification of microwave tubes.

1.2. (c) Cerenkov radiation, transition radiation, and bremsstrahlung radiation type devices

In Cerenkov radiation type devices phase velocity of RF wave in the medium is less than the speed of the electron beam in that medium. Conventional TWT is a popular example of Cerenkov radiation type device. In transition radiation type devices, electron beam traverses in a 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 devices, radiation occurs when electrons undergo an acceleration or deceleration in an electric or magnetic field. Typically in these devices the motion of electrons is oscillatory in nature. The electrons radiate coherent electromagnetic radiation when the Doppler-shifted frequency of the EM wave coincides with the oscillation frequency of the electrons or with one of its harmonics. Gyro devices, Ubitron, Peniotron, Vircator are the examples of bremsstrahlung type devices [6]-[16]. In Fig. 1.2, the various classifications of microwave tubes are summarized.

1.3. Overview of Gyro Devices

The basic purpose of the interaction structure is to support the electromagnetic waves for interaction with the electron beam from which energy can be extracted in the microwave tubes. In order to handle high power this interaction structure should be of larger size. It is well known, the transverse dimensions of the conventional slow-wave microwave tubes like klystron and TWT scale inversely with an increase in the operating frequencies. Due to this reason, the power handling capability of these devices reduces at millimeter and sub-millimeter frequencies. Hence, with the increasing operating frequency of conventional microwave tubes, the RF output power decreases 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 sub-millimeter wave regions, for instance, fast-wave devices like gyrotron based on the cyclotron resonance maser (CRM) instability. In a fast-wave device, an electron beam moving in helical trajectories interacts with the azimuthal component of circularly polarized RF electric field supported by a waveguide structure, like, a cylindrical waveguide or cavity in the fast-wave regime [5]- [16].

1.3.1. Principle of Operation

The operation of gyro devices is based on cyclotron resonance maser (CRM) instability. The origin of the concept of CRM instability for the generation of electromagnetic waves traces back to the late 1950's owing to the efforts of the investigators in different countries, for instance, Richard Twiss in Australia [17], Jorgen Schneider in the USA [18] and Andrei Gaponov in Russia [19]. The existence of interactions based on CRM instability was verified by the early experiments of Hirshfield [20]. A schematic diagram of cyclotron resonance maser (CRM) instability based gyrotron device is shown in figure 1.3. In gyro devices unlike in the conventional microwave tubes it is the transverse kinetic energy, rather than the axial kinetic energy that is converted into RF energy. For radiated energy from the relativistic gyrating electrons to be coherent, it is necessary that the contributions from electrons reinforce the originally emitted radiation, if the device is an oscillator, or augment the incident electromagnetic wave, if the device is configured as an amplifier. This condition is satisfied, if a bunching mechanism exists to create electron density variations of sizes comparable to wavelengths of the imposed electromagnetic energy [16]. The bunching in a gyro device is based on the relativistic dependence of mass of gyrating electrons, and hence that of their cyclotron frequency. Bunching is achieved because, as an

electron lose energy, its relativistic mass decreases and it thus gyrates faster. The consequence is that a small amplitude of electric field of the wave, while extracting energy from the electrons, causes the electrons to be bunched in gyration phase and thus reinforces the existing field amplitude [16].

1.3.2. Cyclotron Resonance Maser (CRM) Principle

The electron cyclotron interaction was first found as a quantum mechanical effect of the coherent emission and absorption of radiation. Subsequently, it was given

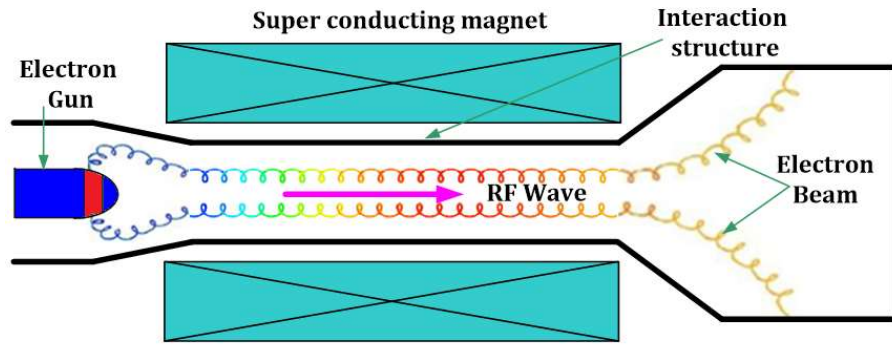


Fig. 1. 3. Schematic diagram of a cyclotron resonance maser (CRM) principle.

the name gyrotron ECM (which stands for "electron cyclotron maser") or CRM (which stands for "cyclotron resonance maser") instability [16]. The cyclotron resonance maser (CMR) instability is the mechanism responsible for the energy transfer from an electron beam to an Electromagnetic wave in gyro devices. It initiates from the electron cyclotron frequency's relativistic dependence on energy [9], [21].

$$\Omega_c = \frac{eB_0}{\gamma m_e} \quad (1.1)$$

$$\gamma = 1 + \frac{eV_b}{m_e c^2} = 1 + \frac{V_b(kV)}{511} \quad (1.2)$$

where e is the electron charge, B_0 is the constant magnetic field, m_e is the electron rest mass, V_b and c are the beam voltage and speed of light, respectively. The mechanism of CRM instability is depicted in Fig. 1.4. Figure 1.4 (a) displays a cross section view of

gyrating electron beams passing through a CRM system in TE_{0n} waveguide mode while being influenced by a DC magnetic field (B_0). In the presence of the transverse field of the waveguide as it begins to move through the interaction space, electrons experience a force that causes some of them to accelerate and others to decelerate or remain undisturbed, with respect to the relative phase of the electric field. This causes the phase velocity modulation of the electrons. Due to relativistic dependence, the accelerated electrons gyrate slower as their energy increases (i.e. Ω_c decreases, γ increases), while the decelerated electrons gyrate faster, as their energy decreases (i.e. Ω_c increases, γ decreases). This process repeats the electrons get bunched in phase in their cyclotron orbits [22], known as phase bunching.

To understand the phase bunching process, let us consider one orbit case with electrons having zero axial velocity ($v_{\parallel} = 0$). The electrons moving in a single orbit are shown in Fig 1.4 (b). Initially, electrons are equally distributed in the circular orbit all over the phase $(0, 2\pi)$, and it is assumed that the electrons are moving in a counter-clockwise direction. In the presence of the transverse RF field inside the RF interaction waveguide in the TE mode, the electrons will be accelerated or decelerated. The electrons 2, 3, and 4 are moving opposite to the E field direction; hence they are accelerated, causing an increase in the relativistic mass factor of the electron and a decrease in the relativistic electron cyclotron frequency and thus an increase in the time period of gyration of the electron, while electrons 6, 7, and 8 are moving in the direction of the electric field; hence they are decelerated, causing a decrease in the relativistic mass factor of the electron and an increase in the relativistic electron cyclotron frequency and therefore a decrease in the time period of gyration of the electron. The electrons 1 and 5 remain undisturbed due to the vanishing electric force on these

electrons. After a few cycles of cyclotron motion, electrons that gain energy lag in phase while electrons that lose energy advance in phase, resulting in phase bunching. If the interaction mode frequency and the electron cyclotron frequency are the same, the electrons will continue to bunch until they reach a zero-field phase point. One can only draw power from these bunched electrons when they are bunched at the maximal field strength. This can be accomplished by slightly detuning the axial static magnetic field to drop the cyclotron frequency below the RF frequency. When this condition is met, bunches begin to move in phase with the RF electric field, and their transverse kinetic energy is transferred to the interacting TE mode RF wave [4], [5], [22], [23].

