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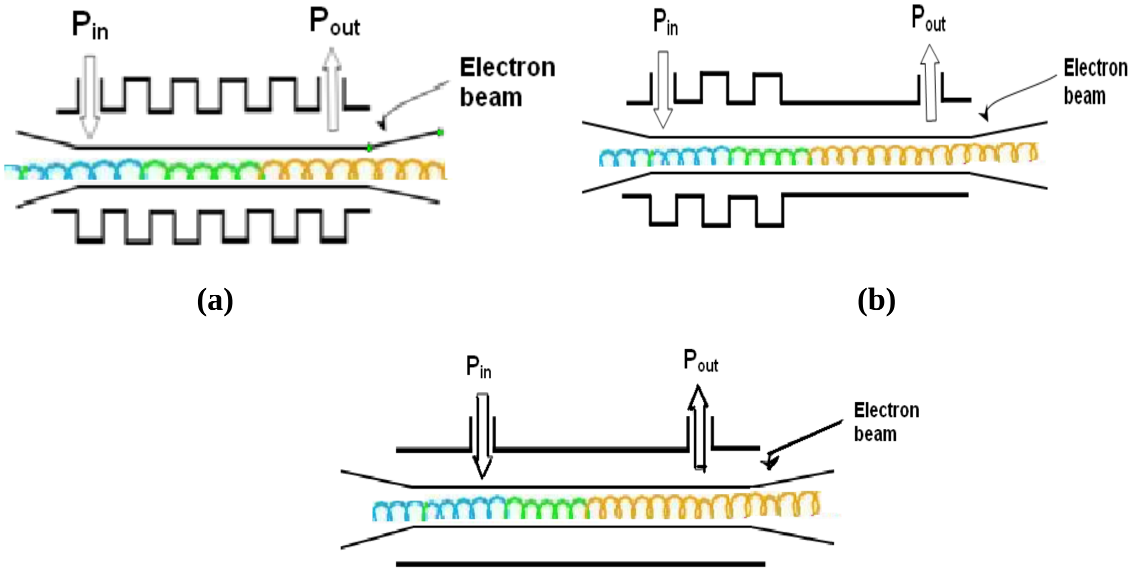
CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

1.1. Introduction

The newer and upcoming application of high power sources at the millimeter and sub-millimeter wave frequencies has led to the continuous research and development activities during the last few decades in an attempt to narrow down the technological gap between the microwave and optical frequencies. Some of these applications are: high information density communication and millimeter wave radars, deep space and specialized satellite communication systems, RF linear accelerators, material processing, plasma diagnostics and chemistry, sintering of ceramic materials, pumping, electron cyclotron resonance (ECR) heating of fusion plasmas, imaging in atmospheric and planetary science, and nonlinear spectroscopy [Collin (1966), Barker *et al*. (2004), Benford and Swegel (1992), Chu (2004), Feinstein and Felch (1987), Flyagin and Nusinovich (1988), Gold and Nusinovich (1997), Grantstein and Alexeff (1987), Nusinovich (2004), Sakamoto (2007), Singh *et al*. (2011), Thumm (2003)]. For high frequency signals, semiconductor devices have lower power handling capability due to the limitation of the size of the device. Thus, to fulfill the power requirement at microwave to millimeter wavelength, research has been carried out at new class of devices called “Microwave Tubes” which generates and amplifies higher frequencies in the microwave range of frequency spectrum. The microwave tubes are mainly classified as slow-wave and fast-wave tubes. In case of slow-wave tubes, the interaction of an electron beam takes place with the RF wave whose phase velocity is less than the speed of light whereas in case of fast-wave devices, the RF phase velocity is beyond or comparable to the velocity of light. Thus, fundamental drawback of the slow-wave tubes is the need of periodically loaded elements, which is used to slow down the electromagnetic waves, so that its phase velocity becomes equal to the mean velocity of the electron beam and the electrons travel in synchronism with the RF fields. In addition, the fast-wave devices utilize cylindrical smooth wall waveguides or cavities as the RF interaction structures and instead of using periodic slow-wave structures, the electron beam is made periodic by introducing the gyrating motion in the beam so that it travels in synchronism with the RF wave. The size of the slow-wave interaction circuit is decided by the wavelength of the electromagnetic radiation which limits the device power handling capability at the higher frequencies. However, due to the efficient operation of the fast-wave devices in the higher order mode of operation, the size of the RF interaction structure does not decrease as much as with frequency as that of the slow-wave structures, thereby can handle higher power with limited ohmic losses. The efficiency of the slow wave devices is very poor at higher order modes and thus the fast-wave devices have a distinct edge at the millimeter-wave frequencies and above [Chu (2004), Shukla *et al.* (2013), Felch *et al.* (1999)]. To fill-up the technological gap for the realization of the high-power millimeter and sub-millimeter wave devices, microwave tube community has made vigorous research efforts in the evolution of fast-wave devices. All the gyro-devices fall under the category of fast-wave devices. Gyro-devices, simply known as gyrotrons, utilize smooth waveguide circuits or large overmoded resonators with periodic electron beams. These device posses advantages of both the lasers as well as the conventional microwave tubes. Although in the range of sub-millimeter to optical region, the free electron laser holds promise to provide high power radiation. The high efficiency feature which has been achieved in gyrotrons and which is predicted for free electron lasers is the key to the sustained level of interest in these devices. In gyro-devices, the resonant frequency is determined by employing the strong DC magnetic field along the interaction structure and the Lorentz force acting on the electrons induce the helical trajectories in the electron beam resulting in the transverse beam-wave interaction. Hence, in high frequency gyro-devices, magnetic field is selected such that the frequency of oscillation is near to the cyclotron frequency either to its harmonics. The magnetic field requirement can be diminished through higher cyclotron harmonic operation. This results in the quite simple oversized resonators and removes the major design constraint of wavelength-size elements in fast-wave devices. The tube diameter is greater than one wavelength; hence the beam diameter and the power density constraints which are significant in case of conventional microwave tubes are not of hindrance in fast-wave devices. These two features empower the fast-wave devices to achieve several orders of magnitude of output power than conventional slow-wave circuit devices. Gyro-devices which include Gyromonotron or Gyrotron, Gyroklystron, Gyro-traveling-wave tube (gyro-TWT), Gyro-BWO, and Gyrotwystron [Chu (2004), Felch *et al.* (1999), Nusinovich (2004)] falls under the category of fast-wave devices. While, the conventional microwave tubes like klystrons, traveling-wave tubes (TWTs), and backward-wave oscillators (BWO), are categorized as slow-wave devices. The family of gyro-devices is divided in two groups, gyro-oscillator and gyro-amplifier. The gyro-oscillator is the category of gyro-devices that utilize single resonant cavity as its interaction structure and the gyro-amplifiers utilize the series of resonant cavities or travelling-wave circuits as its RF interaction structure. The gyromonotron (gyrotron) and gyro-BWO are the key members of the oscillator group of this family. Devices like the gyroklystron, gyro-TWT, and gyro-twystron come under the amplifier group. These devices are analogous to their corresponding slow-wave counterpart's klystron, TWT, and twystron, respectively [Felch *et al.* (1999)]. The most popular and explored member among all the gyro-devices, is the gyrotron oscillator due to its potential applications in the field of basic sciences to recent technologies like molecular characterization, fusion reactors, plasma research, and industrial and heating applications, etc. [Kartikeyan *et al.* (2004), Shukla *et al.* (2013)]. Another application for CW gyrotrons is in material processing [Kumar *et al.* (2011)], and in advanced sintering of ceramics [Link *et al.* (1999)]. However, application of gyrotrons in the information carrying systems such as radars, are not preferred due to the poor signal coherence and spectral quality. Hence, for communication system applications requiring phase coherence and wide bandwidth, gyro-amplifiers, like, gyroklystron, gyro-TWT or gyro-twystron are used [Schlaich (2015)]. The gyro-amplifier configurations are shown in Fig. 1.1.



