CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

1.1. Motivation for the Thesis

The vacuum electron devices (VEDs) have experienced tremendous growth after the Second World War. During this period, the research was mainly focused on low frequency microwave radiation sources to be used in daily life (food processing and cooking) and military (radar and communication) applications [Osepchuk (1984), Osepchuk (2009), Benford (2008)]. However, over the past decades, the VEDs research has been focused on increasing the operating frequency limit up to millimeter wave (MMW) and sub-millimeter wave regime. The MMW frequency band occupies frequencies between about 30 GHz to 300 GHz, and is named because the wavelengths at these frequencies are on the order of a millimeter. The benefits of millimeter wave frequency operation are well understood for various emerging applications including defence, scientific and commercial industries, advanced radar systems [Amboss *et al*. (1980), Andronov *et al*. (1978), Barker *et al*. (2001), Chu *et al*. (1978), Collin (1966), Gaponov *et al*. (1994), Gilmour (1986), Du *et al.* (2014), Kartikeyan (2004)].

The performance of the conventional VEDs or slow wave devices (TWT, BWO, Klystron, etc.) deteriorates as the frequency of operation increase to millimeter wave regime [Felch *et al.* (1999)]. The cross-sectional dimensions of slow wave devices are of the order of their operating wavelength. Hence, as we go for higher frequency operation, the size of the device gets reduced. The narrow circuit dimensions at high frequencies increases the fabrication complexity and decreases the power handling capability, which limits the utility of the device for the practical applications.

An alternative to conventional VEDs is gyrotron devices (a new breed of VEDs also called fast wave device). The circuit dimension of gyrotron devices is determined by the cyclotron resonance condition or specifically, by the externally applied DC magnetic field [Kartikeyan (2004)]. The dimensions of RF interaction circuit can be significantly larger than operating wavelength and even increases at high-order mode of operation. This helps to overcome the limitations of conventional VEDs and vastly increases the power handling capability gyrotron devices at the millimeter wave regime.

This thesis will focus on a high power gyrotron amplifier that operates in W-band (atmospheric window) of the “millimeter wave” regime. The two major areas that benefit directly from high-power sources in the MMW band are communication and defense. Specially, the wideband, high-power millimeter wave amplifiers are used for satellite communication [Menninger *et al*. (2013), Fukui *et al*. (2002)]. The development of high-power wide band amplifiers in the form of an upgrade to a W-band Haystack radar transmitter system for space application is the current interest of research [Kempkes *et al*. (2006)].

The attenuation of the microwave signal due to the atmospheric absorptions is a significant bottleneck in the transmission of high-power microwave radiation. A large amount of signal strength or information is either lost or completely distorted during transmission through the atmosphere. The W-band high power sources are special because of the atmospheric window near 94 GHz frequency range [Felch *et al.* (1999)]. In this atmospheric window, the absorption of signal due to the fog, cloud and water vapour is least and signal transmission occurs with minimum attenuation. Under the humid conditions, the attenuation loss at these frequencies is 1.0 dB /km, which is acceptable for hundreds of kilowatt power level. This atmospheric window in W-band frequency spectrum opens up variety of applications for W-band high power amplifiers in millimeter wave radars, atmospheric probes and space debris radar, and is the main reason of motivation to study the high-power microwave source at this frequency band.

Gyrotron amplifiers such as gyro-klystron, gyro-TWT, and gyro-twystron are the potential candidate as high-power microwave radiation source for radar system. The gyro-TWT offers the largest bandwidth among all due to its non-resonant waveguide circuit, however the operation of gyro-TWT is found to be very sensitive to oscillations. The higher frequency operation of the gyro-TWT has made it possible to use them in many new applications but simultaneously few challenges have to be resolved. For millimeter wave operation, the transverse dimension of RF interaction circuit is significantly reduced. This leads to the increase in heat load on the waveguide walls and problem of beam interception [Nanni (2010)]. High magnetic field requirement for the fundamental mode operation is another serious limitation. The dimension reduction limits the power handling capability of the device. The power handling capability of the vacuum electronic devices scales as $f^{5/2}$ (f is operating frequency), which restricts to attain the sufficient power level at millimeter wave range. The device operation at the higher order mode can surmount the problem but dense mode spectrum in the interaction circuit pose the problem of mode competition. Typically, the mode competition causes several serious problems in a vacuum electron device. The presence of parasitic modes reduces the efficiency as well as affects the spectral quality of the device and hence, the performances of different sub-assemblies of the devices, such as, electron gun, the internal mode converter and RF window, and collector are also reduced. Undesired modes often cause heating and out-gassing due to trapped power inside the device. All these problems of gyro-TWT have motivated the author of the present thesis is to implement lossy dielectric loaded RF interaction circuit in place of the conventional cylindrical waveguide structure. The literature of gyro-TWT suggests that lossy dielectric loading in the RF interaction circuit is one of the very effective methods to suppress these oscillations. The two types of dielectric loading, namely uniformly distributed dielectric loading and periodically distributed dielectric loading, which are used in this thesis for the stable operation of W-band gyro-TWT. The uniform dielectric loading (UDL) may lead to the dielectric discharging problem at high output power, therefore the periodic dielectric loading (PDL) is the practically possible case. The metallic rings are inserted between two consecutive dielectric rings to avoid the dielectric discharging problem.

There has not been much work reported in the literature with dielectric loading at higher cyclotron harmonic operation of gyro-TWT. The present study is also aimed to extend and adapt the existing dielectric loading technique to study the gyro-TWT at second harmonic operation. Therefore, to reduce the requirement of high magnetic field at fundamental harmonic operation and to increase the power handling capability, the W-band gyro-TWT with periodic dielectric loading is designed and simulated to operate at second order harmonic as well as at higher order TE_{02} mode. The investigation of the dielectric loaded circuit is performed analytically by solving the time-domain Maxwell equations and by using finite integration technique based "Computer Simulation Technology (CST) Particle Studio" code. The multimode mode beam wave interaction behavior is also presented by developing steady state multimode code. Apart from the interaction structure, various sub-assemblies of gyro-TWTs are designed and simulated individually to study the overall performance of the device.

In the remainder of this chapter, the various mechanisms to generate microwave radiation using vacuum electron devices are discussed in section 1.2. The basic working principle of gyrotron devices is discussed in section 1.3. The classification of gyrotron devices is presented in section 1.4. A brief of gyro-TWT development over the past decades is discussed in section 1.5. A detailed literature review of gyro-TWT amplifier covering both experimental and theoretical studies over the last decades is presented in section 1.6. The problem definition and the research objective are provided in section 1.7 and the organization of the thesis is described in section 1.8.

1.2. Physics of Microwave Radiation

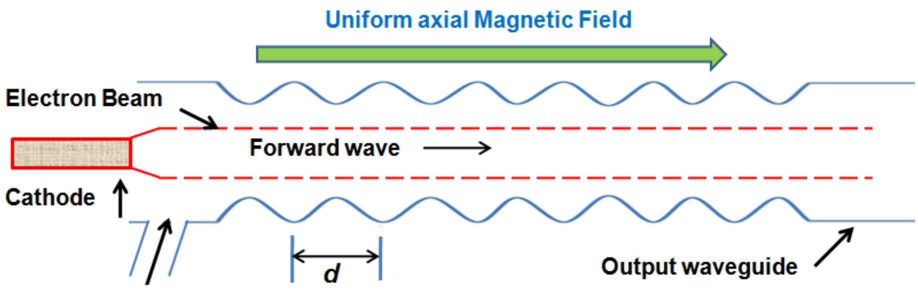
All the vacuum electron tubes use charged particle to generate coherent emission of electromagnetic (EM) radiation. Their working principle is based on the conversion / transfer of some portion of the kinetic or potential energy of highly energetic charged particles (electrons) to the EM wave radiation [Gilmour *et al.* (1986)]. There are three basic microwave generation mechanisms by bunching of charged particles namely Cherenkov radiation, Transition radiation, and Bremsstrahlung radiation [Table 1.1].