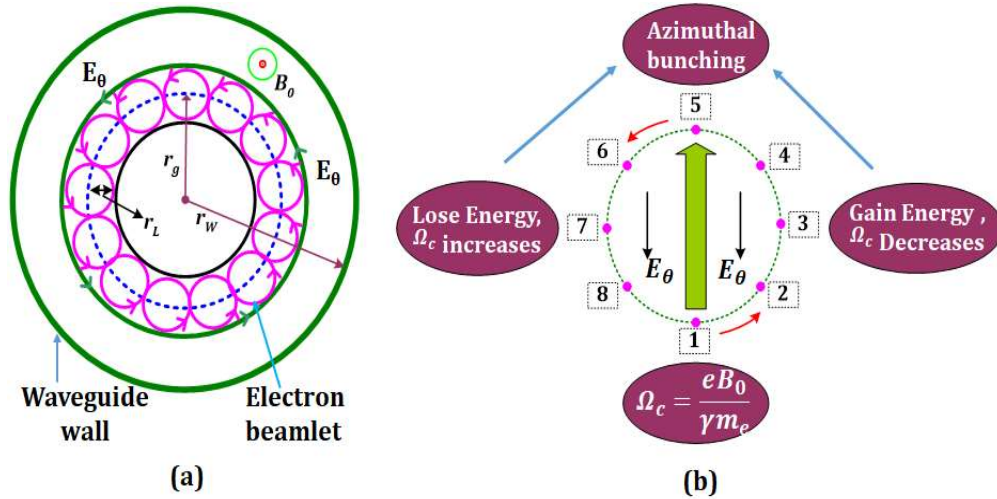


Fig. 1. 4. Schematic description of (a) TE_{0n} waveguide mode and electron beamlets in waveguide and (b) Electron phase bunching in gyro devices.

1.4. Types of Gyro Devices

Gyro-devices are one of the most popular fast-wave high-power devices. These devices can produce high output power in the high-frequency regime, surpassing the output power of conventional slow-wave microwave tubes. Since the introduction of the cyclotron-resonance maser (CRM) instability principle, a considerable proportion of research has been conducted, and many gyro devices have been developed. Gyro

devices are mainly divided into two types (i) Gyro Oscillators and (ii) Gyro Amplifiers. Gyro oscillators generate electromagnetic radiation through self-excited oscillations or a noise signal—gyro amplifiers, in which some external microwave signal is required to amplify the electromagnetic radiation. The complete family of gyro-devices as shown in Fig. 1.5. Gyro devices have found applications in areas like, high resolution imaging radars, high density communication systems, particle acceleration, materials characterization, plasma heating and solid state diagnostics, tracking of space substances, linear colliders, power beaming and electron cyclotron resonance heating of fusion plasmas, etc.

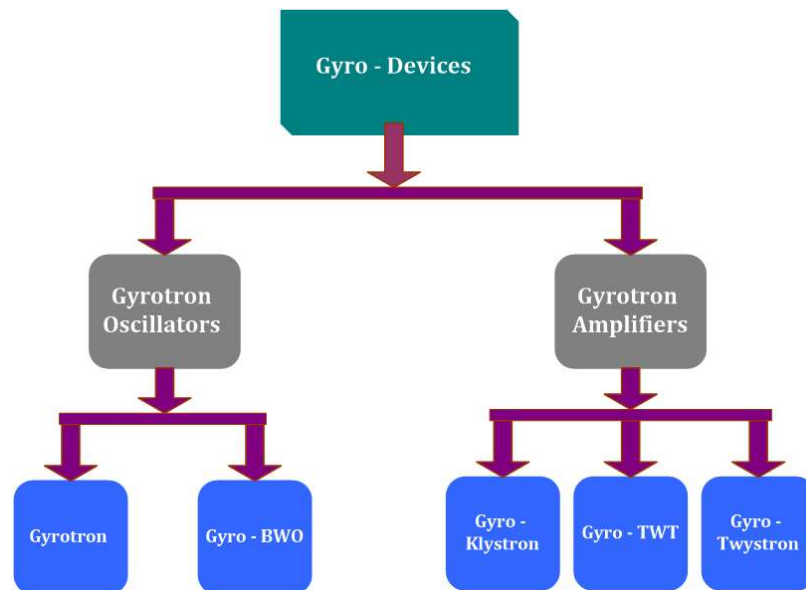


Fig. 1. 5. Family tree diagram of gyro devices

1.4.1. Gyro Oscillators

Gyrotron oscillators include devices such as the gyro-monotron and the gyrotron backward wave oscillator as shown in Fig. 1.6. They can generate electromagnetic radiation by using the localized interaction or the local cavity interaction. Amongst all the gyro-devices, the gyrotron, which is a high power oscillator in the millimeter and sub-millimeter wave range, has been matured both analytically and experimentally

Gyrotron (also known as gyro-monotron) is a high power and high frequency source, which was the first device to be invented in the category of gyro devices (Fig. 1.6 (a)). In this device the interaction circuit is a smooth wall cylindrical cavity where standing waves formed so that interaction with electron beam can take place. The resonant cylindrical cavity is bounded by a down-taper at the input side and an up-taper at the output side. The down-taper works to prevent the EM power from leaking toward the electron gun region, up-taper kept at the other end is used for RF energy extraction. The radius of the cavity is dependent on the mode of the electromagnetic field with which the beam is proposed to interact. The radius is also dependant on whether or not operation with a harmonic of cyclotron frequency is required. 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 [24], [25], for nuclear fusion [26], [27].

Gyrotron backward wave oscillator (gyro-BWO) is a gyro device (Fig. 1.6 (b)) in which the gyrating electron beam interacts with the opposite traveling electromagnetic wave. The main advantage of gyro-BWO is its frequency tunability. The disadvantage of gyro-BWO is its low efficiency which is inherent in all types of microwave sources based on interaction with backward and opposite waves. The reason for this is an unfavorable axial structure of the microwave field which has a large amplitude near the entrance where electrons are modulated by the wave field but a small amplitude near the exit where electron energy is withdrawn by the wave. For the given frequency of operation, the magnetic field requirement of the gyro-BWO is also very high compared to that gyrotron [13], [28].

1.4.2. Gyro Amplifiers

Devices that fall under the category of "gyro amplifiers" include gyro-klystrons, gyro-TWTs, and gyro-twystrons [Fig. 1.6]. These devices need an external input signal to trigger electromagnetic radiation. Gyro amplifiers exist in a variety of configurations that are similar to conventional linear beam vacuum tube amplifiers. However, these amplifiers have the advantage of having a fast wave structure that can handle enormous power at high frequencies.