(a) **(b)**

(c)

Figure. 1.1: Gyro-amplifier configurations **(a)** Gyroklystron**, (b)** Gyro-Twystron, and **(c)** Gyro-TWT.

1.2. An Overview to Gyroklystron Amplifier

The gyroklystron amplifier is a vacuum electron device which is currently under research as the high power millimeter-wave narrowband amplifier. It combines the multi-cavity configuration of a conventional klystron with the energy extraction mechanism of the cyclotron maser instability. The gyroklystron amplifier consists of at least two cavities in which an electron beam is exposed to RF signal, in the input cavity and the amplified RF signal is collected at the output cavity. The bunching process can be further enhanced by adding the additional cavities between the input and output cavities; thereby increasing the overall gain and efficiency of the device. The cavities are electromagnetically insulated from each other and physically separated by the drift tube, which is at cut-off for the RF mode. The physical importance of drift space is to allow the transition of an electron beam with the least possible interaction with the electromagnetic waves and practically form an important part of the electron bunch formation.

1.2.1. Key Elements of Gyroklystron Amplifier

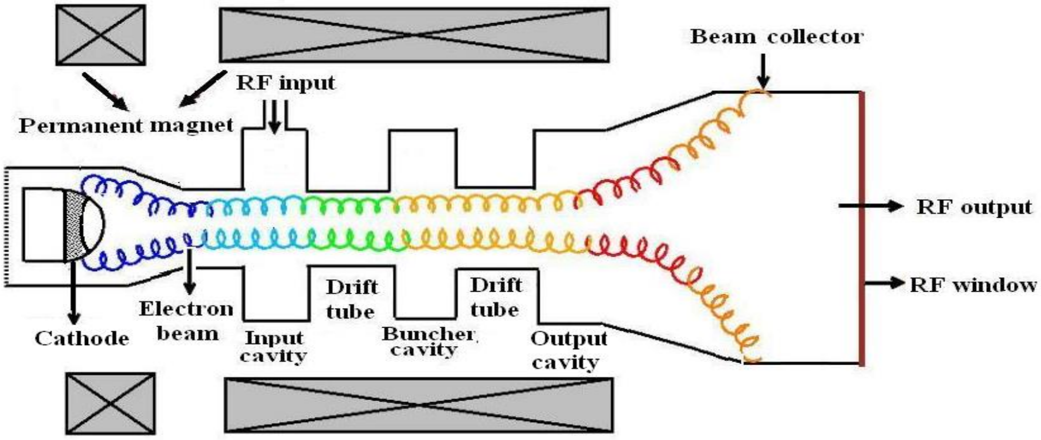


Figure. 1.2: Schematic of Gyroklystron amplifier.

Figure 1.2 shows the schematic of a three-cavity gyroklystron amplifier indicating its components: electron gun, RF interaction structure, output taper, electron beam collector, RF output window, and the magnet system. The role of these elements in the operation of the gyroklystron amplifier is briefly described below.

a) Electron gun

In the gyroklystron amplifiers, the electron gun employs the electrode geometry in which the applied electric and magnetic field are perpendicular to each other in the cathode region. This type of electron gun is called as magnetron-injection gun (MIG), which is responsible for generating high quality electron beam and is crucial for the successful operation of the gyro-device. The MIG consists of a heated truncated-cone-shaped cathode through which electrons are initially accelerated and move towards the anode. The high electric field between this heated cathode and the nearby grounded anode cause the electrons to be pulled off to relativistic velocities. The cathode in MIG is operated in temperature limited region, instead of space charge limited region, to diminish the effect of beam velocity spread. It generates helical electron beam with the desired beam parameters i. e., beam velocity, beam density, and beam diameter etc. The presence of the applied DC magnetic field causes the electrons to follow the helical path at a frequency required for the cyclotron resonance interaction in the gyroklystron. The electron beam continues to gyrate around the magnetic field lines and is then gets accelerated to the applied beam voltage as it passes into the anode region. Thus, the physical construction of the cathode and anode structure causes the electrons to inherit two separate velocities, perpendicular and parallel. The ratio of these velocities is defined as the pitch factor α (alpha) and is typically lies between 1.2 and 1.6. Higher beam α leads to much higher gain, but also higher detrimental effects of the electrons velocity spread. The beam energy transferred to the electromagnetic waves is governed by the perpendicular velocity and not by the parallel velocity. The electron beam quality must be very good in order to produce clean amplification. A good beam quality is characterized by a low velocity spread, which is defined as ratio of the standard deviation of parallel velocity to the parallel velocity and it typically less than 5% for good quality electron beam.

b) RF interaction structure

This is the region where the RF wave interacts with the gyrating electron beam and the electrons transferred their energy to the RF. It mainly consists of a sequence of RF cavities isolated by the region called as drift space, which is at cutoff to the operating mode.

i. RF cavities

The gyroklystron amplifier will consist of probably two to five resonant cavities depending on the design, gain, and output power requirements. Each of the cavities has varying functions. The first cavity is called as input cavity, where a low power electromagnetic wave to be amplified is injected and interacts with the electron beam. As the electron beam is exposed to RF signal in the input cavity, the electric field produces the Lorentz force on the electrons as they spiral around the magnetic field lines. This force causes the change in the perpendicular momentum of the electrons when interacting with an electric field and results in the process called as “electron bunching”. Thus, the electrons are azimuthally bunched in the input cavity in the cyclotron phase angle. The ac beam current produced through the bunching process is significantly enhanced as the electron beam advances through the cavities and drift tubes. In the final cavity (“extraction” cavity or output cavity), the amplified RF output power is extracted out by means of diffractive coupling to the output waveguide [Gilmour (1986), Choi (1998)].

ii. Drift tubes

Drift tube is placed in the space between the two successive cavities in a gyroklystron amplifier. The drift tubes are designed such that no RF field is excited at the frequency of operation, i. e., at cut-off to the operating mode; hence is used to isolate the various cavities of the circuit. In the drift tube length, the electrons group into bunches after undergoing a change in velocity while passing through the cavity gap. The electrons are ballistically phase bunched in the drift tube region which is virtually free of ac charge forces, resulting in the high efficiency, high power, and high gain operation of the gyroklystron amplifier. The proper choice of drift tube length is aimed for maximum bunching effect, which depends on the plasma frequency, and velocity of electrons [Nusinovich (2004), Tran *et al.* (1986)].