Table 1.1: Classification of electromagnetic radiation

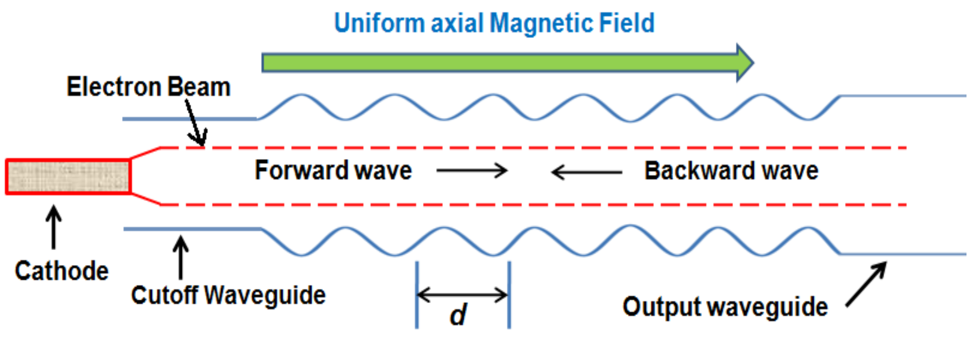
S. No.	Radiation Type	Device
1	Cherenkov	TWTs, BWOs
2	Transition radiation	Klystron
3	Bremsstrahlung radiation	Gyrotrons, CARMs, FELs.

1.2.1. Cherenkov radiation

An electromagnetic radiation that occurs when the medium of electrons travelling have refractive index larger than unity, and also electrons's velocity is greater than the phase velocity of propagating EM wave [Garate *et al.* (1990)]. Such kind of EM radiation is basically considered as Cherenkov radiation and usually realized in slow wave devices such as TWTs and BWOs. In slow wave devices, their interaction structure is modified in order to reduce the phase velocity of the EM wave than velocity of light. Figure. 1.1 shows schematic view of the TWTs and BWOs.



(a)



(b)

Figure 1.1 The basic schematic of (a) TWT and (b) BWO.

1.2.2. Transition radiation

Transition radiation is generated when electrons travel through a boundary between two media with different refractive indices or encounters an alteration in refractive index in the medium of their pathway through some perturbation such as conducting grids, or plates [Happek *et al.* (1991)]. Klystron is a slow wave vacuum electron device based on the transition radiation. The short-gap resonant cavities provide the perturbations as required for the EM radiation. The basic schematic view of the klystron is presented in Figure. 1.2. In the first cavity, the interaction between electron beam with a selected mode of the cavity occurs and results in the modulation of axial drift velocities of electrons by electric fields associated with the cavity mode. A space-charge wave with continuously growing amplitude is excited in the drift space between the two cavities, and bunches the electron beam simultaneously. In the second cavity, the bunched beam excites the cavity mode and the electromagnetic field is coupled out.

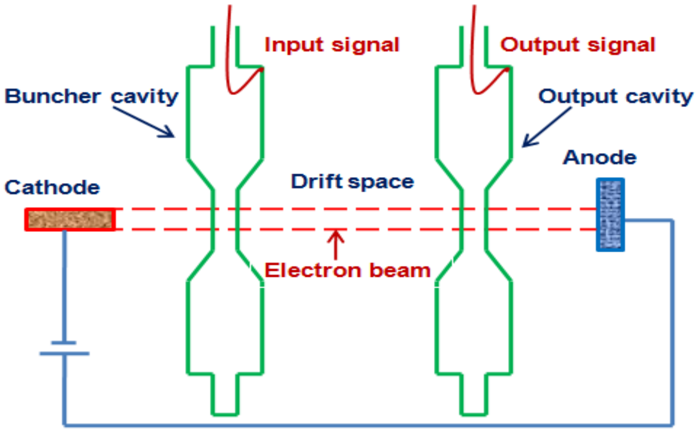


Figure. 1.2 The basic schematic of Klystron.

1.2.3. Bremsstrahlung radiation

Bremsstrahlung radiation occurs when an interaction between relativistic phase bunched electrons and EM wave under the static magnetic field experiences an accelerating or decelerating force and leads to the extraction of transverse kinetic energy of electron beam and generate coherent EM radiation [Blumenthal *et al.* (1970)]. This phenomenon is basically known as cyclotron resonance maser (CRM) principle. The best-known devices based on bremsstrahlung radiation are the cyclotron resonance masers (CRMs) where the electrons gyrate in a static axial magnetic field. The necessary condition for the beam synchronism is

$$\omega - k_z v_z = s\Omega_c \tag{1.1}$$

where, Ω_c is the electron cyclotron frequency, s is the harmonic number, k_z, v_z and ω are the longitudinal (axial) wavenumber, axial drift velocity of the electrons and wave angular frequency, respectively.

Gyro-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 electron cyclotron maser devices. A schematic diagram of cyclotron resonance maser (CRM) instability-based gyrotron device is shown in Figure 1.3. A hollow electron beam gyrating in its Larmor radius interacts with transverse electric field of a waveguide /cavity mode under a constant magnetic field in axial direction to generate the coherent Bremsstrahlung radiation.

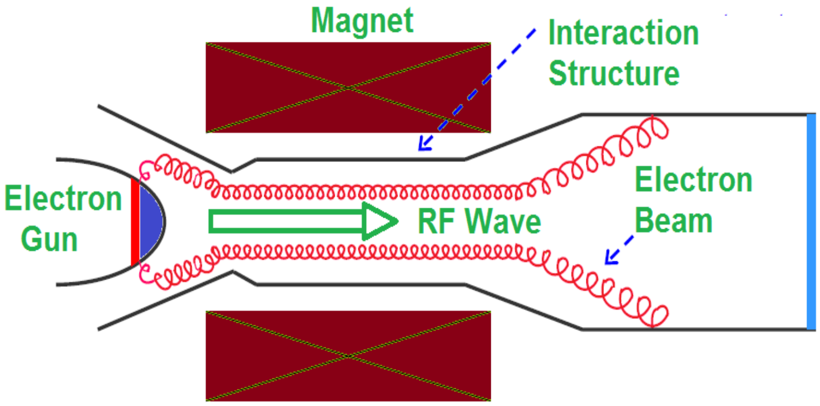


Figure. 1.3 Schematic diagram of a cyclotron resonance maser configuration

1.3. Cyclotron Resonance Maser Principle

The cyclotron resonance maser (CRM) is based on a stimulated cyclotron emission process involving high energy electrons in gyrating motion. The principle of CRM instability can be illustrated from Figure 1.4. Figure 1.4(a) shows the cross-sectional view of the CRM system with TE_{0n} waveguide mode and a hollow electron beam moving through a waveguide with radius of r_{w}. The electron beamlets on the transverse plane is moving with the transverse velocity v_t in its Larmor orbit under the static magnetic field B_0. The Larmor radius of the electron beam can be defined as,

$$r_L = \frac{v_t}{\Omega_c} \tag{1.2}$$

The center of their Larmor orbit is on or around the guiding center radius, r_g. The electron cyclotron frequency, Ω_c can be defined as

