CHAPTER 1

INTRODUCTION

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1.1. An Overview

Microwave tubes are the transit-time devices which overcome the problem of impairment of the high-frequency performance of conventional electron tubes caused by the effects of transit-time of electron motion, and gain-bandwidth product.The power handling capability of these microwave tubes decreases with the increase of the operating frequency primarily due to consequent reduction of their physical dimension. This limits their use at millimeter and submillimeter wave frequencies. The major power-limiting factors are: DC power dissipation, RF losses, attainable electron current density, heat transfer (restricting the average power capability), material breakdown (arcing) (restricting the peak power capability), and also the technological constraints in fabricating the tiny parts. Microwave tubes are classified as slow-wave tube and fast-wave tubes. In contrast to slow wave tubes, the fast-wave tubes or gyro-devices employ an electron beam comprised of annular moving electrons and the free energy resides in motion azimuthal to the applied static magnetic field. In these gyro-devices, the interaction mechanism is due to the cyclotron resonances maser (CRM) phenomenon which provides the physics underneath as well as permitting wave generation in simple and large-size waveguide. The interaction of the gyration motion of electrons with the RF wave in a static magnetic field occurs when the synchronism condition is:

$$\omega - k_z v_z - s\Omega / \gamma \cong 0, \tag{1.1}$$

where ω is the wave frequency, k_z is the propagation constant, v_z is the electron axial velocity, s is the cyclotron harmonic number, and Ω is the electron cyclotron frequency. In order to get the coherent radiation from these relativistic gyrating electrons, it is necessary that the significant contributions from electrons strengthen the initially emitted radiation, if the device is an oscillator, or enhance the input signal, if the device is designed to work as an amplifier. This criterion for coherent radiation can be satisfied; if the wavelength of the imposed RF signal is comparable to the sizes of electron density variations caused by the bunched electron beam [Thumm (2012)]. The wave is amplified in negative-mass instability because the electrons bunch due to the inverse dependence of the cyclotron frequency $\left(\Omega_r = eB_0 / \gamma m_{e0}\right)$ on the relativistic Lorentz factor and there is cumulative interaction between the oscillating field and the orbiting electrons, where B_0 is applied DC magnetic field, γ is relativistic mass factor, and m_{e0} is the rest mass of electron. This produces a sinusoidal energy modulation of electrons along the path and a consequent angular velocity modulation because of the change in relativistic mass with energy. Electron phase bunching and EM-wave amplitude both grow exponentially along the tube axis until saturation of the process occurs. The depletion of free energy and/or particle phase trapping is responsible for wave saturation. In the first regime, the perpendicular energy of the beam is close to the critical value and the saturation is caused by the depletion of free energy. In the second regime, the perpendicular energy of the beam is well above the critical value and the saturation mechanism for the instability is phase trapping of the particles by the excited wave.The excited wave frequency is near the Doppler-shifted electron cyclotron frequency of the gyrating electrons.

Analyses of CRM instability using both quantum-mechanical and classical methods are used for weakly relativistic electrons. They point out that, for frequencies at which the CRM interaction is most interesting, an electron may fall through 10^8 quantum states in giving up its energy to the electromagnetic field, so that classical description is quite good. The electrons stay in resonance when the electron cyclotron mismatch does not exceed 2π:

$$|\omega - s\Omega|T \leq 2\pi \quad . \tag{1.2}$$

In a steady-state amplifier, the input wave amplitude initially grows exponentially, then enters into the nonlinear regime, and finally gets saturated.