c) Collector

The primary role of collector is to collect the spent electron beam after interaction with the RF field. It primarily acts as a trash for the spent electrons. In most gyro-devices, after beam-wave interaction, the electron beam enters into a magnetic decompression region and departed away from the axis to reach up to the collector where the power density is low such that the remaining beam power is safely dissipated [Kartikeyan *et al*. (2004), Edgcombe (1993), Piosczyk *et al*. (1999)]. The complication in collecting the spent electron beam is more in high power gyroklystron due to the employment of relatively thin, hollow electron beam as compared to high power klystrons which employ solid electron beam. In case of output coupling in the axial direction, the spent electron beam will be collected on the section after the up-taper, i. e, uniform output waveguide section and the RF power in the TE_{ml} mode is coupled out axially through the RF window. For the interaction efficiency of 35%, a large fraction of 60% to 65% of the energy is with the electron beam. Hence, the collector must be able to handle the heat loading of a weakly relativistic electron beam and must be properly designed to avoid incurring any hot spots, which leads to a phenomenon that can effectively poison the operation. Thus, thermal design of the collector in high power gyroklystron plays a crucial role in the overall design of the device. Usually, OFHC copper is selected as the material for the collector due to its appreciably good thermal conductivity. To increase the overall efficiency of the device, depressed collector can be used as an energy recovery system which are commonly used for low to medium voltage (< 100 kV), CW microwave tubes [Saraph *et al.* (1998), Piosczyk *et al*. (1999)].

d) Output window

The RF output window is an important component of the output system of the gyroklystron through which the RF output power is transmitted out. It acts as a boundary between the vacuum side of the gyroklystron and the output transmission line. To minimize reflection and absorption of power with better transmission, the designing of output window should be perfect with certain properties such as loss tangent should be low, high thermal conductivity, and mechanically strong. The thermal management of the RF window is an important issue in high power gyroklystron and must be taken into consideration during the design phase of RF window. Therefore, the operating temperature of the window has to be chosen carefully [Yong *et al.* (2007), Gilmour (1986)]. Low-loss materials, like, alumina, beryllia, sapphire etc. are used for fabrication of RF output window. Nowadays, CVD diamond windows are also used for high power applications, but they are costly [Tsimring (2006), Heidinger *et al.* (2002)].

e) Output taper

Output taper is used to convert the standing wave into the traveling waves. It separates the microwave energy from the electron beam, which is guided by the constant magnetic field into a collector. It converts the higher-order operating mode into Gaussian like beam, linearly polarized radiation, thus minimizing the problem of mode conversion. In a conventional gyroklystron, having an axial arrangement for extracting RF wave, the output taper is a nonlinear tapered waveguide which provides the mode purity while transfer of mode from the output cavity to the output window. In the quasi optical gyroklystron, it basically consists of a number of parabolic mirrors, so that RF is collected through the gyroklystron window at right angle to the electron beam transmission [Lawson (1990), Nagarkoti *et al*. (2012)].

f) Magnet system

The magnet system is also an important sub-assembly of the gyroklystron device. It must provide strong enough magnetic field to cause the electrons to emit cyclotron radiation at the desired frequency of operation and it must have a long length of uniformity throughout the cavity structure. The applied magnetic field causes the electrons to execute helical trajectories at a frequency required for cyclotron resonance interaction in the gyroklystron. The electron beam continues to gyrate around the magnetic field lines and is then soon accelerated to the applied beam voltage. For high frequency fundamental mode of operation, magnetic field requirement is high; hence, superconducting magnet coils are generally employed [Hazelton *et al.* (1998), Edgcombe (1993)]. To reduce the magnetic field requirement, the device is also designed to operate at its harmonics. For harmonic operation, superconducting magnets are replaced by permanent magnets.

1.2.2. Working Principle

In the gyroklystron amplifier, the electrons leave the cathode with a strong transverse velocity component and start spiraling, with a frequency called as cyclotron frequency. The gyrating electron beam interacts with the transverse velocity component of the electromagnetic fields and not with the longitudinal component as in case of conventional klystrons. The RF signal to be amplified is coupled into the input resonator cavity and imparts velocity modulation to the gyrating electrons. Azimuthal electric field of desired mode modulates the perpendicular velocity of electrons and the Cyclotron Resonance Maser (CRM) Instability, causes the azimuthal bunching of the electrons which grows as the electron travels towards the output cavity through certain drift space length. Thus, as a result, the bunched electrons will interact efficiently with the RF field provided phase of the RF field has an appropriate value. The drift space is designed in such a way that the RF field excited is negligible. The bunching process and device gain can be further enhanced by placing additional RF interaction cavities. In the output cavity, the azimuthally bunched electron beam is continuously decelerated and transfers their energy to a TE mode which is coupled out axially and thus one gets the amplified output. Further, the entire bunching mechanism in the gyroklystron amplifier can be explained in terms of the two main operating principles:

a) Cyclotron Resonance Maser (CRM) Interaction

b) Phase Bunching

a) Cyclotron Resonance Maser (CRM) Interaction

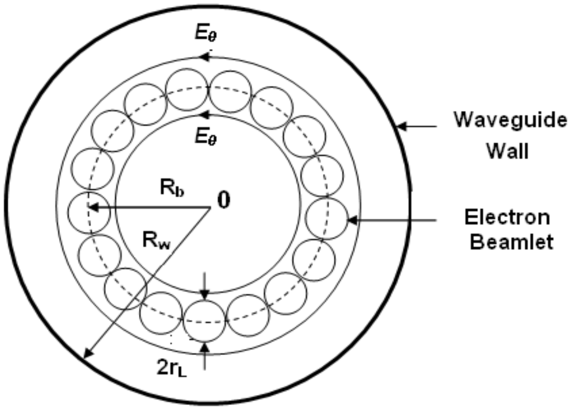


Figure. 1.3: Illustration of the fields of a TE_{01} waveguide mode with a superimposed electron beam.

When the electron beam is passed through a series of RF cavities, it interacts with the RF field in the cavities. The mechanism of this interaction is explained by an instability called as CRM instability [Chu (2004)]. Let us consider an annular gyrating electron beam drifting through a waveguide which immersed in an axial static magnetic field B_0. The typical configuration of CRM interaction [Kartikeyan *et al*. (2004)], is shown in Fig. 1.3.

The employed setup has a circular waveguide with radius R_w. The average beam radius is R_b, which is also the guiding center radius of the beamlets. The beam is usually obtained through Magnetron Injection Gun (MIG) by launching a hollow annular electron beam at an angle to the static axial magnetic field to induce gyrations in the trajectory of each electron. Ideally, the thickness of the beam is equal to twice the Larmor radius (r_L) which is defined by the expression:

$$r_L = \frac{c\, v_t}{\omega_c} \quad , \tag{1.1}$$

where, c is the velocity of light in vacuum, v_t is the electron transverse velocity, ω_c is the angular cyclotron frequency of the electrons. The direction of the field lines of a TE_{01} mode is shown in Fig. 1.3. The electron beam is characterized by an axial velocity v_z, transverse velocity v_t, and the relativistic mass factor γ is given by the expression:

$$\gamma = \frac{1}{\sqrt{1-\left(\frac{v_t^2+v_z^2}{c^2}\right)}} \quad . \tag{1.2}$$