$$\Omega_c = \frac{eB_o}{\gamma m_e} \tag{1.3}$$

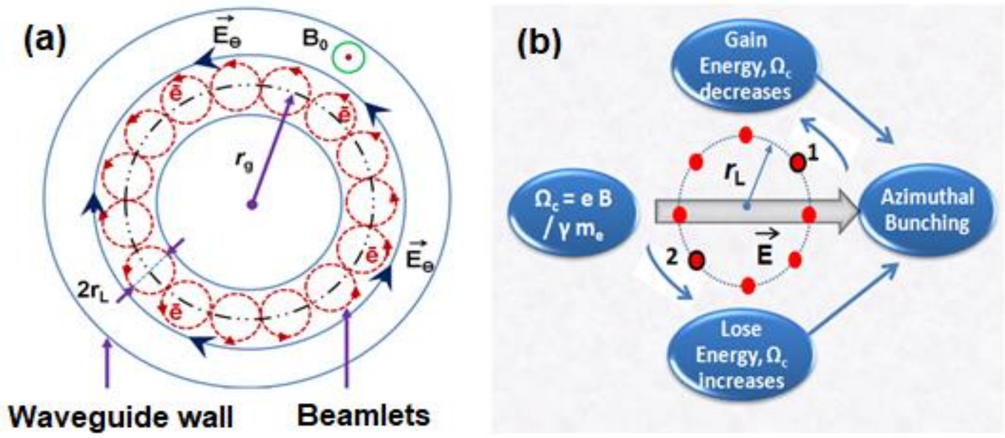


Figure. 1.4 Schematic of (a) TE_{0n} waveguide mode and electron beamlets in metallic waveguide and (b) phase space bunching in gyrotron devices.

The relativistic factor (γ) is dependent on the electron beam energy (e*V*), which given by

$$\gamma = 1 + \frac{eV}{m_e c^2} = 1 + \frac{V(kV)}{511} \tag{1.4}$$

In the presence of transverse electric field $\vec{E}$, the electrons experience either acceleration or deceleration, with respect to the relative phase of the wave. Due to the relativistic dependence, the accelerated electrons gyrates slower (Ω_c decreases) as their energy increases (γ increases), while the decelerated electrons gyrates faster (Ω_c increases), as their energy decreases (γ decreases). This process repeats and results into an electron bunch in cyclotron phase space [Chu *et al.* (2004)], known as "phase bunching". Initially, in the absence of electric field the electrons are arranged in random phase, hence the net energy exchange is zero. When the electric field is applied, the electrons are bunched in phase and half of the electrons is accelerated and the other half is decelerated, still there is no net energy exchange between the wave and electrons. So, to get a net electron beam-wave energy exchange, the RF wave frequency is kept slightly greater than the cyclotron frequency of electrons [Kartikeyan *et al.* (2004)]. From the above discussion we can see that the relativistic effect of electron cyclotron movement forms the basis of CRM instability in gyrotron devices. Due to this effect, the electrons gaining energy become heavier in relativistic masses and lag behind in phase, while the one losing energy acquire phase advances. Such kind of phase bunching imparts an AC component to the electron beam current and thus enables the emission of EM waves. As a matter of fact, the electron movement in gyro-devices can be easily understood by relating to the motion of the moon in solar system. An electron (like 'moon') orbits the guiding center (like 'Earth') in Larmor circle along the magnetic flux line, while the guiding center orbits the cavity transverse center (like 'Sun').

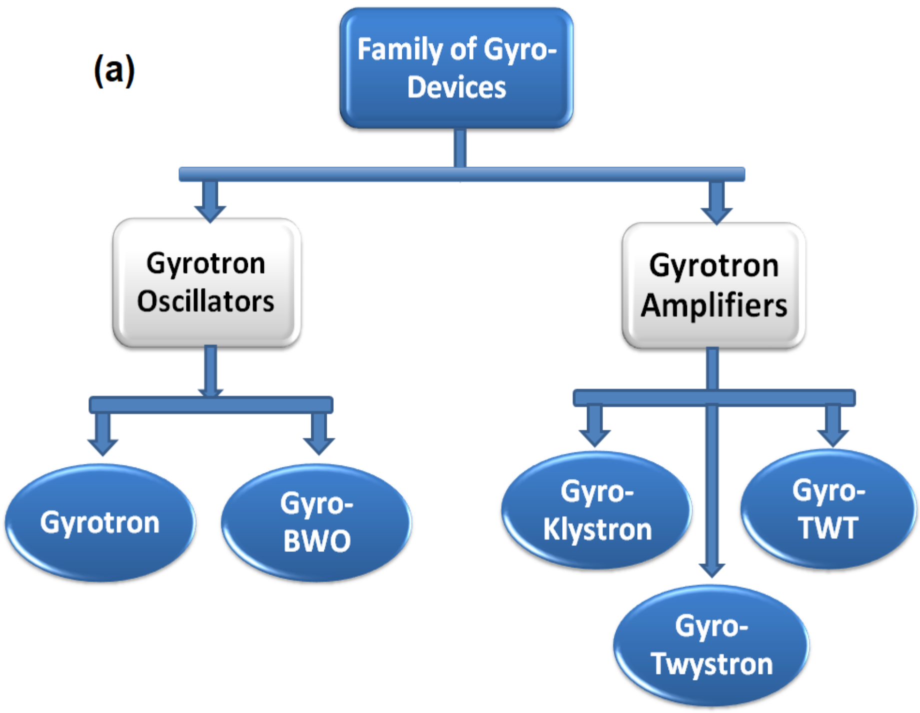
1.4. Classifications and Applications of Gyrotron Devices

The configurations based on the CRM principle consist of a family of devices, simply known as Gyrotron devices. The family of gyrotron devices includes gyrotron oscillator, gyrotron backward-wave oscillator (gyro-BWO), gyro klystron amplifier, gyrotron travelling-wave tube amplifier (gyro-TWT), gyro-twystron [Chu *et al.* (2004)]. Each device is differing by its wave-particle interaction configuration and dispersion diagram. The family tree diagram of gyrotron devices with their respective dispersion diagram is shown in Figure 1.5(a) and 1.5(b). In each device, the gyrating electron beam under a DC magnetic field propagates in the cavity / waveguide, where it interacts with the electromagnetic mode of the cavity / waveguide. Some portion of the kinetic energy of electron beam is transferred to the electromagnetic signal. The generated microwave signal is extracted through the microwave window, while the spent electrons are collected on the collector wall [Kartikeyan *et al.* (2004)]. On the basis of growth characteristic (amplifier / oscillator), the gyrotron devices can be classified into two variants, (i) gyrotron oscillators, in which electromagnetic radiation originates through the self-excite oscillations or noise signal and (ii) gyrotron amplifiers, for which some external microwave signal is required to be amplified as an electromagnetic radiation. The classification of the gyrotron devices with unique features and major application are listed in Table 1.2. The devices under these classifications are briefly discussed in this section.