The gyro-devices can be divided into – gyromonotron oscillator or gyrotron, gyroklystron amplifier, the gyrotron travelling-wave tube (gyro-TWT) amplifier, and gyrotron backward-wave oscillator (gyro-BWO), each of which offers unique properties and advantages for particular applications. They differ principally in the interaction structure and each has a counterpart in the classical microwave tubes, as implied by the terminology.The gyro-TWT amplifier is supreme in the family of gyro-devices, mainly because of its capability to provide high power with larger gain and wide bandwidth in the millimeter and sub-millimeter wave frequency range. Gyro-TWT has absence of fragile slow-wave structures. In the gyro-TWT, the electrons are in a resonance with a large number of forward and backward-waves both at the fundamental and higher cyclotron harmonics. The bandwidth of a gyro-TWT has been significantly improved by tapering the interaction waveguide circuit and profiling the axial magnetic field to maintain synchronism. Waveguide radius with a negative gradient and applied magnetic field tapering with a positive gradient significantly improves efficiency of a gyro-BWO. On the other hand, a gyro-TWT with positively tapered waveguide radius and negatively tapered applied magnetic field increases bandwidth apparently. The modes of the circular gyro-TWT have been primarily of two types, viz., azimuthally symmetric modes (TE_{on}) and whispering gallery modes (TE_{mn} with m >> 1 and m > n). The symmetric modes are characterized by low wall losses, and devices employing them are not as large in cross section as the whispering gallery-mode devices. Therefore, a magnetron injection gun

(MIG) to generate a high-quality electron beam can be easily constructed [Leou (1994), Yeh *et al.* (2000, 2001)]. On the other hand, the whispering gallery modes have superior mode stability and have been used for the very high power devices.

Gyro-TWT often suffers from the problem of self-oscillations due to backward wave oscillations arising due to the long interaction structure and the velocity spread effects [Gilmour (1986), Nusinovich (2004)]. Oscillation near cutoff caused by the absolute instability occurred and it is stabilized using a waveguide with a resistive wall. The second kind of oscillation is gyro-BWO. The lossy and severed sections of the multi-stage gyro-TWT seem to increase effectively the start-oscillation currents of the absolute instabiltiy, gyro-BWO, and reflection oscillation. The former lossy section improves the suppression of absolute instability, i. e., it not only cuts off the path of the reflective feedback loop, but also functions as an effective energy sink for the absolute instability. Meanwhile, the severed sections are employed to shorten the interaction region and thus prevent the appearance of gyro-BWO. However, in contrast to the severed section; the lossy section has a much lower wall resistivity such that the drive wave can still be amplified in it. Gyro-BWO modes oscillate if the length of the interaction region exceeds the start-oscillation threshold. Therefore, the interaction circuit must be kept shorter than the start-oscillation length to ensure amplification in the operating mode.

The two-stage approach led to improved gain, efficiency, and saturated output power [Park *et al.* (1995)] over the single-stage case, but with a reduced bandwidth. Russian and United Kingdom groups developed the helically corrugated interaction structure [Denisov *et al.* (1998)]. The corrugation alters the low-portion of the waveguide dispersion curve to an approximate straight line centered at the point. This novel circuit provides the important advantages of broadband operation and relative insensitivity tothe electron velocity spread.

The University of Maryland has been conducting research on two-stage frequency-multiplying schemes, including a frequency-doubling inverted gyrotwystron [Guo *et al.* (1997), Rodgers *et al.* (2001)] and a frequency-doubling gyro-TWT [Chu *et al.* (1997)].

1.2. Problem Definition

To achieve high power at higher frequency, gyro-TWT has to operate at higher order mode and use an oversized interaction structure which obviously increases the mode density in the waveguide. Since the center frequency of a gyro-TWT is directly proportional to the requirement of higher DC magnetic field, the availability of high-field magnets places an upper limit on the frequency which can be amplified by a fundamental harmonic gyro-TWT. Because of its intense interaction, a fundamental harmonic gyro-TWT amplifier is also quite susceptible to spontaneous oscillations. To reduce the requirement of higher magnetic field, device has to operate at harmonics which also suffers from the problem of mode competition from the nearby modes as well as the fundamental modes [Brand *et al.* (1992), Liu *et al.*(2000)]. Mathematically, a lower v_t / v_z value results in a steeper slope for the cyclotron resonance line, so that the grazing intersection point is shifted away from the cutoff where the absolute instability is strongest, while physically, a smaller v_t / v_z ratio corresponds to a beam with less free transverse energy to give up and, therefore, the system will be weaker in gain, less efficient, and more stable to the absolute instability. If the particle density is sufficiently large, the field induced by the beam current density will couple to more than one waveguide mode. The high density of mode spectrum and switching into parasitic modes affects the performance of the device, such as, power, and efficiency of the operating modes. Hence, it is required that the operation of an overmoded gyro-TWT should be investigated, to assess the performance of the desired mode and the potential of destructive interference by the competing modes. Mode competition in gyro- devices may manifest itself in several ways. Several waveguide modes can interact with the beam, either near the fundamental cyclotron resonance or near its harmonics. All these modes are amplified by the device simultaneously when the interaction with the electrons is fairly linear [Symons and Jory (1981)]. However, some of the fields of the competing modes remain in the structure as a result of their excitation at the operating frequency. As a result of asymmetries in the structure, these orthogonal modes will usually increase the velocity spread of the electrons, thereby disrupting rather than enhancing the bunching of electrons by the desired mode, and hence reduces the saturated efficiency of the desired mode. Another kind of mode competition can exist in gyroklystron amplifier. If the long drift tubes are used, which are cut off for the desired cavity mode, but other lower order modes may propagate at the operating frequency. Thus, the drift tube can act like a gyro-TWT for those propagating modes, thus giving exponential growth.