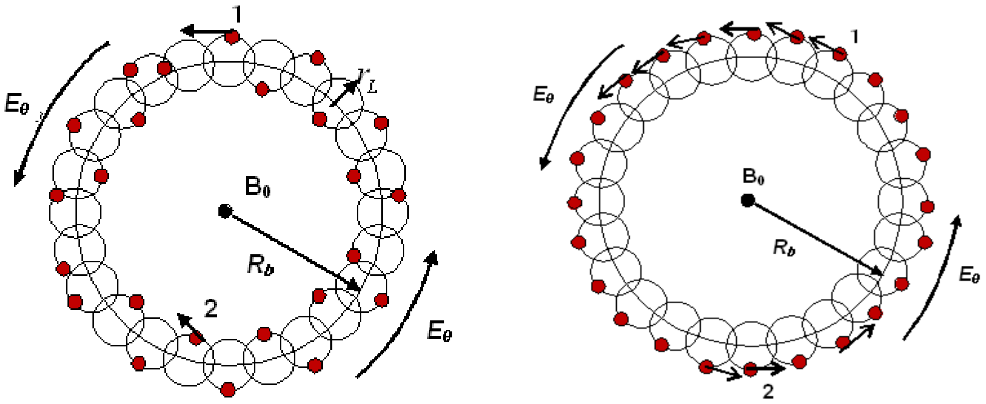
The CRM instability is a relativistic instability which is based on the relativistic cyclotron frequency of the electrons ω_c given by:

$$\omega_c = \frac{eB_0}{\gamma m_e} \quad . \tag{1.3}$$

Referring to Figure 1.3, the RF electric field component E_θ will interact with the electrons in transverse motion. This beam-wave interaction results in the change in the electrons transverse and axial velocity, i. e., v_t and v_z, which in turn modifies the relativistic mass factor as according to equation (1.2). The change in the relativistic factor γ caused by this interaction will change the relativistic cyclotron frequency of the electrons (equation (1.3)). This change in cyclotron frequency of electrons introduces instability, known as Cyclotron Resonance Maser (CRM) instability which signifies that cyclotron frequency of some the electrons will increase whereas for some it decreases resulting in the energy transfer to the RF field. This in turn results in the phase bunching of electrons.

b) Phase Bunching

The phase bunching process occurs when the electron axial velocity vanishes ($v_\parallel = 0$). To analyze the process of phase bunching, let one of the beamlet is captured. Figure 1.4(a) shows one of such beamlet with radius R_b and an axial DC magnetic field B_0. The electrons are equally distributed in the circular orbit all over the phase (0, 2π) with radii equal to Larmor radius r_L, typically $r_L \ll R_b$ for the small orbit case.



(a) **(b)**

Figure. 1.4: Illustration of phase bunching mechanism **(a)** circular electron beam with initial arbitrary phasing of electrons in their cyclotron orbits; **(b)** circular electron beam with phase bunched electrons in their cyclotron orbits.

Let the initial phase of the electrons is random in their cyclotron orbits as shown in Fig. 1.4(a). In the existence of the transverse RF electric field TE_{ml} mode, the electrons will be either accelerated or decelerated. The cyclotron frequency of an electron is inversely proportional to its relativistic mass γm_e, thus the electrons gaining energy from the RF results in lower cyclotron frequency and hence gyrates slower while the ones that lose energy gyrates faster causing the electrons to bunch in their Larmor radius. Phase bunching and the resulting transfer of energy will occur when the RF frequency is slightly greater than the initial value of the cyclotron frequency, i. e.,

$$\omega' - \frac{eB_0}{m_e \gamma_0'} > 0 \quad . \tag{1.4}$$

As predicted from Figure 1.4(a), electron 1 moving in the direction similar to that of the RF field will be decelerated by the azimuthal electric field; hence experiences an increasing value of ω_c' and lose energy. While electron 2 travelling in a direction opposite to the RF field will be accelerated; hence experiences a decreasing value of ω_c' and gain an equal amount of energy. After a few cycles of cyclotron motion, phase lagging occurs in the electrons that gain energy and the electrons that lose energy go forward in phase. This results in the evolution of instability in which the electrons get phase bunched within their cyclotron orbits and transfers their transverse kinetic energy to the interacting *TE* mode [Gilmour (1986), Chu (2004), Kartikeyan (2004), Symons and Jory (1986)] as shown in Fig. 1.4(b). This results in a phenomenon known as phase bunching.

1.2.3. Applications

Gyroklystron amplifiers can be used for a variety of applications, such as, particle accelerators, RF plasma heating systems, drivers for TeV linear colliders, and as high frequency accelerators etc. [Gold and Nusinovich (1997), Granatstein and Lawson (1996), Kwo *et al.* (1985), Lawson *et al.* (2002)]. The gyroklystron finds very important potential application for the millimeter-wave radars around the atmospheric propagation windows in the Ka-band and W-band [Antakov *et al.* (1993)]. In addition, these devices can also be used in the field of spectroscopy [Joye *et al.* (2004)]. Furthermore, the millimeter-wave gyroklystrons have been used for the technological applications for the varieties of atmospheric diagnosis, such as, humidity assessment, cloud monitoring, and determination of turbulence structure. These millimetre-wave amplifiers are the foremost contender for providing microwave power for the space-debris discharge and the phased-array mapping radars along with for the ground probing radars used in the various military applications. Some of the applications of gyroklystrons are briefly discussed below.

1.2.3a Millimeter - Wave radars

As the attenuation coefficient of the atmosphere increases with the increase in frequency, the current communication system is recommended to be enhanced to meet the forthcoming demand of the high information density communication system, and yield high power to the millimetre-wave radars for their enhanced resolution with high range. The millimeter-wave radars enjoy the advantages of both the microwave radar and laser radar. Compared to the microwave wave radar, millimeter-wave radar has advantages, such as, narrow beam width, high resolution, multipath effects and anti-jamming capability, smaller size and light weight. It can work effectively even in the rain, fog, and battlefield smoke work environment, compared with infrared and optical radars. Research in this area is mainly focused at the frequencies of about 35GHz and 94GHz, due to availability of the two atmospheric windows at these frequencies. The gyroklystron amplifier is an efficient source for these specific purposes. Another important factor is the capability of the gyroklystron amplifiers to provide significantly high average and peak powers at these frequencies with minimum attenuation. U.S. and Russia are using the gyroklystron amplifiers in their military radars. A Russian Ka-band gyroklystron which is developed jointly by the Institute of Applied Physics (IAP) and industrial company delivered 750kW output power and which is the highest power level for millimeter wave amplifiers [Antakov *et al.* (1993)]. A comprehensive study of the two-cavity and three-cavity Ka-band gyroklystron amplifier was carried out at Naval Research Laboratory (NRL) during second half of the 1990s. The first W-band gyroklystron amplifier was developed at the IAP Russia in 1993 [Antakov *et al.* (1993)]. In Russia, a 120-element phased-array radar system operating at 34GHz uses two 500kW gyroklystrons with 50MHz bandwidth, 100μs pulse duration and duty factor of 0.01. In US a W-band radar system using a 92kW, 94GHz gyroklystron with 420MHz bandwidth and a 0.11 duty factor with 10 kW average power has been built [Nusinovich (2004), Kasatkin *et al.* (2008), Granatstein *et al.* (1997), Gold *et al.* (1997), Gilmour (1986), Thumm (2001)]. Later on, many laboratory experiments of high performance Ka-band and W-band gyro-amplifiers have been carried out [Felch *et al.* (1999)]. In addition, the gyro-amplifiers must be efficient of operating in high average power with duty factors ranging from 5% to 100%, for radar applications.