Table 1.2: Classification of Gyrotron Devices

Type	Gyro-devices	Features	Major Applications
Oscillators	Gyrotron	High average power	Fusion plasma Heating Industrial processing
	Gyro-BWO	Continuous frequency tunability	Spectroscopy Medical imaging
Amplifiers	Gyro-TWT	Phase control Broad bandwidth	High-resolution radar
	Gyro-Klystron	Phase control High gain Narrow bandwidth	Particle accelerator Space radar
	Gyro-Twystron	Moderate gain Moderate bandwidth	Particle accelerator Space radar

(a)



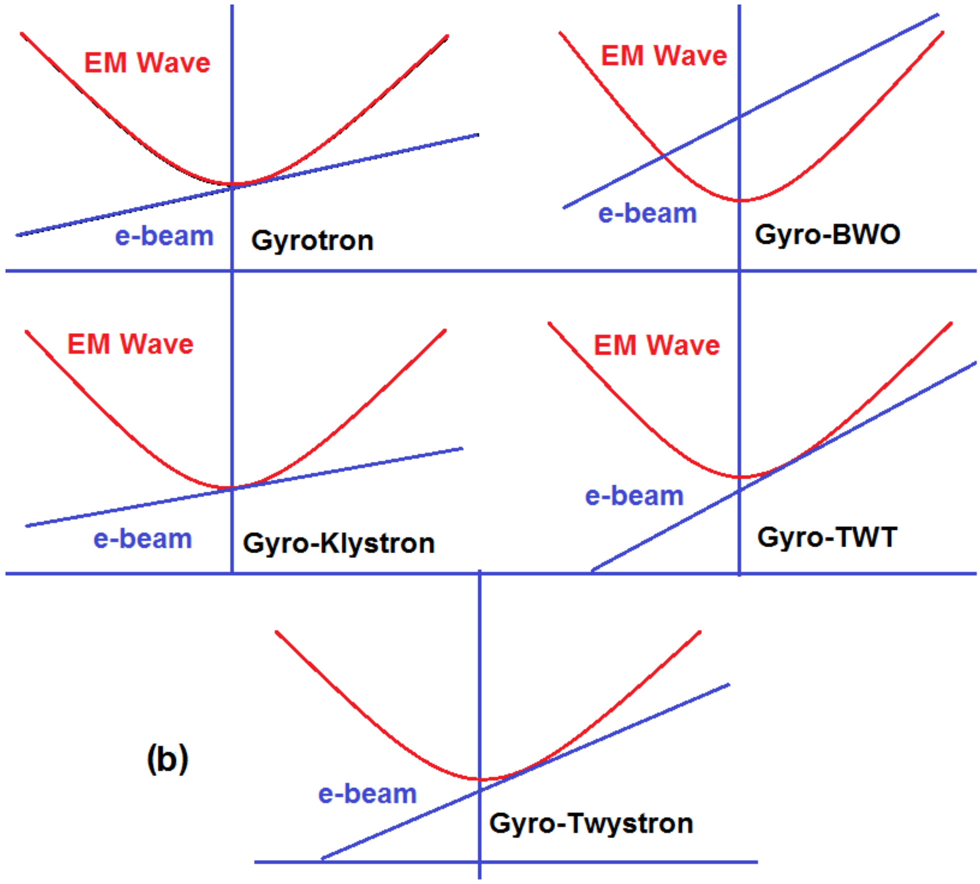


Figure 1.5 (a) Family tree diagram and (b) dispersion diagram of gyrotron devices.

1.4.1. Gyrotron Oscillators

Gyro-monotron and gyrotron backward wave oscillator are the devices that come under the category of gyrotron oscillators. They can generate the EM radiation through the local cavity interaction. The gyro-monotron, also known as gyrotron, which is basically employs a single cavity as an RF interaction structure and operated near to the cut-off frequency of the cavity mode. It generates EM radiation through self-excited oscillations. As the gyrotron is operated near to the cut-off frequency, it offers a strong coupling between the wave and particle, high power with excellent stability, and higher efficiency. The gyrotron is the most developed device among the gyrotron family. The applications of gyrotrons have been extended from microwave wave to low THz wave technology. The W-band gyrotrons have been developed as nonlethal active denial weapon to serve for crowd control and anti-terrorist activities [Neilson *et al*. (2009), Kumar *et al.* (2014)]. The gyrotrons have played an important role in the development nuclear fusion experiments by generating power in excess of 1 MW at frequencies higher than 100 GHz [Beringer *et al*. (2010)]. It is the main source for continuous wave high power (megawatt level) microwave radiation program at 170 GHz for world's largest experiment to demonstrate the scientific and technical feasibility of Fusion power i.e., International Thermonuclear Experimental Reactor (ITER) [Piosczyk *et al*. (2003), (2005)]. In the latest, gyrotrons have found its application in spectroscopy with few tens of watts power level in THz frequency band [Glyavin *et al.* (2008)].

A gyro-BWO utilizes the internal feedback mechanism between the forward travelling electron beam and backward propagating EM wave. It is able to excite the EM radiation through the self-start oscillations without any external feedback. In gyro-BWO, the beam-wave synchronization occurs in the backward wave region of the dispersion curve. As the coupling strength between the wave and particle exceeds a threshold limit, the gyrating electrons are modulated by the backward wave due to the internal feedback mechanism. If this feedback is strong enough, a self-excited oscillation is developed. The gyro-BWO has wideband tunable capability, which makes it suitable for frequency tunable system.

1.4.2. Gyrotron Amplifiers

The devices that falls under the category of gyrotron amplifiers are namely, gyro-klystron, gyrotron traveling wave tube (gyro-TWT) amplifier, and gyro-twystron. These devices are required an external input signal to excite the EM radiation. The configuration of gyrotron amplifier's variants closely related to the conventional linear beam vacuum tube amplifiers with the advantage of fast wave configuration.

The gyro-klystron amplifier is a device similar to the convention klystron as operated with standing waves in two or more cavities. The input cavity is fed by an RF signal, which velocity modulates the electron beam in the input cavity. There is a ballistic bunching of electron in the drift space between the cavities. The amplified high-power EM radiation is excited by the modulated beam in the output cavity. The gyro-klystron delivers the high power over the narrow frequency bandwidth (~ 1 %) only due to the resonant cavity structure [Blank *et al.* (2000)]. The major application of gyro-klystron includes the linear accelerator and space radar system.

Similar to the conventional TWT amplifier, the gyro-TWT amplifier is operated with traveling wave fields. It uses a non-resonant RF interaction waveguide instead of resonant structures. The beam-wave synchronism in the forward wave region (grazing intersection) leads to the convective instability in the device, which causes the amplification of the operating wave [Song *et al.* (2004)]. The high-power broadband EM radiation capability of gyro-TWT makes it the most suitable candidate for high-resolution remote-imaging radar system and is attractive for millimeter wave defense application. 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, etc. for broad-banding of the device. An important problem that must be dealt with in gyro-TWT design is maintaining stability and preventing backward wave oscillations (BWO) in the interaction space [Du *et al.* (2014)]. At the same time, acceptable performance, including high overall gain, stability to local reflective oscillations, and high average power capability must also be achieved.

Similar to the conventional twystron, the gyro-twystron is operated with pre-bunching provided by standing-wave fields in the cavity section and extraction of energy occurs via traveling wave fields in the output waveguide section [Kou *et al.* (1997)]. The gyro-twystron, like the conventional twystron, is a hybrid device with a modest bandwidth capability. It is derived from the gyro-klystron by using the gyro-klystron interaction in the cavities near the RF input and by replacing the output cavity with a slightly tapered waveguide section as in the gyro-TWT to be discussed in the subsequent section. The output section is excited by the electron beam, which has been bunched by the interaction in the klystron section. The configuration of the gyro-twystron can prevent the problem of breakdown at high-power levels because the RF power density in the output waveguide can be much smaller than that in the gyro-klystron output cavity. It has the applications in both linear accelerator and space radar system [Blank *et al*. (2003)].