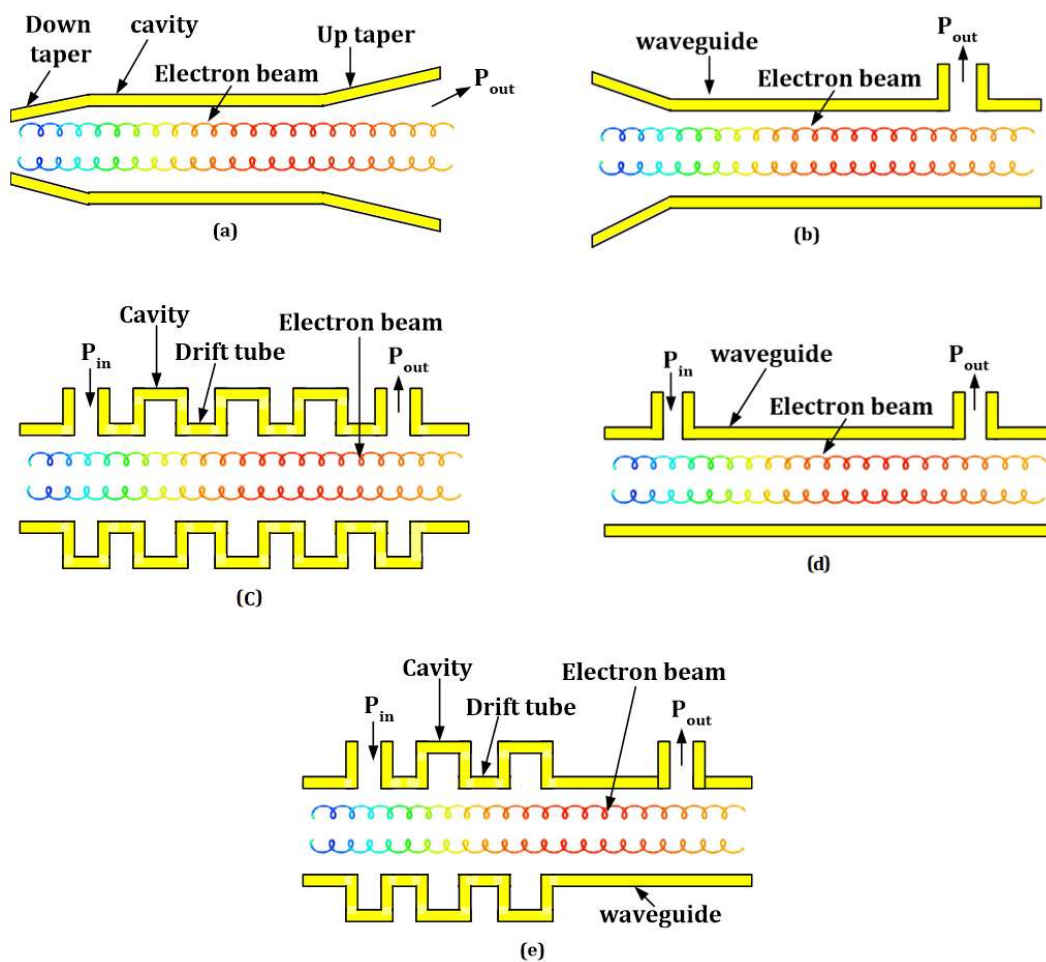


Fig. 1. 6. Schematic structures of gyro devices (a) Gyrotron, (b) Gyro – BWO, (c) Gyro – Klystron, (d) Gyro – TWT and (e) Gyro – Twystron.

The gyro klystron [Fig. 1.6 (c)] is another member of the gyro device family, which is an amplifier analogous to its slow wave counterpart, namely, the klystron. The

resonant cavity arrangement in a gyrokystron is similar to that in a conventional klystron for localized and intensified beam wave interaction that yields high power and efficiencies. The bunching of electrons is relativistic in a gyrokystron as in a gyrotron. The signal is fed into the input cavity, which bunches the gyrating beam. These bunched electrons travel through the drift tube to the outer cavity, where the bunched electron beam induces the RF signal. An amplified version of the input RF signal is developed in the outer cavity. To enhance the gain of the device, one or more buncher cavities can be added. The bandwidth of the gyrokystron is, however, limited to 1% by the quality factor of the resonator. For increased bandwidths, one can go for the cavity design similar to that in conventional klystrons, for instance, the frequency tunable first cavity and several passive resonators with slightly different eigen frequencies placed between the input and output resonators. The design may provide near cyclotron resonance in the first resonator and exact cyclotron resonance in the drift region, thereby eliminating the effect of the electron velocity spread on electron bunching, mismatch of cyclotron resonance in the output resonator for the deceleration of the electron bunch. The gyrokystron has potential applications in particle accelerators and radars [29].

The gyro-TWT [Fig. 1.6 (d)], another member of the gyro device family, configured as an amplifier, is an analogous fast wave version of the conventional TWT. Unlike a gyrotron, which uses an open-ended resonant cavity as the interaction structure, a gyro-TWT uses a non-resonant RF interaction structure, namely a waveguide, to support a traveling wave for distributed interaction. Obviously, the gyro-TWT has a better wide-band amplification potential than a gyrokystron [30]. Axial phase synchronism takes between the electrons gyrating in helical paths and a co-propagating traveling RF wave. The electrons were moving in helical paths under the influence of the modulating RF electric field, forming a bunch that twists around the

helical system with a pitch substantially greater than the electron pitch [23]. The velocity is approximately equal to the phase velocity of the RF wave in the waveguide. This process yields a continuous interaction and energy transfer from the phase-modulated electrons to the RF wave over a relatively long length of the interaction structure, along which the RF wave grows exponentially. At large interaction lengths near the exit of the interaction structure, the spatial growth rate of RF waves saturates due to nonlinear effects [4], [13], [23]. Since gyro-TWT develops high-power electromagnetic radiation over a broad spectrum, it is the most promising source for a high-resolution radar system and millimeter-wave defense applications. The gyro-TWT can magnify an RF wave that is one order of magnitude greater than that of a normal TWT and has a good spectral purity. For wide-band interaction, the gyro-TWT must be operated in close proximity to the grazing condition. This can be accomplished by modifying the DC magnetic field for grazing point interception, i.e., making the RF wave group velocity equal to the axial beam velocity. There are many methods for broad banding a device, including metallic vane loading, 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 [31]- [35].

Even though gyro-klystron, gyro-TWT were rewarded as the successful amplifiers for millimeter radar systems, they have its own drawbacks. For example, gyro-klystron amplifier cannot sustain at higher levels of power. This is because poor output coupling of high quality factor output cavity present in gyro-klystron. Similarly gyro-TWT has the drawback of maintaining its stability against backward wave oscillations (BWO) in the interaction circuit. Also there are competing modes

propagating in the forward direction. Due to the presence of forward and backward propagating competing modes, power fluctuates between the desired mode and the competing modes in the gyro-TWT. This causes frequency and power instability in the device. A hybrid device, comprised of a klystron followed by a TWT known as a gyro – twystron [Fig. 1.6 (e)] [36], is introduced to mitigate these problems and combine the merits of both these devices. One may look upon it as a device that is derived from the gyroklystron by extending the length of the drift section and replacing the output cavity with a waveguide section as in a gyro-TWT. The combination of the chain of resonators and the output waveguide makes gyro-twystrons attractive as wide band high efficiency, high gain amplifiers. The gyro-twystron combining the advantages of two gyro amplifiers (gyro klystron, gyro – TWT) has ignited significant research interest in broadening the bandwidth with sufficient power level for applications such as high-resolution radar and high information density communication systems in the millimeter-wave frequency band. The operating principle and structural details of the gyro-twystron are discussed in the next section.

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

Like the conventional twystron, the gyro-twystron is also a hybrid device which uses one or more input cavities followed by an output waveguide circuit as its RF circuit. Additional cavities present between the input cavity and the output waveguide basically increases the gain of the amplifier. The gyro-twystron amplifier is an efficient high power microwave and millimeter wave coherent radiation amplifier and working on the principle of the cyclotron resonance maser (CRM) instability. As discussed in section 1.3.2. 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 of the

electromagnetic spectrum. With moderate power and moderate bandwidth, the gyro-twystron offers a viable solution for many millimeter wave radar systems.

1.5.1. Working Principle

The Magnetron Injection Gun (MIG) produces an annular electron beam, which travels through the down taper under the influence of a growing magnetic field to reach the preferred pitch factor at the interaction circuit. In order to prevent the propagation of the backward wave into the gun region, a pre-drift tube is used between the down taper and interaction circuit. The RF input signal is fed to the input cavity of gyro-twystron amplifier using an input coupler (ex. wraparound coupler, Y-shaped coupler). The RF signal causes a modulation in the energy and phase of the gyrating electron beam in the input cavity. In the field-free drift tube, these perturbed electrons are ballistically bunched. In a multi cavity gyro-twystron, the subsequent action of perturbation and ballistic bunching occur in intermediate cavities and drift tubes, respectively. The bunching factor measures the quality of a pre-bunched electron beam at the waveguide's entrance. These pre-bunching electron beams gyrate with cyclotron frequency that excites the RF wave in output waveguide. In a traveling wave section, the pre-bunched electron beam interacts with the growing RF wave and electrons are transferring their kinetic energy to the RF wave. Gyro devices extract energy from the transverse component of the electron, whereas gyro-twystron devices extract energy from both the transverse and axial components of the electron. The extraction of energy from transverse and axial components is governed by the beam velocity pitch factor and recoil parameter. The beam-wave interaction operation in the output waveguide is susceptible to oscillations at higher beam currents and pitch factors. The reflection from the output system also causes the instability using external feedback mechanism. After the interaction, particles and amplified RF wave propagated through an up taper without

any mode conversion. The particles are colliding at the collector after transferring their kinetic energy to the RF wave, which is propagated towards/through RF window in axial extraction output system. In the radial extraction mechanism, a quasi-optical mode converter is employed between the up taper and particle collector. The beam wave interaction mechanism is discussed through the dispersion curve.