1.2.3b Particle accelerators

After the successful Large Hadron Collider (LHC) experiment at CERN, the high energy physics community is eyeing towards an electron–positron collision experiment through the linear accelerator (Super Collider) for probing the depths of the subatomic world. The accelerating gradient for such an accelerator should be more than 100MeV/m to keep the accelerator length to a reasonable size. In order to achieve such an accelerating gradient at minimum cost one must use the RF drivers both at higher values of power and frequency. The cost of such a Super Collider will depend on the cost and number of microwave amplifiers required as the drivers [Granatstein *et al.* (1988)]. Klystrons are the current state-of-the-art as microwave drivers for particle accelerators but being a conventional slow-wave microwave amplifier it cannot handle both high power and frequency simultaneously due to the decrease in transverse dimension with frequency. The klystron development programs can serve for linear colliders in the 1TeV energy range. However, for energy gradient more than 1TeV, i. e., supercolliders experiments, the drivers producing greater than 100MW peak power of 1μs pulse length at around 34GHz are required. The gyroklystron can be used for such type of applications due to their capabilities to provide high power at millimeter wave frequencies. University of Maryland has been working for more than last two decades to develop gyroklystrons for the linear collider applications. The experimental work of University of Maryland, mostly concentrated in developing the X and Ku-band both conventional and coaxial types of gyroklystrons. As an example of gyroklystrons developed at University of Maryland for particle accelerator, a two-cavity gyroklystron produces 32MW power at frequency

19.76GHz with a gain 27dB and an efficiency of 29% by utilizing an electron beam of 457kV, 244A. At present, the developments of gyroklystrons for accelerators are aimed at increasing the pulsed power to 100MW at frequency 17–18GHz. The achievement of such a power level is quite impossible with the conventional type of gyroklystrons. Therefore, coaxial-cavity gyroklystrons are being developed at the University of Maryland for this purpose. One of their coaxial-cavity X-band gyroklystron experiments produces peak power of 85MW, at a pulse length of 2μs with efficiency 32%, and gain 30dB [Granatstein *et al.* (1996), Nusinovich (2004), Kasatkin *et al.* (2008)].

1.2.4. Types of Gyroklystron Amplifier

Gyroklystron amplifiers are mainly classified on the basis of the types of their RF interaction circuit.

a) Cylindrical-cavity gyroklystron

These are the simplest type of gyroklystrons and are popular for their easy designing and fabrication as compared to the other gyroklystrons. In simplest type of gyroklystron, cylindrical-cavity is used instead of reentrant cavity which is used in conventional klystron.

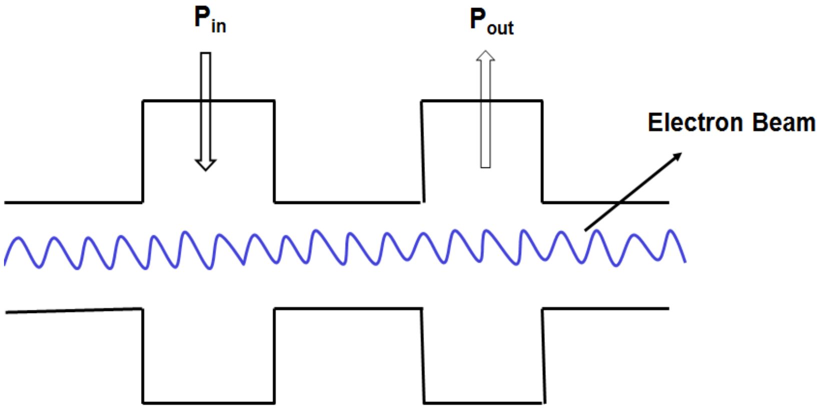


Figure. 1.5: Schematic of a cylindrical two-cavity gyroklystron amplifier.

These type of gyroklystron mainly work in small orbit operation and provide us a large gain, good linearity in a very small half-power bandwidth. The magnetic field requirement for these devices are higher for fundamental harmonic operation and due to the overmoded drift sections, they are not suitable for higher mode of operation. Figure 1.5 shows the configuration of a cylindrical two-cavity gyroklystron amplifier.

b) Coaxial-cavity gyroklystron

To extend the gyroklystron performance above the MW power for future particle accelerators requirements, higher-order mode operation of the device becomes necessary.

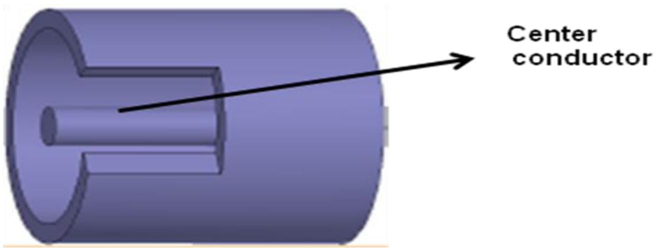


Figure. 1.6: Schematic of a coaxial-cavity in gyroklystron amplifier.

This can be achieved by increasing the beam voltage and beam current but the beam voltage cannot be increased after a certain value due to practical and lab safety reasons; therefore it is preferred to increase the beam current. This requires larger beam radius, and as a consequence it is difficult to transport such a large beam through cylindrical drift section and also leads to the elimination of microwave radiation through it. Hence, in order to overcome this problem, cylindrical cavity in gyroklystron amplifier is replaced by the coaxial-cavity. The coaxial-cavity gyroklystron mainly operated in large orbit operation; as a result of which the beam size can be easily increased and the introduction of centre conductor helps us to have control on the eigenfrequency and quality factor of the desired mode. The schematic of a coaxial-cavity in gyroklystron amplifier is shown in Fig. 1.6.

This also helps to overcome the problem of overmoded drift section and RF cavity [Lawson *et al*. (1995), Gouveia (2004)].

c) Clustered-cavity gyroklystron

Nowadays, high-power, high-gain, and wideband gyro-amplifiers have potential applications in driving future linear accelerators, in high-resolution millimeter-wave radars, and in high-density, high-directivity communication systems. However, the existing gyroklystron amplifiers are capable of high gain and high efficiency amplification of electromagnetic waves in a relatively narrow bandwidth of less than 1%, which is mainly limited by the quality factor of the cavity. To overcome the problem of narrow-bandwidth associated with the existing cavity-related gyro-amplifiers, various techniques have been employed. Firstly, the bandwidth can be significantly increased by detuning the resonant eigenfrequencies of the cavities which is referred as the stagger-tuning, widely used in the conventional klystrons [Staprans *et al.* (1973)]. The stagger-tuned cavities are applied to gyroklystrons to broaden their bandwidth, but at the cost of of device gain [Nusinovich *et al.* (1997)]. Therefore, the tradeoff between the gain and bandwidth has to be arrived.

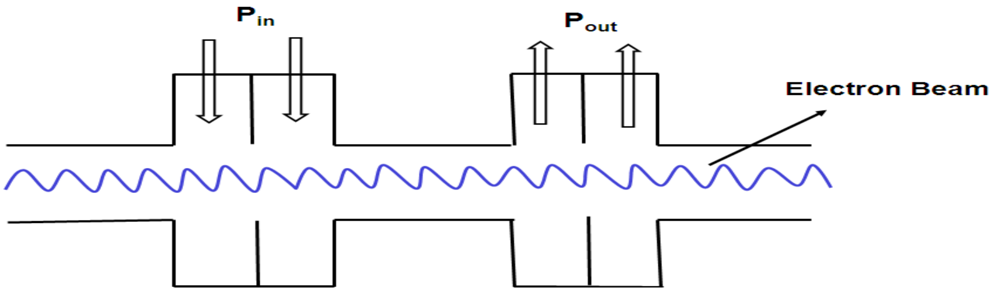


Figure. 1.7: Schematic of a clustered-cavity gyroklystron amplifier.