1.4.3. Applications of Gyrotron Devices

The gyro-devices or simply gyrotrons are used in a variety of applications at microwave to millimeter/submillimeter wave frequencies where high-power electromagnetic radiation is the primary requirement. At microwave and millimeter wave frequencies, the gyro-devices exhibit numerous unique advantages as a high-power source as compared with other sources either solid-state devices or convention vacuum electron devices (VEDs). Recently, with the development of high-power source in millimeter and sub-millimeter wave regime, the microwave sources especially gyro-devices have received a lot of publicity as the potential source for variety of applications including, civilian and military, industrial, medical and scientific research areas. The civilian applications include broadcast media transmission (Television and radio), cellular (wireless) communication radars, satellite communication radar for air-traffic control, weather monitoring. The gyro-devices are widely used in military applications as high-power source for defense radar system and as high-power microwave (HPM) weapons and non-lethal weapons. A non-lethal anti-personnel weapon called active denial system (ADS) was developed by Raytheon for US Air Force Research Lab based on a 95 GHz gyrotron [LeVine (2009)]. In this non-lethal weapon, the gyrotron is operated at 95 GHz with 30–100 kW power that is used for the illumination of humans. The industrial application of the gyrotron includes heating of plasmas, ceramic sintering, chemical processing, material processing, food processing, etc. [Clark *et al.* (1996)]. The millimeter-wave radiation is drawing the attention of the research community especially in Ka- and W-band, where the microwave atmospheric window opens up a lot of applications for high power microwave radiation sources such as, millimeter wave advanced radar system with improved resolution of the objects, Active Denial System for crowd control and anti-terrorist activity, radar system for airport surface movement detection. The atmospheric window allows these sources to work more effectively in the rain, fog, and battlefield smoke work environment, compared with infrared and optical radars [Du *et al.* (2014)]. The W-band high power gyro amplifier developed by Naval Research Laboratory (NRL), and Lincoln Laboratory and Massachusetts Institute of Technology (MIT) Haystack Observatory, USA for advanced high-resolution radar system, W-band advanced radar for low observable control (WARLOC) and Haystack Ultra-wideband Satellite Imaging Radar (HUSIR) transmitter, respectively [Danly *et al*. (2002), Linde *et al.* (2008), MacDonald *et al.* (2014)]. The Italian Space Agency (ASI) have investigated the feasibility of using W-band amplifier under their major projects DAVID (DAta and Video Interactive Distribution), Wave (W-band Analysis and VErification) [Bonifazi *et al.* (2002), Jebril *et al.* (2005)]. In 2006, the National Aeronautics and Space Administration (NASA) has also started a mission 'CloudSat' to carry a space-ready high-power W-band amplifier operating at 94 GHz [Stephends *et al.* (2002)]. Terrestrial radars applications are employed at airports. Smaller dimensions mini radar of W-band technology, called SMART is in operation in airport surveillance applications [Galati *et al.* (1995)]. These are installed at Frankfurt Airport in 2001 and at the Venezia "Marco Polo" airport. These two are used for the control of air traffic on the airport surface (surface movement radar). These are operated at 95GHz and have shown improved target detection as compared to other similar radars. Electron Spin Resonance (ESR), sometimes called Electron Paramagnetic Resonance (EPR), is an area where the use of W-band microwave sources has enabled many breakthroughs [Tatsukawa *et al.* (1998)]. The concept of ESR is that in a sample with one or more unpaired electrons, such as free radicals having unpaired electrons, a transition between spin states can be induced by the application of a magnetic field and electromagnetic energy in the form of microwaves. This allows one to measure the absorption spectra and from this classify the sample. The use of high frequencies like W-band allows superior sensitivity and resolution in the measurement of samples. Their recent advancement toward higher frequencies (300 GHz -3 THz) called submillimeter wave or simply terahertz (THz) region has opened the door to many new applications in the broad fields of high-power terahertz science and technologies. Among them are advanced spectroscopic techniques, most notably NMR-DNP (nuclear magnetic resonance with signal enhancement through dynamic nuclear polarization) [Idehara *et al.* (2010)].

1.5. The Development of Gyro-TWTs

Since 1970s, the gyro-TWT experimental research has made use of various types of interaction structures, including simple cylindrical waveguides, rectangular waveguides [Barnett *et at.* (1979), (1980)], transverse varying rectangular waveguides

[Park *et al.* (1995)], distributed loss-loaded cylindrical waveguides [Chu *et al.* (1998), (1999)], dielectric-loaded cylindrical waveguides [Leou *et al.* (1996)], lossy dielectric-loaded cylindrical waveguides [Garven *et al.* (2002)], radially sliced lossy cylindrical waveguides [Wang *et al*. (1995), Chong *et al*. (1998)], helically corrugated waveguides [Denisov *et al.* (1998), Bratman *et al.* (2000)], and cavities based on photonic-band-gap defect structure [Sirigiri *et al.* (2001)] and quasi-optical confocal waveguides [Sirigiri *et al.* (2003)]. The above experimental studies indicate that the stabilization against self-excited oscillation is the main concern of gyro-TWT in order to maintain broadband cyclotron resonance between the electron beam and a waveguide mode. There should be certain kind of disturbance or control mechanism introduced into a gyro-TWT interaction circuit to suppress oscillations and to achieve zero-drive stability (output should be zero when there is no input) [Chu *et al.* (2004)]. All of these different interaction systems can be classified into three categories of technological development in the gyro-TWT research. Introducing certain kind of loss in the interaction waveguide wall of gyro-TWT is basically comes under the operation mode control methods for example, Aquadag-loaded or lossy ceramic-loaded waveguide. The helical grooved waveguide structure is the example of dispersion relation control technology and use of confocal waveguide or PBG structures are the example of mode filter technology.

1.5.1. Operation Mode Control Methods

The gyro-TWT is very sensitive to the oscillations caused by absolute instability of the operating mode near the cutoff and backward wave oscillation caused by spurious mode excitation. Therefore, it is very necessary to control the excitation of spurious and operating mode. For this purpose, two methods have been popularly used.

The **waveguide wall loss** method was first employed by K. R. Chu [Chu *et al.* (2002)]. In this method, the inner wall of the interaction waveguide is coated with a resistive material to provide the attenuation to the spurious oscillating mode. In 1990s, a TE_{11} mode gyro-TWT experiment has been demonstrated at National Tsing Hua University (NTHU) by K. R. Chu. The experiment has employed a thin distributed lossy layer in the linear stage of the interaction structure. The lossy layer provided the attenuation to the parasitic oscillations and improved the start oscillation thresholds of self-exciting oscillation [Chu *et al.* (1998)]. The lossy linear section also reduced the amplification growth rate of the operation mode; therefore a unloaded nonlinear section is added to achieve the desired gain and power growth.

Later, in the development of gyro-TWT, the more practical way to introduce the loss has been employed by introducing the alternate lossy dielectric and metallic rings. The metal rings have been introduced to reduce the dielectric charging problem. In 2000, the NRL has carried out a series of gyro-TWT experiments based on the interaction circuit employing a lossy circuit loaded with dielectric rings and metal rings along the axis [Calame *et al.* (2002)]. Using the complex and ingenious design, the attenuation of the operation mode was made small, while the competing modes were strongly attenuated by the lossy structure.

1.5.2. Mode Filter Technology

The **Confocal waveguide** can also be used as an interaction structure for a gyro-TWT [Sirigiri *et al.* (1999), (2003)]. The open side wall of the confocal waveguide effectively reduces the mode density inside by introduces scattering loss to parasitic mode and thus suppresses the mode competition and parasitic oscillations. In 2003, Sirigiri *et al.* have experimentally tested a gyro-TWT based on the confocal waveguide structure. The interaction circuit uses an optical sever which helps to achieve higher stability. As compared with the conventional smooth waveguide, the confocal waveguide offers the advantages of low mode density, high starting oscillation current for a spurious oscillation due to the scattering and these factors helps together to achieve the zero-drive stable amplification by effectively suppresses oscillations and mode competitions.