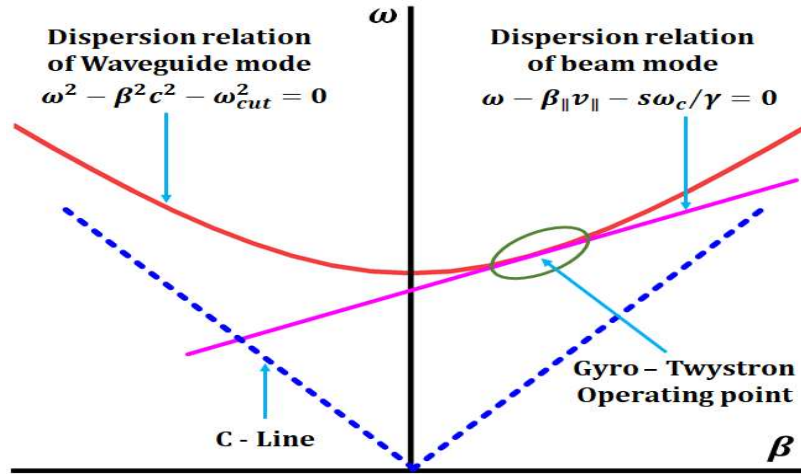


Fig. 1. 7. Dispersion diagram of gyro – Twystron.

1. 5.1 (a) Dispersion relation

The interaction mechanism between electron beam mode and electromagnetic modes can be analyzed using dispersion diagram (Fig. 1.7). A dispersion diagram, a variation of the phase velocity of the RF wave with frequency, is also known as k - plot or Brillouin diagram, which describes the operational characteristics of the device. Additionally, the device synchronization condition between an RF mode and a fast electron cyclotron mode (fundamental or harmonic) can be obtained at the grazing intersection of the beam mode and waveguide mode dispersion curves. A device could be an oscillator or an amplifier, depending on the nature of the interaction between the fast waveguide mode and the electron beam.

The gyro-twystron output waveguide section supports many transverse electric modes, which are represented by a waveguide mode equation.

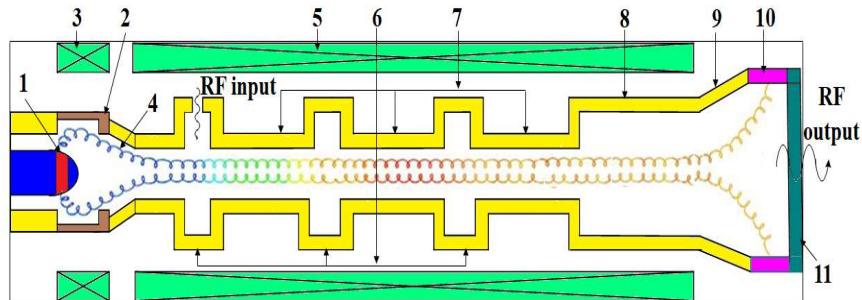
$$\omega^2 = c^2 (k_z^2 + k_{mn}^2) \quad (1.3)$$

The gyrating electron beam are represented by a beam mode dispersion relation

$$\omega - k_z v_z - \frac{s\Omega}{\gamma} = 0 \quad (1.4)$$

where ω is the angular frequency of the RF wave, k_z is the axial propagation constant, v_z is the axial electron beam velocity, s the harmonic number, γ the relativistic mass factor. In a gyrotwystron, the beam mode line makes a tangent on the waveguide mode curve ($k_z > 0$) at the operating point, unlike in a gyrotron oscillator ($k_z \sim 0$). Fig. 1.7 demonstrates that the fundamental harmonic beam mode line makes a tangent on the operating TE₀₁ waveguide mode curve at an arbitrary frequency. In the presence of many modes, the dispersion curve reveals multiple interaction points, including a tangent at the operating point, and discusses additional design considerations.

The gyro-twystron is composed of numerous sub-assemblies, as seen in Fig. 1.8. This incorporates a gyrating beam-generating magnetron injection gun (MIG), an RF input cavity, a drift tube, an interaction zone under a powerful superconducting magnet, a particle collector, and an output window.



1. Particle Emitter 2. Anode 3. Gun Solenoid 4. Compression Zone 5. Main Solenoid 6. Cavities 7. Drift Tubes 8. Output Waveguide 9. Up Taper 10. Collector 11. RF Output Window

Fig. 1. 8. Schematic diagram of gyro – twystron amplifier.

1.5.2. Magnetron Injection Gun (MIG)

The electron gun is a critical component of all microwave tubes, providing a proper beam of electrons for the beam-wave interaction. A Magnetron Injection Gun (MIG) is typically used in a high power gyrotwystron to generate a gyrating electron beam with the required beam parameter in which electrons execute smaller cyclotron orbits at a frequency necessary for cyclotron resonance interaction in a gyrotwystron. The Magnetron Injection Gun (MIG) derives its name from its cathode assembly is similar to that of a magnetron [37], [38]. In MIG, electrons are emitted from a conical cathode, which is generally temperature limited thermionic cathode, in which current variation is easily possible. The emitted electrons move in the helical path under the influence of the cross-electric and magnetic fields. The efficient operation of the Gyrotwystron depends on the quality of the electron beam. Therefore, MIG design parameters, including magnetic compression ratio, down taper dimension, cathode slant, and cathode anode gap, are optimized according to the requirement of electron beam characteristics in the interaction region [37], [38]. MIGs are offered in two primary configurations: single anode and double anode. The potential difference and distance between the anode and cathode are changed to achieve the appropriate beam characteristics. The transverse efficiency is directly proportional to the pitch factor in gyrotron devices. As the velocity spread rises with the pitch factor, gyro-twystron bandwidth is restricted. The causes are the space charge, the initial thermal velocity spread, the emitter roughness, and the inhomogeneity of external fields in the vicinity of emitters with finite width [39].

1.5.3. Input Coupler

An input coupler is used in gyro amplifiers to feed the input signal to RF interaction structures [40]. Feeding the RF input signal at higher-order mode operation

always requires a mode converter. The mode conversion mechanism and design methodology of an input coupler depend upon the rectangular waveguide's operating TE mode to the circular cavity's operating TE mode. As per the requirement of the gyro device, the input coupler should have high mode purity, good transmission, and low reflection with broad bandwidth without mode competition. To meet these requirements, feed the RF signal to the input cavity of the gyro-twystron using a variety of input couplers, such as wrap-around couples and Y-shaped input couplers.

1.5.4. Beam Wave Interaction Circuit

The interaction circuit of gyro-twystron amplifier consists of an input cavity followed by an output waveguide. In order to provide perfect isolation between the different sections of RF circuit, field free drift regions are present between the cavity and the output waveguide section. The electrons move towards the interaction circuit through a growing magnetic field. Due to adiabatic invariance of the magnetic momentum, the electron orbital momentum increases[6]. The dimensions of cavities are chosen to resonate in the desired frequency and mode. The dielectric rings are introduced downstream of the cavity to lower the cavity's quality factor. In addition to isolation between cavities and waveguide, the drift tubes provide the ballistic bunching [9]. Nonlinear beam-wave interaction takes place in the output waveguide section. Thus, the RF field developed at the output waveguide section is the amplified version of the applied RF field at the input cavity.

1.5.5. Collector Section

The spent beam of electrons enters a magnetic decompression region and diverges off the axis to settle on the walls of the collector surface. Two distinct types of collectors, the undepressed collector, and the depressed collector, are used at the output

section to extract the residual energy from the spent electron beam, depending on the nature of output power extraction. An undepressed collector, preferred in axial extraction, is simply a cylindrical waveguide to collect the spent electron beam. In the depressed collector [41], the beam is collected on a surface with reduced potential 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 most applications, the device's overall efficiency is of paramount interest since it will considerably influence the power and cooling system requirements. To increase efficiency, one should design and build gyro-twystrons with a suitable energy recovery system, namely, depressed collectors. Nowadays, all gyro devices employ at least a single-stage depressed collector technique. Efficiency can also be increased by using multi-stage depressed collector techniques, but the design of a multi-stage depressed collector system is quite complex [4].