To overcome the limitation, the concept of clustered-cavities is then proposed for improving the bandwidth characteristics of high-gain gyroklystron amplifier with minimum degradation of gain and efficiency. In this concept, the individual intermediate cavity of a multi-cavity gyroklystron is replaced by artificially loaded two or three cavities which form a cluster (Fig. 1.7.). The *Q*-factor of each cavity in a cluster is reduced to one-half or one-third of the single cavity they replace; while the overall dimensions of the tube remains unchanged. Thus, for a clustered-cavity device, the bandwidth is either doubled or tripled that of the single cavity device. But, the difficulty that arises is the practical fabrication of the device as the clustered-cavity increases the complexity in the practical realization of the device [Nusinovich *et al.* (2002)].

d) Frequency-multiplying gyroklystron

The development of gyroklystron amplifiers at sub-millimeter-wave frequencies is limited due to the non-availability of the drivers of the desired power level and the large magnetic field requirement at such higher frequencies.

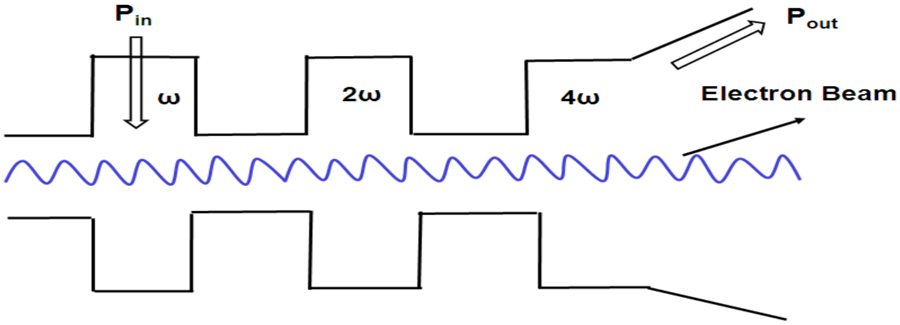


Figure. 1.8: Schematic of a frequency-multiplying gyroklystron amplifier.

Now, to reduce the required magnetic field for producing coherent radiation at a given frequency, research has been focused on the higher harmonic gyroklystrons. However, the device operation at higher cyclotron harmonics is complicated due to the weakening of the beam-wave interaction and parasitic oscillations due to the lower harmonic modes. To overcome these problems, frequency-multiplying gyroklystrons are developed which reduces the magnetic field requirement and also provides easier choice of input drivers. In frequency-multiplying gyroklystrons, the successive doubling of frequency takes place in each stage as shown in Fig. 1.8 [Savilov and Nusinovich (2007)]. This scheme provides significant improvement in the electron bunching which generally decreases as the device is operated at cyclotron harmonics. Moreover, the operation of the input cavity at lower frequency makes the input cavity dimension larger, which allows one to increase the beam diameter and correspondingly beam current. Thus, the maximum efficiency from output cavity operating at higher harmonics can be taken at larger beam currents, thus results in producing high output power. Due to the operation of the cavities at different harmonics, the frequency-multiplying gyroklystrons are of nonlinear in nature. However, these devices are unsuitable for communication purposes but can be successively used for radars and particle accelerator applications [Walter *et al.* (2000), Di-Wei *et al.* (2009)].

e) Multibeam gyroklystron

The concept of multibeam is largely applied to the linear beam klystrons. For the conventional klystron, it has been successfully used for producing high power and larger bandwidths at lower beam voltages. In the similar way, the similar concept of multibeam configuration has also been applied in gyroklystrons to achieve high gain-bandwidth product at low beam voltages [Kirshner *et al.* (2003), Boyd *et al.* (1962)]. This requires an increase in the electron beam perveance. In a multibeam gyroklystron, many electron beamlets are allowed to travel through separate beam-tunnels close to the channels' walls to reduce the space-charge effect between the cavities. This allows the total beam perveance to be high, while individual beam perveances are low. Due to the low beam preveance of individual beamlets, the gain and efficiency of the device is higher, also due to the increase in the overall beam current the device can be operated for higher RF output power operation. The use of multibeam configuration also reduces the overall size of the device to a greater extent due to its low beam voltage operation [Nusinovich *et al.* (1998)].

f) Photonic Band Gap (PBG) cavity gyroklystron

The higher frequency operation of the conventional cylindrical cavity gyroklystron is quite complex due to the reduction in its overall dimension. This reduction in the dimension results in the difficult and expensive fabrication. Limits the power handling capability of the device, thus the heat load per unit area is more. The passage of the electron beam without interception also becomes difficult. Gyroklystron operation at the higher order mode can alleviate the entire above problems but results into the dense mode spectrum in the RF cavities of the gyroklystron which in turn causes the problem of mode competition. The presence of parasitic modes not only reduces the efficiency of the device, but it also spoils the frequency spectrum of the device. All these problems can be resolved by using a mode selective structure, like PBG cavity structure. The use of PBG cavities in gyroklystron reduces the mode competition problem due to its mode selective property. It also provides a novel method for adjusting the quality factor in a cavity without the use of lossy dielectrics or ceramics [Joo *et al.* (2006), Sirigiri *et al.* (2001), Ashutosh and Jain (2012)]. Furthermore, PBG structure provides features such as filtering, amplification and mode selection. PBG cavity has very high Q-values since it has negligible loss due to the transparent cavity wall.

1.3. Gyroklystron Amplifier - A Review

Recently, a number of independent research works have been performed by different groups in gyroklystron amplifiers. Once the concept of gyro-amplifiers has been understood, the gyroklystron was invented. The first gyroklystron experiment was carried out in the X-band in the late 1960s, however the results were reported much later in the literature in the year 1978. The attractive feature of this experiment was that its efficiency is as high as 70%. This high efficiency is believed due to the operation with a very beam pitch factor (~ 3), which was possible due to the low beam current operation, i. e., use of a low perveance electron beam in the experiment [Andronov *et al.* (1978)]. The development of gyroklystrons began in the U S at Varian in the late 1970s. The tube is operated at 28GHz, and was designed to deliver 200kW RF power. However, due to the excitation of spurious modes, the tube delivered maximum power of 65kW [Jory *et al*. (1977), Nusinovich (2004)]. In another experiment, they demonstrated the second harmonic operation of a 10GHz (X-band) gyroklystron. They achieve an output power of 20kW with 8.2% efficiency from this experimental gyroklystron [Symons and Jory (1981)]. In the beginning of 1970s, the millimeter-wave (Ka-band and W-band) gyroklystrons have been developed for radar applications which are published much later in the late 1990s. Afterwards, the research at the Naval Research Laboratory (NRL), US started for the development of the gyroklystrons. In their first experiment, they were able to produce an output power of more than 50kW with 25% efficiency using three cavities at 4.5GHz [Bollen *et al.* (1985)]. Later, in the 1990s, a comprehensive study of 200kW two-cavity, three-cavity and four-cavity Ka-band gyroklystrons for applications in millimeter-wave radars were carried out at NRL [Choi *et al.* (1998), Calame *et al.* (1999), Garven *et al.* (2000)]. One of the important conclusion of this study is the excellent agreement obtained between experimental results and numerical calculations obtained with the help of numerical codes MAGY and MAGIC.