The other mode selective interaction circuit is based on the one of the active research field *i.e.*, **Photonic Band Gap (PBG) Structures**. The PBG structures are periodic lattices of dielectric, metal or composite arrangement and which are transparent (pass) for certain band of frequencies and opaque (stop) for the rest of frequencies [Sirigiri *et al.* (2001)]. The local defects in photonic crystals can be used to localize the electromagnetic fields within the frequency band-gap of the unperturbed photonic crystals. The localized mode frequency depends on the exact nature of the local defect. The defect in PBG structures can be used to guide EM signals, to create frequency-selective waveguides by properly designing the nature of the repeated defect. The waveguide modes that lie in the band gap range are restricted inside the defect while the modes outside the bandgap range are scattered out by propagating through the PBG structures. The PBG waveguide structure is characterized as overmoded and mode selective structure. The first ever gyrotron device based on photonic band-gap structures has been demonstrated at MIT in 2001. This gyrotron oscillator was operated in quasi-TE_{041} mode and showed 30 % magnetic tuning range near the operating point without any mode competition. Later, MIT also carried out a 250 GHz gyro-TWT experiment by employing photonic band-gap structures operating in TE_{03}-like mode. These experiments are being important for future development of gyrotron oscillators and amplifiers operating at high-order modes and high harmonic.

1.5.3. Dispersion Relation Control Technology

The gyro-TWT amplifier based on a helically corrugated waveguide has been successfully developed at the Institute of Applied Physics (IAP) and the Strathclyde

University of UK [Denisov *et al.* (1998), Bratman *et al.* (2000), He *et al.* (2008), Zhang *et al*. (2018), Samsonov *et al.* (2020),]. The helically corrugated waveguide structure is potential candidate of the broadband gyro-TWT interaction circuit with minimum sensitivity to spread in electron's axial velocity. It radically changes the dispersion of the circular waveguide. The operating mode in the corrugated waveguide is basically resulted the coupling between two counter-rotating modes under the condition of Bragg's resonance. In this interaction waveguide, the dispersion curve of the resultant operating eigenmode is approximately a straight line close having constant group velocity near the region to zero axial wavenumber (k_z = 0). Therefore, the resultant eigenwave can interact with the cyclotron harmonic beam-mode line over the wide frequency band. As the helically corrugated interaction structure is compared with a conventional smooth cylindrical waveguide, the helical waveguide scheme is found to be more insensitive to axial velocity spread.

1.5.4. High-Order Mode Interaction Structure

The operation of CRM devices at higher order modes (HOM) is the main reason that they are capable of generating higher power than the conventional VEDs in high frequency region like millimeter and submillimeter wave regime. One of the major developments of gyrotron devices is the tendency to explore the high-order mode interaction [Chu *et al.* (2004)]. The HOM operation enlarges the interaction space for beam-wave interaction and accordingly boosted the power handling capacity of the device. The state of the art of gyro-TWT amplifier experiments till now have employed operation modes including rectangular waveguide TE_{10} mode [Park *et al*. (1995)], cylindrical waveguide TE_{11} mode [Pershing *et al.* (2002), Nguyen *et al.* (2001)], cylindrical waveguide TE_{21} mode [Chu *et al.* (1998)], cylindrical waveguide TE_{01} mode [Calame *et al*. (2002)], helically corrugated waveguide TE_{11} / TE_{21} coupled mode

[Bratman *et al.* (2000), Denisov *et al.* (1998)], and HE_{06} mode in confocal waveguide [Sirigiri *et al.* (1999)]. It is concluded that, in contrast with the gyrotron oscillator, most of the gyro-TWTs experiments were carried out on relatively low-order modes and while a few higher-order mode gyro-TWT experiments were also there with a special mode control technology. For example, at MIT Sirigiri *et al.* have experimentally demonstrated a 140 GHz gyro-TWT by employing a mode selective confocal waveguide with opened side walls, the operating mode was hybrid HE_{06} [Sirigiri *et al.* (2003)].

1.5.5. Higher-Order harmonic Operation

The development of high order harmonic gyro-TWT results in significant advantages [Chu *et al.* (2004)]. Firstly, it reduces the requirement of high magnetic field by the factor of harmonic order ‘s’ as the magnetic field strength has inverse relation to the harmonic order. Taking an example of W-band gyrotron amplifier for defense radar application, the second harmonic mode operation needs a magnetic field requirement of nearly 1.8 T and to produce this much magnetic field the normal permanent coil magnets are available. However, the fundamental harmonic operation for the same mode requires a double magnetic field strength (~ 3.6 T) and for this only superconducting magnet is the choice. A second harmonic gyrotron amplifier based on a permanent magnet coil will reduce the cost and improve the reliability. In addition, the coupling strength of the harmonic mode is weaker than the fundamental mode interaction, which increases the threshold limit of operating beam current for the absolute instability. Thus, gyro-TWT can have zero drive stability even at higher beam current and produces stronger radiation power [Wang *et al*. (1995)]. Another advantage of harmonic operation is with the use of large-orbit cyclotron beams (guiding center r_c = 0), which offers low mode competition at harmonics. That is in a large-orbit interaction system, only TE_{mn} modes with azimuthal index equal to harmonic number ($m = s$) have nonzero coupling coefficient, thus can only interact effectively with the s^{th} harmonic mode. This will definitely, to some extent, suppresses the mode competition.

1.6. Gyro-TWT: A Detailed Literature Review

The research on gyro-TWT amplifier was first started in the early 1970s, mainly at Naval Research Laboratory (NRL). The theoretical studies of the device were carried out in the X and Ku bands operating in the fundamental waveguide mode [Barnett et *al*. (1979), (1980)]. In, 1979, the first experimental gyro-TWT was demonstrated by Seftor and his group, at NRL [Seftor *et al.* (1979)]. The gyro-TWT achieved an output power of 10kW and a stable gain ~17dB at the operating frequency of 35GHz. However, the experimental results show huge difference with the theoretical prediction of the gyro-TWT. The high gain and power of the gyro-TWT was limited by oscillation caused by the absolute instability and backward wave oscillations (BWOs). The instability due to these oscillations was investigated by Lau et *al.* using the resistive wall loss waveguide interaction circuit [Lau *et al*. (1981)]. In 1981, a W-band gyro-TWT predicted an output power of 28kW, 30dB gain, 8% efficiency and a bandwidth of 8% [Eckstein *et al*. (1981)]. Another W-band gyro-TWT operating at 95GHz has predicted 15kW output power, 6.2% efficiency, 30dB gain and 1.6% bandwidth [Grantstein and Alexeff (1987)]. A linear theory using Laplace transform explaining the physical understanding of mechanisms of various spontaneous oscillations of high-power harmonic gyro-TWT was described and its analysis failed in the saturation region, where nonlinearities is become important [Kou *et al.* (1992)]. Nonlinear analysis and design of high-power harmonic gyro-TWT has proved that the high harmonic operation can increase the start oscillation current and generate high output power than fundamental harmonic operation. A three stage second harmonic operation predicted an output power of