1.5.6. RF Output Window

The RF window is an essential component of the gyro-twystron output system. It acts as a barrier between the vacuum and the external atmosphere [42]. It should be able to handle high power, mechanical, and thermal strains, as well as be leak-proof. It must be made from a material with minimal loss, such as alumina, beryllium, sapphire, and boron nitrate. Currently, CVD diamond windows are seen as more appropriate for high-power applications, but they are expensive. Due to the high power, thermal management of the RF window becomes a significant issue that must be considered during the RF window's design phase. Therefore, the operating temperature of the window must be selected with care [4].

1.6. Advantages and Applications of Gyro-Twystron

1.6.1. Advantages of Gyro-Twystron

Even though gyro-klystron, gyro-TWT were rewarded as the successful amplifiers for millimeter radar systems, they have its own drawbacks. For example, gyro-klystron amplifier cannot sustain at higher levels of power. This is because poor output coupling of high quality factor output cavity present in gyro-klystron. Similarly gyro-TWT has the drawback of maintaining its stability against backward wave oscillations (BWO) in the interaction circuit. Also there are competing modes propagating in the forward direction. Due to the presence of forward and backward propagating competing modes, power fluctuates between the desired mode and the competing modes in the gyro-TWT. This causes frequency and power instability in the device. Gyro-twystron is a hybrid gyro amplifier. Similar to its linear beam counterpart gyro-twystron utilizes bunching cavities of the gyro-klystron with output waveguide of the gyro-TWT. Such a hybrid-type device is, obviously, capable of combining merits of the gyro-klystron (high efficiency and gain) and gyro-TWT (large bandwidth) that make gyro-twystron promising amplifier of coherent electromagnetic radiation. For the same level of the radiated output power the energy of the RF field localized in the output waveguide of the gyro-twystron may be much smaller than the microwave energy stored in the high-Q output cavity of the gyro-klystron and, therefore, the twystron configuration can possibly mitigate the problem of microwave breakdown occurs in the gyro-klystron at high levels of the radiation power. The gyro-twystron also has an advantage over gyro-TWTs because its interaction length is shorter. This is important for the suppression of parasitic modes, whose starting current typically scales inversely as the cube of the length [43]. Thus gyro- twystron amplifier is considered as the

promising candidate for very high power applications and also for many millimeter wave radar systems with moderate gain and bandwidth[44].

1.6.2. Applications of Gyro-Twystron

Gyro-twystron is a hybrid gyro amplifier that combines the merits of Gyro-Klystron and Gyro-TWT, making Gyro-twystron a promising amplifier of coherent electromagnetic radiation. Further, with high gain-bandwidth output and high power-bandwidth output, the gyro-twystron is a promising contender for millimeter wave radar applications such as space debris detection, weather monitoring, and asteroid tracking [45]. Furthermore, by reducing the microwave breakdown problem, the gyro-twystron amplifier becomes a more suitable candidate for particle accelerator applications [46]. However, gyro-twystron has significant potential as well. Still, it received very little research and development attention during the past decades, and its claims are limited to RADAR and particle accelerators, which are discussed in detail below.

1.6.2.1. Millimeter Wave Radar

Millimeter wave radars are primarily designed to focus on atmospheric windows at frequencies of 35 and 94 GHz [45], [47]. Millimeter wave radar is more compact, lighter, and has a focused beam with high resolution and multipath effects. For a high-performance radar, high gain, high efficiency, low noise figure, compactness, and light weight are desirable in addition to high output and wide bandwidth. In the 1960s, various conventional twystron tube were developed by Varian for RADAR applications and were successfully commissioned in US AIR force RADAR. Russian Scientist develops the RUZA radar system at 35 GHz for detecting and tracking space objects using two 550 kW gyroklystron [48]. A W-band cloud profiling RADAR is needed to understand the effect of global warming as the dynamics of clouds, precipitation

mechanism, development of turbulence, and storms are part of the cloud profiling study [49]. A W-band WARLOC radar system is developed at NRL, USA, with multiple applications in a target recognition, low-angle tracking, and atmospheric research [49]. A 94 GHz gyroklystron is employed as a transmitter in the RADAR system, which delivered 80 kW of RF power with an efficiency of 20% [50]. In 50 years of space technology advancement, space became crowded by satellites, and to upgrade space surveillance RADAR, Haystack Ultra-wideband Satellite Imaging Radar (HUSIR) system was developed to achieve accuracy up to 0.5 mill degrees using gyro-twystron [51]. A 94 GHz gyro-twystron is employed in the HUSIR system, which delivers 50 kW of RF power with significant power bandwidth. It is an improvement of 46 kW-GHz [52], [53]. The literature mentioned above suggested that the gyro-twystron amplifier is a promising VEDs for radar applications.

1.6.2.2. Particle Accelerator

In order to accelerate the particles in RF structures, high RF power is required. In particle accelerators, the RF energy of VEDs is transferred to the particles, in contrast to the beam-wave interaction process of VEDs [45], [47]. Particle accelerator variations are used in particle and nuclear physics, material research, and industrial material processing [45]. 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 [54]. The University of Maryland created a series of X- and Ku-band gyro-amplifiers to minimize the collider's length and cost [54]. 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 gyroklystron is susceptible to 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 produced 12 MW of RF power at 19.76 GHz [43], [55]. In 2001, Wilson, from the 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 [56]. A three-cavity gyro-klystron working 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 [57]. 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 CRM instability motivated the exploration of fast-wave devices. Twiss [58], Gaponov [59], Schneider [18], and Zheleznyakov [60] discovered the CRM mechanism in the late 1950s, which led to the establishment of CRM devices. Twiss, an Australian astronomer, proposed that population inversion and stimulated transition are necessary conditions for EM wave instability [58]. Schneider proposed the quantum mechanical CRM technique for simulating emissions with an extended contact period [18]. Gaponov investigated the classical and quantum mechanical approaches and considered axial bunching and orbital bunching [59]. In 1960, *Ka*-band CRM devices (trochotrons) were developed, delivering 1 kW of RF power with a 10% efficiency. Trochotrons' performance was restricted by the axial velocity spread. The TE

mode at the cutoff frequency ($k_z=0$) reduces the effect of axial velocity spread and efficiently interacts with the beam. In 1965, a second harmonic CRM monotron with 190 W of RF power (CW) was established and designated gyrotron by A. L. Goldenberg in Saratov, Russia [61]. Later, gyrotron attained fundamental and second harmonic efficiency of 50% and 20%, respectively [62]. The International Thermonuclear Experimental Reactor (ITER), one of the world's most significant active projects, aims to develop 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. [63] have successfully performed plasma heating through gyrotron radiation accompanied by a considerable increase in plasma temperature. With this impetus, V. A. Flygin and Salut collaborated to construct a 40 kW gyrotron with a 1 cm wavelength [64]. Higher operating modes with larger transverse dimensions of the RF section of the gyrotron at a higher frequency are chosen to enhance the high-power handling capabilities. Gyrotrons operating in the axisymmetric mode of higher order suffer from mode competition [65]. The whispering gallery modes are ideal for developing high-power, high-frequency gyrotrons. For long pulse operation, waveguide and taper designs ignite spurious mode, limiting RF power conversion into Gaussian mode. The radial extraction of RF power by quasi-optical mode converters mitigates the spurious mode creation following the interaction cavity [9]. In the literature [9, 5], the physics and analysis of gyrotron are studied in depth.