The first experiment in W-band regime was successfully demonstrated at the Institute of Applied Physics (IAP), Russia for the four cavity gyroklystrons operating in pulsed and CW regimes. In pulsed mode, a peak output power of 65kW with 34% efficiency and a gain of 33dB with 280MHz bandwidth was achieved. In the CW operation, the maximum output power of 2.5kW was produced with an efficiency of 25%. The reported gain and bandwidth for this gyroklystron was 30dB and 0.35%, respectively [Antakov *et al*. (1993), Nusinovich (2004)]. After that, a four-cavity W-band gyroklystron amplifier has been developed at the NRL, US for radar with high power called as WARLOC [Blank *et al.* (2002)]. This tube has delivered 100kW peak power and 10kW average power at around 94GHz center frequency with a 700MHz bandwidth. Recently, an experimental result of 93.2GHz gyroklystron amplifier operating in TE_{021} mode has been reported by IAP, Russia. In this experiment, a 340kW peak output power with 27% efficiency, 23dB saturated gain, and 0.41% (380MHz) bandwidth was obtained with a 75kV, 17A electron beam [Zasypkin *et al.* (2012)]. Simultaneously the development of gyroklystrons for radar applications, a program for the development of gyroklystrons driven by relativistic electron beams was also started at University of Maryland. The aim of this program is to use the device as RF drivers' in future TeV linear colliders. A peak power of 30MW is obtained for a 10GHz gyroklystron amplifier [Chu *et al.* (1985)]. Gyroklystrons are also developed for its applications as Charged Particle Accelerators. Devices were designed for operation at the fundamental cyclotron resonance at 9.85GHz, and the operating mode in all the cylindrical cavities was the TE_{01} mode. The tubes were driven by a 425kV, 200A electron beam with pulse duration of about 1.5 microseconds. In experiments with two-cavity gyroklystrons, 27MW output power with the 36dB gain and 32% efficiency was demonstrated [Lawson *et al.* (1991)]. In order to increase the frequency of outgoing radiation, a frequency-multiplying two-cavity and three-cavity gyroklystrons were developed. The first experiment on the coaxial-cavity gyroklystron was carried out at the fundamental cyclotron resonance. All cavities are designed for operation in the TE_{011} mode at the frequency close to 8.6GHz. Output power achieved is in the range

75-85MW, the maximum efficiency was about 32% and the gain was near to 30dB [Lawson *et al.* (1998)]. Also, Ka-band and W-band relativistic gyroklystrons have been designed [Arjona and Lawson (2000), Neilson *et al.* (2002)]. The gyroklystron could be a good choice as an amplifier because the gyroklystron utilizes a series of cavities, which can provide higher gain at higher power levels. These cavities can also be tuned to different resonant frequencies to widen the bandwidth at the expense of amplifier gain, a method known as stagger-tuning, similar to the method used in conventional klystrons [Nusinovich *et al*. (1997)]. The cluster-cavity technique can be used for widen the bandwidth without losing gain [Nusinovich *et al*. (2002)]. Some recent gyroklystron design advances and variations include a third harmonic gyroklystron [McNally *et al*. (1994)], a dual-cavity coaxial gyroklystron [Xu *et al*. (1998)], and sub-millimeter second harmonic designs [Nusinovich *et al*. (2000)]. In addition, many advances have been reported in the theory of gyroklystrons, such as the optimization of gyroklystron efficiency [Tran *et al.* (1986)], AC space charge analysis [Latham 1990], the effects of penultimate cavity position and tuning [Zasypkin *et al.* (1995)]; the theory of multibeam stagger-tuned and frequency quadrupling gyroklystron amplifiers [Nusinovich *et al.* (1998), Savilov *et al.* (2007)].

1.4. Problem Definition

On going through the thorough literature survey, the following problems are identified. The development of gyroklystron amplifiers to acquire high power at higher frequencies leads to the problem of wall heating and beam interception due to the miniaturization of RF interaction structure at these frequencies. 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. Hence, there is a need to enhance the size of the interaction cavity in order to handle the increased level of ohmic losses in the cavity walls. To achieve this, the higher order mode of operation of the device is essential. With the increase in the order of the operating mode, the mode spectrum is dense and the electron beam is likely to interact with several parasitic modes in the cavity along with the operating mode that lead to unstable the device operation and lower the efficiencies. In precise, the device operation at the higher order mode can surmount the problem of ohmic losses but leads to the serious problem of mode competition from the nearby competing modes. Additionally, at higher frequency of gyroklystron operation, the magnetic field requirement is high. In order to reduce the requirement of the DC magnetic field, the device is often operated at its harmonics though at the cost of gain and efficiency of the device. However, higher harmonic mode operation also suffers from the serious problem of mode competition from the nearby competing modes and fundamental harmonic modes. All these mode competition problem of gyroklystron devices have motivated the author of the present thesis to have an in-depth study of the multimode interaction in high frequency and higher harmonic gyroklystron amplifiers. Significant work in the development of theories including linear and nonlinear analysis has been carried out during the past for the analysis of gyroklystron amplifiers. But as per the literature review described in the previous section, to the best of knowledge, the time-dependent multimode study of gyroklystron amplifiers is not yet reported. In 1986, Tran *et al*. developed the nonlinear single mode analysis [Tran *et al*. (1986)] which describes the accurate results for lower frequency and fundamental harmonic operation of gyroklystron amplifier but do not take account mode competition by the nearby parasitic modes. In the analysis, only single mode operation is considered; hence it is not accurate for higher frequency and higher harmonic operation due to overmoded cavities. Another important problem identified is the designing of a gyroklystron at higher frequencies and higher harmonics which remains a critical issue for its developers. The application of gyroklystron amplifier as high-resolution advanced imaging radar should fulfill a criteria of stable, high power and high bandwidth. But the existing conventional-cavity gyroklystron amplifier produces the higher power in a relatively narrow bandwidth and hence the performance improvement in terms of bandwidth has to be fulfilled.

1.5. Significance of the Presented Work

In the present work, the problem of mode competition in higher frequency and higher harmonic gyroklystron amplifier is investigated developing a self-consistent, time-dependent, multimode nonlinear analysis which includes the time-dependent description of the electromagnetic fields and the electron motion expressions. Hence, in order to obtain more practical performance, multimode analysis is revisited and described in detail that determines the actual output power and efficiency in the operating mode of the gyroklystron amplifier. In addition, the self-consistent approach is adopted for analyzing the electron beam and RF interaction in which the axial structure of the field is modified by the high frequency component of the electric field density. The developed analysis is generalized and incorporates the device operation at arbitrary cyclotron harmonics employing any arbitrary shape of the interaction structures. The efficiency of the device reduces as the harmonic number increases; therefore the present work is limited to the study of second harmonic gyroklystron amplifier. The 3D PIC simulation of the gyroklystron, reconfiguring the commercially available "CST Studio Suite" is carried out. The multimode effect in gyroklystron amplifier is also studied by simulating the structure to validate the obtained analytical results. The design of the gyroklystron amplifier is more rigorous at higher frequencies, and at higher cyclotron harmonic operation. Further, a comprehensive design methodology for designing the gyroklystron amplifier is developed following the analytical approaches. Crucial design constraints for the selection of operating mode are also discussed. To estimate the efficiency of the designed device at higher frequencies and higher harmonics, the self-consistent multimode nonlinear formulation and simulation of the device is carried out to investigate the performance of the device due to mode competition. An attempt is also made to overcome the narrow-bandwidth problem associated with the simple-cavity gyroklystron amplifier by making use of a new gyro-device interaction circuit called the clustered-cavity circuit which is theoretically studied and modeled using PIC simulation code “CST particle studio”. The comparison of the results obtained through this technique is also observed with the circuit without clustered-cavity. These performance related issues along with the criticality in the design of gyroklystron have motivated the author of the present thesis to take up the multimode analysis, design and simulation studies of a gyroklystron amplifier as research problem. The effect of various beam and device parameters, like, beam voltage, beam current, magnetic field, quality factor and electron beam pitch factor in the overall performance of a gyroklystron amplifier are investigated in order to make the present study of more practical use. The effect of variation in RF driver power and driver frequency is observed to determine the amplifier performance in terms of gain and bandwidth of the device.