533kW, efficiency 21.3%, and 7.4% saturated gain [Wang *et al.* (1992)]. In 1994, Leou has presented the theoretical investigation of two (Ka-band and W-band) stable high-power gyro-TWTs using lossy sever section in the RF interaction circuit. Both configurations were operated in a low-loss TE_{01} mode and yielded a peak power of 230 kW at 35GHz with 23% efficiency, 46 dB gain and 105 kW at 94 GHz with 21% efficiency, 45 dB saturated gain, respectively [Leou *et al.* (1994)]. In 1996, a gyro-TWT amplifier operating at 3rd harmonic by employing a slotted RF interaction waveguide for its stability was studied. This amplifier with an axis-encircling beam of 6% axial velocity spread has developed an output power of 30 kW at 95 GHz, 20% efficiency, and 40 dB saturated gain [Chong *et al.* (1996)]. Consequently, the first experimental 3rd harmonic gyro-TWT in X-band with a multi-section slotted RF circuit was reported as a scaled proof-of-principle test of the 95GHz amplifier. The effect of sever in a two-stage W-band Gyro-TWT using slotted RF sections was also reported [Zhang *et al.* (1998)]. Later, a detailed experimental investigation and stability analysis with linear and nonlinear theories of gyro-TWT amplifier was reported by Prof. K. R. Chu [Chu *et al.* (1990), Chu *et al.* (1995), and Chu *et al.* (1999)]. After the successful experimental verification, the study of various oscillations and instabilities has been carried out through a detailed electrodynamic modeling of the interaction structure which led to a significant step toward the suppression of oscillations and realization of the potential of gyro-TWT. In 1989, NTHU, Taiwan has experimentally tested a Ka-band gyro-TWT that developed 18.4 kW power, with an efficiency of 18.6% and ~10% bandwidth [Chu *et al.* (1989)] and later a Ka-band gyro-TWT with a sever section was experimentally tested that generated 27kW output power, 35dB gain, 16% efficiency with 7.5% bandwidth [Chu *et al.* (1990)]. In 1995, a distributed wall section is employed for effectively suppression of oscillation and produced a 62kW power at 35GHz, 33 dB saturated gain, 21% efficiency and 3-dB bandwidth of 12% [Chu *et al.* (1995)]. The absolute instability was investigated by simulation approach and predicted that the distributed loss is more effective than the severed loss. The Ka-band gyro-TWT produced 62kW, 21% efficiency, and 12% bandwidth with a 33dB gain [Chu *et al.* (1995)]. An early 94GHz, gyro-TWT has produced 20kW output power, 8% efficiency, 30dB saturated gain with 3dB bandwidth of 2% [Granatstein *et al.* (1997)]. A 95GHz gyro-TWT amplifier with slotted waveguide interaction circuit operating at third harmonic has produced 6kW output power, 5% efficiency, 11dB saturated gain with 3% bandwidth [Chong *et al.* (1998)]. The study of instability and suppression of spontaneous oscillations by distributed wall losses, predicted an RF output power of 93kW, 26.5% efficiency, and 70dB gain with a 3GHz bandwidth [Chu *et al.* (1999)]. A mode selective second harmonic W-band gyro-TWT has produced 600kW, with an efficiency of 24%, 30dB saturated gain and a 3dB bandwidth of 2.7% [Wang *et al.* (2000)]. The design of a heavy loaded W-band gyro-TWT amplifier was studied for high power and broadband capability and predicted 140 kW output power for 5% beam velocity spread, 28 % efficiency, 50dB saturated gain and a 3dB bandwidth 5% [McDermott *et al.* (2002), Song *et al.* 2004]. Communication and Power Industries (CPI) demonstrated a W-band gyro-twystron that produced an output power of 60kW, 34dB saturated gain, 15% efficiency with bandwidth of 1.6GHz and gyro-klystron produced 100kW power, 35dB saturated gain, 30% efficiency and bandwidth of 0.7GHz [Blank *et al.* (1999), Blank *et al.* (2002)]. In the last of 20th century at NTHU, Chu and his group have experimentally demonstrated an ultra-high gain Ka-band gyro-TWT that employed a uniformly distributed wall loading for the suppression of spurious oscillations. This TE_{11} mode gyro-TWT has produced 93 kW saturated peak power with zero drive stability, 70 dB gain and a 3-dB bandwidth of 3 GHz [Chu *et al.* (1999)]. At the beginning of 21^{st} century at NRL, Nguyen and his group experimentally tested a TE_{11} mode Ka-band gyro-TWT using lossy ceramic elements that developed 78 kW power, 60 dB saturated gain, 19% efficiency and a 3-dB bandwidth of 17.1% [Nguyen *et al.* (2001)]. Further, in 2002 Graven and his group have experimentally demonstrated a Ka-band lossy ceramic loaded TE_{01} gyro-TWT that developed 137kW RF output power, 47 dB saturated gain, 17% efficiency with a 3-dB bandwidth of 3.3% [Graven *et al.* (2002)]. At MIT, Sirigiri and his group have experimentally tested a 140 GHz gyro-TWT using a novel mode selective confocal waveguide structure. The gyro-TWT was operated at hybrid HE_{061} mode and produced 30kW output power, 29 dB saturated gain, efficiency of 25%, and bandwidth of 1.1% [Sirigiri *et al.* (2003)]. The analysis of multi-stage gyro-TWT by using self-consistent code predicted 155kW output power, 15% efficiency, and 45 dB gain with 2.2GHz bandwidth [Yeh *et al.* 2003] at 32.9 GHz for the velocity spread of 5%. Similarly, a 2^{nd} harmonic multistage W-band gyro-TWT predicted a peak power of 215kW at 89.9 GHz. For a 100kV, 15A electron beam with an axial spread of 5%, the efficiency and saturated gain of the device were calculated as ~ 14%, and 60 dB, respectively [Yeh *et al.* (2004)]. Tsai and his group have examined theoretically, the various source of the absolute instability behavior for a W-band TE_{01} mode gyro-TWT by employing uniformly distributed losses [Tsai *et al.* 2004)].

Recently, the advancement of various simulation codes / tools based on the numerical techniques such as, method of moment (MOM), finite difference time domain (FDTD), finite integration technique (FIT) method, etc. that have been used for electrodynamic modeling and particle-in-cell (PIC) simulation of such devices. Xu and his group have studied a Ka-band gyro-TWT using distributed loss technique for 100kW peak output power, bandwidth of 1.8GHz, electronic efficiency of 23.8%, and the gain of 56dB [Xu *et al.* (2010)]. Ran Yan and his group have designed a Q-band gyro-TWT loaded with periodic rings of lossy dielectric operating in the circular TE_{01} mode at the fundamental cyclotron harmonic gives peak output power of 152kW, saturated gain 41dB, and 21.7% efficiency at 47.6GHz with zero drive stable at the operating point [Yan *et al.* (2012)]. In 2012, E. F. Wang and his group have designed and employed a periodic lossy material loaded circuit for suppressing of spurious oscillations in the experimental TE_{01} mode Ka-band gyro-TWT. They have measured a peak power of 290kW with maximum gain 56dB, 3dB bandwidth of 2.1GHz, and 34.2% efficiency [Wang *et al.* (2012)]. In 2013, C. H. Du and his group designed a W-band TE_{01} mode gyro-TWT pulse prototype for high gain and broadband capabilities, which predicted the amplifier's highest efficiency of 32.4%, and the bandwidth of4.2GHz with output power 50kW [Du (2012)]. The analytical and PIC simulation of a Ka-band gyro-TWT amplifier has been studied for its beam-wave interaction behavior by Thottappan and his group, in which ~135kW saturated RF power with a saturated gain of~41dB and a conversion efficiency of ~23% has been reported. In 2014, Ran Yan and his group designed a W-band zero-drive stable gyro-TWT loaded with non-uniform periodic lossy dielectric rings operating in the circular TE_{01} mode circuit at the fundamental cyclotron harmonic produced a peak RF output power 112 kW with a 69.7dB saturated gain and 23.3% efficiency at 93.5GHz [Yan *et al.* 2014]. In 2014, Yong Tang and his group simulated a W-band TE_{01} mode gyro-TWT with periodic lossy interaction circuit that produced a peak output power of 198 kW, saturated gain of 62.3dB with efficiency of 28.3% at 92.5GHz [Tang *et al.* (2014)]. Wang and his group at the University of Electronic Science and Technology of China, Chengdu, China, experimentally investigated a TE_{11} mode Ku-Band gyro-TWT amplifier by employing a mode selective lossy interaction structure. The hot test results showed 400kW peak power, 23% efficiency, 35 dB gain and 1.6 GHz bandwidth [Wang *et al.* (2017)]. In