The analogy between slow-wave monotron and CRM monotron allowed for the development of a novel generation of gyrotron devices known as gyrotron amplifiers (gyro-amplifiers). Gyrotron amplifiers like gyro-klystron, gyro-TWT, and gyro-twystron are used in RADAR and particle accelerator applications. With the advancement of gyrotron, recent research on gyro-klystron has attracted attention in

gyro-amplifiers at 10 GHz and 28 GHz [14]. Most of the gyro-amplifiers for RADAR applications were developed in *Ka*-band and W-band, as atmospheric windows are present at 35 GHz and 94 GHz, respectively [45], [66], [67]. In 1994, IAP, Russia, developed an *X*-band gyro-klystron amplifier that delivered 700 kW of RF power for continuous power operation [68]. A two-cavity gyro-klystron operating in TE₀₂ mode delivered ~ 260 kW RF power at 35 GHz with efficiency and gain of 18% and 17 dB, respectively [69]. At NRL, a C-band gyro klystron was developed, employing the three rectangular cavities and producing the RF output power of ~ 52 kW with an efficiency of 30% and measured bandwidth is 0.4 % [46]. In the late 1990s, the NRL developed and constructed a gyro-klystron capable of producing 200 kW of RF power at 35 GHz [70]. The two-cavity gyro klystron operating in the *Ka*-band delivered ~210 kW RF power with an efficiency of 37 % and gain of ~ 24 dB [80], while a three-cavity gyro klystron delivered a power of 225 kW with 30.3 dB saturated gain and 32% efficiency [71]. A four-cavity gyroklystron amplifier produced an output power of 208 kW with 30% efficiency, 178 MHz bandwidth, and a gain of 53 dB [72]. The NRL developed a four-cavity W-band gyro-klystron that produced 67 kW of RF power with an efficiency of 28% [73]. This gyro-klystron was ordered for use in the 94 GHz WARLOC radar [73]. At the University of Maryland, an *X*-band gyro klystron was developed for particle accelerator applications that delivered 20 MW power with 26 dB gain [74], and the addition of one more intermediate cavity in the existing structure can enhance the power to 27 MW with the gain of 34 dB [75]. However, the output cavity of these gyro-klystrons was subject to microwave breakdown, and their bandwidth was limited [46].

The gyro-amplifiers required for radar applications must typically be capable of high average power and bandwidth, which drives the need to investigate various gyro-amplifier configurations. The CRM counterpart, like traditional TWT, offered a wide

bandwidth and became a viable amplifier for RADAR applications [45]. 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. In 1979, Seftor and his group at NRL demonstrated the first experimental gyro-TWT. It achieved an output power of 10kW and a stable gain of ~17dB at an operating frequency of 35GHz [76]. In 1981, Barnett et al. reported another experimental gyro-TWT amplifier with a gain of 18 dB [77]. The continuous interaction of beam and wave in a metallic waveguide drives the development of the operating mode and various parasitic modes—the development of different parasitic modes results in mode competition and instability. The waveguide's RF propagation has been engineered to reduce mode competition issues and improve stability. Several novel interaction structures were investigated and classified as mode control, mode filter, and dispersion control technology [78]. In the beginning, septa were placed between the waveguide to reduce oscillations [79]. At high currents, oscillations in RF power were detected, and the distributed loss technique was used to establish stability. The initial improvement was the dielectrically loaded structure, which Leou et al. reported in 1992 [80]. The benefit was its high bandwidth, while the drawback was its low efficiency. Periodic dielectric loading (PDL) is more suitable for high-power operation than uniform dielectric loading (UDL) [42]. As a mode filter for low-power operation, photonic band gap (PBG) structures are deployed [78]. As gyro-TWTs are operated far from cutoff ($k_z > 0$), velocity spread restricts their bandwidth [78]. Denisov et al. [81] presented a unique cylindrical waveguide with helical corrugation at the inner surface for gyro-TWT and achieved an output power of 1 MW with 20% efficiency for a 200-kV, 25 A electron beam at X-band. In 1999, Chu et al. developed an ultra-high gain stable gyro-TWT amplifier using the distributed wall loss technique for suppressing

spurious oscillations [82]. 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 reflective feedback path, suppressing the spurious oscillation and improving the gyro -TWT performance [82]. An experimental *Ka*-band gyro-TWT was studied and found to have 93 kW of saturated peak power, 27% efficiency, 70 dB gain, and a 3-dB saturated output power bandwidth of 3 GHz [82]. A *Ka*-band gyro-TWT using PDL was developed at NRL by Garven *et al.* that delivered ~ 137 kW of RF output power with a gain of 47 dB and bandwidth of 1.1 GHz [83]. The stability analysis of the *Ka*-band gyro-TWT demonstrated that the TE_{01} mode of operation in a PDL waveguide behaves similarly to the TE_{01} mode of operation in a lossy metal waveguide [84]. Du *et al.* described the modal transition effect in a PDL waveguide in 2009 [85], in which the second harmonic TE_{02} mode is well suppressed, and most power is concentrated in the TE_{01} mode. A *Ka*-band gyro-TWT was demonstrated with 160-kW RF power, 23% efficiency, 5% bandwidth, and 40 dB gain [86]. In 2018, Liu *et al.* explained the propagation characteristics of EM modes in the CW *Ka*-band gyro-TWT with 110 kW RF power, 15% efficiency, 1.75 GHz bandwidth, and 34 dB gain [87]. In 2020, Xu *et al.* used an additional cut-off waveguide section with the interaction section in *Ka*-band gyro – TWT and reported a 20 kW avg. Output power with the bandwidth and gain of 3.2 GHz and 52 dB, respectively [88]. At the 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 [89]. In 2014, Ran *et al.* introduced the nonuniform dielectric loaded *W*-band gyro-TWT and obtained the RF output power of 112 kW with a gain and efficiency of ~ 70 dB and ~ 23 % [90]. A *W*-band gyro -TWT with the optimized electron gun generated the RF output power of ~ 36 kW with a 3 dB

bandwidth of 5 GHz [91]. Shou-Xi Xu and his team designed a W band gyro -TWT that generates 100 kW peak RF power with an efficiency of 28 % and bandwidth of 3.2 % [92]. Recently, Liu *et al.* performed an experiment on *W*-band dielectric-loaded gyro -TWT and reported a peak power of ~160 kW with an efficiency of 16 %. The reported gain and bandwidth are 75 dB and 8.5 GHz, respectively [93]. Furthermore, the evolution and progress of the gyro-twystron amplifier research is addressed below.

1.7.2. Gyro-Twystron

The structural change was induced by the reorganization of the cavity and waveguide section to achieve optimum performance between the traditional amplifiers, such as klystron and the TWT. In 1962, at the University of California, Lichtenberg and his colleagues developed a hybrid tube comprised of pre-bunching cavities and an output waveguide section known as a twystron and noticed a substantial improvement in efficiency, from 20% to over 35% [36]. Likewise, Varian Inc. has improved the performance of twystron by employing a coupled cavity as the pre-bunching section in S-band TWT (VA-125B). With the inspiration of substantial performance improvement, several linear beam twystron tubes have been developed by Varian Inc., and this mature hybrid vacuum amplifier is utilized in the AN/TPS RADAR of USA AIR FORCE [94]. In 1969, the VA-145 series of S-band twystron delivered 2-7 MW of RF power with a bandwidth of 8 % [95], and the VA-146A series of twystron with stagger-tuned cavities delivered 5 MW of RF power with a bandwidth of 10 % and efficiency of 40% [96]. The first developed gyrotron oscillator (gyro-monotron) was exhibited to the research community at Saratov's in 1966. Furthermore, Varian Inc.'s efforts developed twystron tubes much before the advent of the gyrotron. The analogy between the linear beam and CRM devices reveals the concept of gyro-twystron [97].