1.6. Significant Contributions

In 1986, Salop and Caplan developed the time-independent single-mode nonlinear analysis of the gyroklystron amplifier by extending the basic analytical approach as followed for the gyrotron oscillators. By following the similar procedure, the author developed a time-dependent multimode nonlinear analysis for the gyroklystron amplifier by extending the time-dependent multimode nonlinear formulation of the gyrotron oscillators reported by Fliflet *et al*. The generalized coupled nonlinear equations of motion of electrons are typically analyzed for the calculation of momentum and phase of the particles by considering the cumulative effect of all possible modes in the cavity. The field-profile in each of the cavities is calculated self-consistently using the modified Vlasov equation. Coupled time-dependent equations are solved to calculate the mode amplitude and phase in each cavity at each time step. A numerical code has been written based on the developed analysis and further benchmarked for the performance evaluation of the reported experimental three-cavity Ka-band second harmonic gyroklystron amplifier. The velocity spread effect and the space charge effect on the beam-wave interaction in the cavities is neglected. The linear analysis has been used for calculating the initial device design parameters, like coupling coefficient, start oscillation condition which provides the device design in terms of the beam radius, beam current and magnetic field corresponding to the operating mode along with the other possible competing modes. From the developed analysis, the temporal evolution of the RF output power in all the modes is plotted. To further validate the developed multimode analysis, the PIC simulation of the same experimental three-cavity Ka-band second harmonic gyroklystron amplifier as is carried out to investigate the multimode beam-wave interaction mechanism in which the presence of all modes in the RF interaction structure of gyroklystron amplifier is observed in terms of signal amplitudes which provide a more realistic scenario. The device simulation presented here covers the modeling of the RF interaction structure, eigenmode study to determine the RF operating mode and resonant frequency, and PIC simulation to determine the performance of the device in terms of RF output power, efficiency, and most important calculation of device gain, and bandwidth. The simulation results obtained are then benchmarked with the previously reported experimental results and the analytical results. Further, the design methodology of a gyroklystron amplifier has been explained and further applied for the design and optimization of a D-band second harmonic four-cavity gyroklystron amplifier. For the device design parameters, and chosen TE_{02} mode, the design constraints have been obtained which are well within the limit. The performance evaluation of the designed device in terms of RF output power, gain and efficiency is also carried out using the developed analysis and PIC simulation tool "CST Particle Studio". The generalized formalism for the clustered-cavity gyroklystron amplifier has been studied and using this formalism the performance improvement of a two cluster gyroklystron with two cavities in each cluster has been analyzed. The bandwidth of the clustered device has been achieved which is approximately doubles that of conventional cavity case. The results show that the bandwidth of gyroklystron amplifier is enhanced with the small increment in the gain, and efficiency of the device. The effect of stagger tuning on the performance of clustered-cavity gyroklystron is also studied briefly. The analytical results obtained here have been verified with the help of the PIC simulation results.

1.7. Plan and Scope

The concept of multimode interaction in the gyroklystron amplifiers at higher frequencies and higher harmonics has motivated the author to carry out the work embodied in the present thesis. In the present work, a detailed insight of the design, analysis and simulation of the gyroklystron amplifier, including the multimode nonlinear beam-wave interaction description, as well as performance improvement of the gyroklystrons are presented. The work embodied in the present thesis is organized into six chapters, as follows.

In Chapter 1, which is an introduction to the work embodied in the present thesis, the fundamentals of the conventional microwave tubes along with the fast-wave microwave tubes, and their applications are talked about. An overview and literature survey of the principles and status and development of gyroklystron amplifiers are presented. The conventional gyroklystrons as well as various advancements in the gyroklystrons are reviewed and found gyroklystron amplifier as an attractive device for millimeter and sub-millimeter waves' amplification. Basic principle, working, advantages of the device are reviewed with their scope and limitations. The problems facing in the present status of gyroklystron amplifier are identified, and the objectives and scope of the present work to overcome the problems are discussed in detail. The significant contributions of the author in the present work are also discussed in detail. Different issues and limitations along with the different gyroklystron types for its performance improvement are also highlighted.

In Chapter 2, a self-consistent, time-dependent, multimode nonlinear analysis is carried out to explore the multimode beam-wave interaction behavior of the gyroklystron amplifier. Since, the single-mode analysis considers only one mode present in the cavity, this does not provide reasonable scenario mostly for the higher order mode operation of the interaction cavity. Hence, in order to obtain more practical performance, multimode analysis is revisited. The numerical code is written for the developed analysis and for the analysis validation, numerical benchmarking of the developed analytical approach is also presented against the reported experimental results. Further, the RF temporal growth of the operating mode, as well as the competing modes, is analytically investigated. The effects of various parameters, such as beam current, beam voltage, pitch factor on the electronic efficiency, and RF output power, are also obtained.

Chapter 3 deals with the PIC simulation and validation of the analytical results obtained in Chapter 2. The 3D PIC code “CST Microwave Studio” is reconfigured for the gyroklystron physical structure and electrical parameters. The beam-wave interaction behavior is studied using a commercial 3D PIC simulation code ‘CST Particle Studio’. The electromagnetic simulations are carried out both under cold (electron beam absent) and hot (electron beam present) conditions. Bunching phenomenon is observed along the interaction length which indicates the net energy transfer from the electron beam to the RF wave. The simulation procedure and the beam-wave interaction investigation are thoroughly described. The device simulation presented here covers the modeling of the RF interaction structure, creation of hollow electron beam similar to gyrotron, frequency of operation, RF output power, efficiency, and most important calculation of device gain, and bandwidth. The PIC simulation results obtained in this chapter are also benchmarked with the available published results and the analytical results obtained in Chapter 2.

In Chapter 4, the conceptual design methodology of a gyroklystron amplifier is discussed and subsequently used for the design and optimization of a second harmonic D-band four-cavity gyroklystron amplifier. Essential design constraints for the choice of operating mode are explained. Various important design constraints and their role in selecting the design parameters are also illustrated. The start oscillation current is computed to acquire the information regarding possible mode competitions. Further, the multimode beam–wave interaction behavior of the device operating in the TE_{02} mode is analyzed using the developed analysis and also simulated using a particle-in-cell code “CST Particle Studio”.

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

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

1.8. Conclusion

In the present chapter, the fundamentals of microwave tubes and the status of development of both conventional and fast-wave tubes for the generation and amplification of millimeter and sub-millimeter waves have been presented. The operating principle of gyro-devices has been studied. An overview to gyroklystron amplifier including its key elements and working mechanism has been discussed. The various applications of the gyroklystron has been reviewed and found it as an attractive device for millimeter and sub-millimeter waves' amplification. The state of the art of the gyroklystron is presented with their scope and limitations. Different configurations of the device for its performance improvement are also highlighted. The motivation of the present work has been illustrated in which the problems due to higher frequency and higher harmonic operation of the gyroklystron has been described along with the possible solution to surmount these problems has also been proposed.