2019, the group performed a gyro-TWT experiment with circular TE_{01} mode with ~31.5 kW saturated average output power at 16.2GHz, ~40.5dB saturated gain, 28% efficiency and 2.1GHz bandwidth. Using helically corrugated waveguide, a peak pulse output power 144.8kW was obtained for the average input power of 5.8 kW with an efficiency of 66.3% [Zhang *et al.* (2015)]. For eliminating the mode competition, PBG structures were employed and analyzed the gyro-TWT in Ka-band that predicted an RF output power ~91 kW, efficiency ~13% with a gain of 40dB and its 3D PIC simulation predicted ~90 kW with a bandwidth of around ~14% [Thottappan *et al.* (2016)]. By using a helically corrugated waveguide a continuous output power of 6.0 kW with a bandwidth of 2.1GHz was achieved [Samsonov *et al.* (2016)]. In 2020, Samsonov and his group have presented the experimental details of second harmonic TE_{02} mode W-band gyro-TWT with the use of helically corrugated interaction waveguide. The CW operation of the device produced a maximum output power of 3 kW, gain of 54dB and 15 % efficiency with 2.5 GHz bandwidth [Samsonov *et al.* (2020)].

1.7. Research Objective

The objective of the research undertaken for this thesis is to investigate the multimode beam-wave interaction behavior of W-band gyro-TWT amplifier using nonlinear theories and 3D particle-in-cell simulation code.

The literature study shows that despite of high-power broadband characteristic, the operation of gyro-TWT is highly susceptibility to various severe oscillations. The oscillations caused by absolute instabilities of operating mode and backward wave oscillations are accountable for internal feedback driven instability. The other source of oscillations in gyro-TWT is due the reflections from the input/output waveguide end and accountable for external feedback driven instability. The existing single mode theory which is used for stability analysis and that accounts only one propagating mode and interacting with the electron beam and fails to analyze the mutual effects between the operating and potential oscillating modes. The other major issue with the gyro-TWT is its sensitivity to beam velocity spread due to finite axial wavenumber of the operating point. The spread in beam velocity directly affect the efficiency and bandwidth of the device.

The research tasks carried out for this thesis are as follows:

1. The uniform / periodic dielectric loading scheme has been investigated for W-band gyro-TWT amplifier to effectively suppress the absolute instability and potential BWOs. The multimode beam-wave interaction study has been carried to investigate the mutual effect of operating and potential BWOs on the stability of the gyro-TWT amplifier using nonlinear multimode code and 3D Computer Simulation Technology (CST) PIC code.

2. The magnetron injection gun (MIG) with single anode (diode MIG) and double anode (triode MIG) have been designed and simulated for the fundamental and second harmonic W-band gyro-TWT operation using beam trajectory code EGUN and CST.

3. A Y-shaped power divider TE_{01} mode input coupler for the fundamental harmonic gyro-TWT, a novel TE_{02} mode converter with gradually tapered slotted waveguide section for second harmonic gyro-TWT operation have designed and simulated. The couplers are optimized to feed the gyro-TWT with the desired signal and high mode purity.

4. A three-stage depressed collector to collect the spent beam energy has been designed and simulated using PIC simulation tool “MAGIC”. The three-stage depressed collector predicted 74 % recovery of the spent electron beam.

5. To extract the amplifier RF power different types of microwave windows have been designed and simulated for the fundamental and second harmonic gyro-TWT. The

transmission and reflection characteristics of output window have been analyzed using MATLAB code based on analytical equations and verified with CST simulation results. The analytical code is able to provide a closely comparable result to “CST Microwave Studio” simulation results.

6. A 3D electrodynamic model of W-band gyro-TWT with three-folded helically corrugated waveguide has been modeled and investigated for the beam wave interaction study using PIC simulation. This model is designed to benchmark the experimental W-band helical gyro-TWT performed by He *et al.* (2017). Also, the cold dispersion characteristic of 3-folded helical waveguide has been analyzed using the coupled mode theory and validated with CST 3D simulation tool.

1.8. Organization of the Thesis

The need of multimode mode beam-wave interaction behaviour of RF interaction circuit and stability in the operation over a wide range of frequencies for high frequency gyro-TWT has motivated the author to carry out the work embodied in the present thesis. The present work explores the multimode study of gyro-TWT amplifier employing lossy dielectric loaded cylindrical waveguide as its RF interaction circuit. A detailed insight of the analysis, design, and simulation studies of the lossy dielectrics for the gyro-TWT is presented. The various subassemblies of gyro-TWT are also designed and simulated for the stable and wideband operation of the device. In Chapter 1, the basics of the vacuum electron devices (VEDs) and their applications have been discussed. The current state-of-the art of gyro-TWTs is reviewed with their scope and limitations. The problems pertaining to gyro-TWT at millimetre and sub-millimetre wave region have been illustrated. Further, the possible solutions to get rid-off of these problems have been proposed.

In Chapter 2, fundamental theory of lossy dielectric loaded waveguide and non-linear multimode theory of dielectric loaded gyro-TWT are presented in order to study the beam-wave interaction behaviour of a gyrotron amplifier. The non-linear steady state multimode code is developed to understand the multimode wave-particle interaction phenomenon in the amplifier. The non-linear analysis results are benchmarked against the published W-band gyro-TWT results.

In Chapter 3, the design and simulation studies of gyro-TWT with uniform dielectric loaded RF circuit is presented and validated with the analytical multimode code developed in Chapter 2. The various subassemblies like single anode MIG, Y-shaped TE_{01} mode input coupler, collector and output window are also designed and simulated for the W-band operation. The beam-wave interaction behavior is studied through the beam present simulation using the commercial tool 'CST Particle Studio'. The PIC simulation results are compared with the results obtained from the multimode mode analyses. Both the results are found in good agreement.

Chapter 4 covers the design and simulation of a periodically dielectric loaded interaction waveguide structure to be used in the gyro-TWT as an RF interaction circuit. The periodic dielectric waveguide overcome the problem of dielectric discharging in the uniform dielectric loaded RF interaction structure. The design of MIG has been improved to triode MIG, which allows more parameter space to control the velocity ratio and velocity spread in the electron beam. A three-disk window is designed and simulated for the wideband transmission of the output signal. A three-stage depressed collector is also designed to recover the spent beam energy which in turn increases the efficiency of the gyro-TWT.

Chapter 5 discusses the design and simulation study of a second harmonic operation of W-band TE_{02} mode gyro-TWT. The periodic dielectric loaded waveguide structure is used as an RF interaction circuit for second harmonic operation as it can effectively suppress the undesired modes. A novel TE_{02} mode input coupler is presented to feed the operating mode for gyro-TWT operation. A double-disk window is designed and simulated for the wideband transmission of the output signal.

Chapter 6 discusses a new type of interaction structure with helical corrugation on its inner surface for the W-band harmonic operation of gyro-TWT. This structure radically changes the dispersion characteristic by coupling the two waves and generated an eigenwave with constant group velocity and close to zero axial wave number. This structure provides the ideal dispersion relation for the gyro-TWT and offers insensitivity to the beam velocity spread. A circular TE_{11} mode input coupler is also discussed and the benchmarking of the experimentally demonstrated W-band gyro-TWT has been presented using CST particle-in-cell (PIC) simulation.

In Chapter 7, the work embodied in the present thesis is summarized, and the significant conclusions are drawn from the major findings. The limitations of the present study are also discussed pointing out the scope for further work.