In the 1970s, a theoretical attempt was made to study CRM-twystron physics. Bratman et al. conducted theoretical research in 1973 and named an axial variant of CRM-twystron called gyro-twystron. Moiseev proposed in 1977 that the gyro-twystron is an efficient amplifier with tapered input and output sections [98]. CRM-bandwidth twystron is restricted by velocity spread, and its amplification band is independent of drive input power [98]. Furthermore, theoretical studies revealed that the CRM-twystron amplification band is determined by the difference between the operating and cut-off frequencies of the output waveguide section [98-99]. Tran et al. executed the first analytical studies of gyro-twystron in 1985 by introducing a waveguide section in a pre-existing gyro klystron and extending the formalism related to the gyro klystron to the gyro - twystron and developing self-consistent analytical calculations of field profile and transverse efficiency in a small signal regime [100],[101]. Nusinovich and Li developed the analytical approach for the gyro traveling-wave amplifier (gyro-TWA) at the University of Maryland [102] and extended it over the generalized theory of relativistic gyro-twystron [103] to study the energy modulation of relativistic electrons in the input cavity and their phase bunching in the drift space. The large-signal operation in the output waveguide of a gyro-twystron for both first and second harmonics was thoroughly examined [103]. At frequencies close to cut-off, the efficiency of gyro-twystron employing an output waveguide is highly tolerant to electron velocity spread. According to this work, optimizing the recoil parameter increases energy extraction from the axial and transverse components of electron motion [103]. With the advent of theoretical research, an experimental effort on gyro-twystron was developed in the 1990s at the University of Maryland and NRL, USA, for particle accelerator and RADAR applications, respectively. At the University of Maryland, Latham et al. performed the first-ever experiment on gyro-twystron in the X-

band [43]. The pre-experimental investigation of *X*-band gyro-twystron was conducted in 1993 to evaluate stability difficulties and optimize operational parameters [104], [105]. Stability experiments revealed a considerable decrease in efficiency with increasing reflections from the end and indicated that the operating mode would become saturated more quickly with larger bunching parameters [104]. The operating points are established by balancing maximal available energy with minimizing the detrimental effect of velocity spread [105]. The pitch factor increases energy conversion from the transverse component of the electron beam, while Doppler up shift increases energy conversion from the axial component. However, the detrimental effect of velocity spread is amplified for Doppler up-shifted gyro-twystron operation [105]. A large beam current has offset the impact of velocity spread [105]. The gyro-twystron with a single cavity operating in TE_{01} mode with 21 MW of RF output power with 22% conversion efficiency and 24 dB gain was experimentally demonstrated in 1994 [43]. Further research on experimental gyro-twystron was conducted in order to optimize performance metrics and examine the impact of parasitic modes and velocity spread. The performance of the gyro-twystron depends on various parameters like beam voltage, beam current, applied magnetic field, spread in the 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 [106]. With the introduction of advanced electron beam sources, such as MIG, which generate gyrating beams with low-velocity spread, resulting in an effective beam-wave interaction efficiency and Doppler up-shifted operation is possible [106]. In the stability study, parasitic TE_{11} mode is incorporated to examine the performance of the gyro-twystron amplifier [107]. The reflection of the RF window restricts the operation of the gyro-twystron at a high pitch factor, resulting in decreased efficiency. Lawson et al.

developed a second harmonic gyro-twystron amplifier in 1995 [108] to enhance the figure of merit, which provided 12 MW of RF power with a 12% efficiency and a gain of 12 dB. The performance of the second harmonic gyro-twystron is limited by mode competition and oscillations in the down taper area near the electron gun [108]. Malouf et al. explored the design methodology of a C-band gyro-twystron. Its numerical simulation estimated an output power of 60 kW with an efficiency of 22.5% and a gain of 22 dB [109]. Parametric analysis of C-band gyro-twystron has 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 [109]. To illustrate the improved bandwidth, a research group at the NRL led by Perry M. Malouf was developing a C-band gyro-twystron amplifier for RADAR applications [109-111]. Nusinovich et al. presented the mathematical model of beam-wave interaction in a three-stage gyro-twystron in 1994 [110]. The mixed geometry three-stage gyro-twystron provided 46 kW of RF output power with an efficiency of 23% and a gain of 37 dB [111] compared to the numerical prediction of 55 kW with a gain of 26 dB and a bandwidth of 6% [110]. These investigations predicted a significant improvement in the gain-bandwidth product as well as predicted transverse efficiency of gyro-twystron near/below unity pitch factor [111]. The cross-polarized mixed geometry gyro-twystron amplifier was patented by Perry M. Malouf and G. S. Nusinovich in 1998 [112]. Blank et al. conducted research at the NRL to investigate the bandwidth capabilities of the gyro-twystron amplifier [113]. A time-dependent MAGYKL code was used to theoretically and practically develop and explore three alternative configurations of three-stage gyro-twystron using circular geometry [113]. For beam parameters of $I_b=1$ A and $V_b=16$ kV, the X-band gyro-twystron delivered 4.4 kW of RF power with a bandwidth of 1.6%, which is restricted by velocity spread [113]. Still, the bandwidth was limited by the quality factor of the

output waveguide [113]. This work also confirmed the suggested design technique and theory for future gyro-twystron amplifier development at higher frequencies.

The low attenuation at 35 GHz and 94 GHz opens the window to communications and radar applications and encourages the development of high-power gyro amplifiers at these frequencies. For radar, applications must typically have high average power and broad bandwidth. High bandwidth requirements led to the investigation of several methods to enhance the device's output performance. As a result, significant research is being performed to discover alternative techniques for improving the device's bandwidth. There are two primary ways to increase bandwidth. The first method is stagger tuning [114], whereas the second is cluster cavity [115]. These bandwidth enrichment approaches are often employed to expand bandwidth at the expense of a gain reduction in cavity-based gyro amplifiers. The effect of stagger tuning on several gyrokystron designs was investigated by the University of Maryland and the Naval Research Laboratory (NRL) [114], [115], [116]. Nusinovich and Chen et al. established linear and nonlinear theories of multi-cavity gyro-twystron to investigate performance metrics such as gain and gain bandwidth product in comparison to synchronous tuning [117], [118]. According to the investigation, the bandwidth in the two-cavity pre-bunching section is 1.65 times more than in the single-cavity pre-bunching section [118]. The nonlinear formalism of multi-cavity staggered tuned gyro-twystron was developed using the point gap model [117]. Furthermore, it was observed that the bandwidth is reduced above the optimal value of the bunching parameter [117], [118]. The theoretical studies of multi-cavity stagger-tuned gyro-twystron, operating in a 35 GHz band, are focused on stability analysis at a high value of the beam velocity pitch factor [119]. The analytical study of a three-stage *Ka*-band gyro-twystron operating in TE_{11} delivered 90 kW with a gain of 55 dB. The stagger-tuned cavities

used in the multi-cavity *Ka*-band gyro-twystron gives the 0.7 GHz bandwidth, and the magnetic tapering enhances the efficiency from 33 % to 43 % [119]. At the NRL, Blank et al. designed and developed a 94 GHz gyro-twystron [44]. This multi-cavity gyro-twystron produced 50 kW of RF output power while maintaining a 17.5% efficiency and a bandwidth of 925 MHz [44]. The bandwidth was enhanced at the expense of RF power by a modest increase in the magnetic field. The W-band gyro-twystron nonlinear computation predicted 80 kW of RF power with a velocity spread of 4% [44]. Blank et al. published a survey of gyrotron amplifiers in 2002, reporting that the gyro-twystron has the highest power-bandwidth product of 46.3 kW-GHz [120]. The gyro-twystron amplifier was later deployed at the RADAR site in 2007 [53] because of its outstanding capabilities. Ngogang et al. explored the influence of a large amplitude signal on the relativistic electron beam for gyro-twystron and gyro-TWT amplifiers in 2006, and they discovered overlapping of cyclotron resonance at different harmonics [121]. Because the waves were generated at the output waveguide section by a pre-bunched electron beam carrying signal frequency harmonics, the gyro-twystron operation is more susceptible to cyclotron harmonic overlapping. However, this investigation concluded that overlapping cyclotron harmonics do not affect device performance [121].

1.8. Motivation and Objective

The motivation for research and development of a device is related to its applications where it can be used successfully. In the last few years, gyro amplifiers such as gyro-klystron, gyro-TWT, and gyro-twystron have emerged as potential high-power microwave radiation sources at the *Ka*-band (atmospheric window) of the millimeter wave regime. This atmospheric window in the *Ka*-band frequency spectrum opens up various applications for *Ka*-band high-power sources in millimeter-wave radars, atmospheric probes, and space debris radar and is the main reason for the

motivation to study the high-power microwave source (i.e., gyro-twystron amplifier) at this frequency band.

However, gyro-klystron amplifiers are susceptible to microwave breakdown at high power operation and also give narrow bandwidth. By employing a traveling wave output section, the gyro-twystron amplifier mitigates the problem of microwave breakdown and provides broad bandwidth. A short output waveguide increased the suppression capabilities of parasitic modes as compared to gyro-TWT. With a hybrid interaction structure, gyro-twystron provides a significant gain-bandwidth improvement over gyro-klystron. It also mitigates the deleterious repercussions of velocity spread. Despite its potential advantages over gyro-klystron and gyro-TWT, It is observed that the gyro-twystron 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 the gyro-twystron amplifier, are necessary to reach its full potential.

Mainly this thesis focus on a high-power gyro amplifier (gyro-twystron) that operates in the *Ka*-band (atmospheric window) of the “millimeter wave” regime. The two significant areas that benefit directly from high-power sources in the millimeter wave band are communication and defense. Especially wideband, high-power millimeter wave sources are used for radar applications. The present work concentrates on the design, multimode beam wave interaction behavior, and simulation of *Ka*-band gyro-twystron amplifiers utilizing nonlinear theories and the 3-D Particle-In-Cell (PIC) simulation code. This work describes the many design challenges associated with gyro-twystron amplifiers and formulates the design methodology. A design process that determines the interaction structure dimensions and beam parameters of gyro-twystron

is structured/composed. Simultaneously with the designing process, the modeling of interaction structures is carried out to present their 3D view. The design computation is validated by the 3D RF wave propagation investigation. Design, modeling, and simulation of subassemblies such as input coupler, Magnetron Injection Gun (MIG), collector, and RF window address the challenge of inclusion with an interaction structure.

The design and PIC simulation of a millimeter wave single cavity gyro-twystron amplifier demonstrates the nature of the beam-wave interaction mechanism while also analyzing performance metrics. The analytical model has multimode computing capability for investigating competing and operational modes. The current investigation revealed oscillations and parasitic instabilities caused by competing modes. In addition, rectifying the oscillations in gyro-twystron amplifiers offers competitive mode suppression options through stability and design analysis.

Multimode analysis of a periodic dielectric loaded (PDL) waveguide is used to find the characteristics of growth and suppression of operating and parasitic modes, respectively, which determines the output power, gain, and efficiency of the gyrotron amplifier in addition to the gyro-twystron amplifier. An investigation of an intermediate cavity introduction to a single cavity gyro-twystron. Not only does it predict an enhancement in output RF power, gain, and efficiency, but it also gives a sufficient theoretical research framework for the design and investigation of multi-cavity gyro-twystron. The effect of beam quality on enhancing gyro-twystron efficiency is explored, and an improved particle emitter and collector are designed to improve the device's overall performance.

Gyro-twystron is an excellent choice for many radar applications that demand wide bandwidth. Hence an attempt is made to increase the bandwidth of the device by

using a technique known as stagger-tuning as compared to the device without stagger-tuning. In addition, a three-stage depressed collector to collect the spent beam energy has been designed to enhance the overall device efficiency. Furthermore, a Meta surface window has been designed and simulated to extract the amplifier RF power for fundamental harmonic gyro-twystron.

1.9. Outline of the Thesis

A series of investigations have been carried out and addressed in the corresponding chapter of the present thesis to examine challenges and design issues in millimeter wave gyro-twystron amplifiers. The present work explores nonlinear theories and the 3D PIC simulation code CST studio suite to design and simulate the millimeter-wave gyro-twystron amplifier. The detailed insight of the multimode analysis, systematic design methodology, vast 3D PIC simulation results to understand the beam-wave interaction mechanism, and Stagger tuning approach used for the performance enhancement of the gyro-twystron amplifier is presented. The various Subassemblies like the electron beam source (MIG), beam collector, and RF window of gyro-twystron are also designed and simulated for the stable and wideband operation of the device.

The present thesis is structured into seven chapters, and the chapter organization is as follows.

In the present chapter, the basics of conventional microwave tubes, classification of the microwave tubes, the development, and limitations of traditional 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—as well as their application and limitations are described. A literature review is conducted on the concept and development status of gyro-twystron amplifiers. Consequently, the gyro-twystron amplifier is found to be a superior RF source for use in

RADARs and particle accelerators compared to conventional gyro amplifiers. The challenges present in the current state-of-the-art gyro-twystron amplifier, as well as the solutions to these problems, are investigated.

In Chapter 2, the fundamental theory of traditional gyro-twystron is presented. The design methodology of conventional gyro-twystron is developed to establish the RF dimension of each gyro-twystron sub-section. The electron dynamics and wave dynamics equations in a hybrid interaction structure are discussed to investigate the beam-wave interaction behavior. The nonlinear theory of gyro-twystron is extended to nonlinear study state multimode for the analysis of beam-wave interactions.

In Chapter 3, the design and simulation study of millimeter wave gyro-twystron is presented and validated with the analytical multimode code developed in Chapter 2. The various subassemblies like single anode MIG, Collector, and output window are also designed and simulated for the ka -band operation. The beam-wave interaction behavior is studied through the beam present simulation using the commercial tool 'CST Particle Studio' to evaluate the RF power, efficiency, gain, operating frequency, and other parameters. The PIC simulation results are compared with those obtained from the multimode mode analysis.

Chapter 4 discusses the design and simulation studies of a Ka -band periodic dielectric-loaded gyrotwystron. The PDL gyro-twystron amplifier suppresses the self-generated backward-wave parasitic modes. A Y -shape TE_{01} mode input coupler is presented to feed the operating mode for gyrotwystron. The design of the MIG has been improved to triode (double anode) MIG, which allows more parameter space to control the velocity ratio and velocity spread in the electron beam. A curved shape undepressed collector is also designed to recover the spent beam energy of the gyro-gyrotwystron. A

double-disk window is designed and simulated for the wideband transmission of the output signal.

Chapter 5 discusses performance enhancement investigations of two cavities followed by periodically loaded *Ka*-band gyro-twystron. The design methodology of two cavity *Ka*-band gyro-twystron has been developed to study its beam wave interaction characteristics. With the drawn design parameters, modeling and cold analyses of two cavity gyro-twystron have been done. A double anode MIG is designed, and the trajectory of the electron beam is optimized using CST software. The simulation findings indicate that a prebunched electron beam delivers an increase and saturation of RF power in a short waveguide. A single-stage depression collector is meant to recover the spent beam energy, hence increasing the gyro-twystron efficiency. A triple-disk window is designed and simulated for the wideband transmission of the output signal.

In Chapter 6, the gyro-twystron 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 gyro-twystron 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 a trade-off in gain bandwidth product for the device is carried out. First, a generalized analytical approach for stagger-tuned gyrotwystron is developed and successfully implemented on the gyrotwystron amplifier for its bandwidth enhancement. The analytical results obtained in this chapter are validated through PIC simulation results. A three-stage depressed collector is designed to recover the spent beam energy, which in turn increases the efficiency of the gyro-twystron. A novel Meta surface window was also designed and simulated to extract the amplifier RF power for fundamental harmonic gyro-twystron.

In Chapter 7, the thesis's work is summarized, and the key conclusions are made from the significant findings. In addition, the limitations of the present study are addressed, along with the possibilities for future exploration. 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

The present chapter outlines the work signified in the present thesis. The fundamentals of conventional microwave tubes and gyrotron devices such as gyro oscillators and gyro amplifiers have been explored briefly. The gyro-twystron amplifier's available literature is extensively studied, including its scope, limits, and performance enhancement strategies. The physics of gyro-twystron has been explored with subassemblies and crucial elements. Numerous configurations of the device that enhance its performance are also emphasized. The merits of a hybrid gyro-amplifier have been addressed, leading to a wide range of applications, and gyro-twystron is an interesting VED amplifier for RADAR and particle accelerators.