For the above explained devices, multi-mode approach is used to predict accurate power and efficiency which incorporates the effect of presence of all nearby modes inside the waveguide. In the nonlinear single-mode analysis, we do not take account mode competition by the nearby modes. In the small amplitude regime, the problem of multi-mode competition is solved by exploiting the inherent decoupling of the eigenmodes in linear theory [Symons and Jory (1981)]. By drawing curves for the required starting current of all resonant modes versus the magneto-static field for given beam parameters and waveguide geometry, information is obtained about the priority of excitation of the eigenmode. Although, this information is extremely useful for gyro-TWT design, it does not answer equations regarding the stability of the excited mode, when the large amplitude regime is reached. Such equations have to be addressed by a nonlinear analysis. In the multi-mode approach, the effect of competing modes is studied using fully nonlinear formulation.

The full nonlinear system of coupled equations for the interacting modes is simplified by means of a perturbation expansion in powers of the electric field amplitudes. There is a difficulty in nonlinear multimode calculations for configurations involving several modes with different azimuthal and radial mode indices. This difficulty is associated with the large number of initial phases needed to average over the possible relative initial phases of the interacting modes which in some cases can increase the multimode computation time by a factor of 100-1000 over a corresponding single mode calculation. Such calculations have recently become feasible by giving adequate access to a fast digital computer.

1.3. Significance of the Presented Work

The purpose of our work is to develop and apply a self-consistent multi-mode formulation which is simultaneously adoptable for efficient numerical simulations and applicable for analytical considerations. In the linear analysis, electron beam is described by a distribution function. The distribution function is analogous to a density function which depends on space, time and momentum. Hence, it is not suitable to incorporate practical beam conditions, such as beam velocity spread and guiding centre spread. The relativistic Vlasov equation is used to obtain the perturbed electron distribution function in the presence of electromagnetic wave [Chu *et al.* (1978)]. These perturbations are linearized to obtain the analytical values. Linear analysis can be used to predict start oscillation conditions and dispersion relation which can provide guidelines for the design of a stable device.

On the other hand, the nonlinear analysis is used to predict output power, efficiency, and bunching phenomena of electrons thereby providing better understanding of the saturation mechanism. Nonlinear analysis can include the drift of electron guiding centre, the effect of velocity spread, and inhomogeneity of applied magnetic field. The arbitrary type of interaction structure can also be comprised in the nonlinear analysis. Another advantage of this method is that the electron overtaking and the saturation effects caused by defocusing of the electron bunch from the RF phase can be taken into account which results in the better explanation for the nonlinearity.

The present work is focused on the multimode study of second harmonic gyro-TWT amplifier. For higher frequency of operation, larger magnetic field is required for the fundamental mode of operation which limits the application of gyro-TWT amplifier as a millimeter-wave source and makes the system heavy and difficult to achieve. The attractive alternative is to operate the device at a harmonic of the operating frequency so that the magnetic field requirement is reduced by the harmonic number *s*. Such magnetic field can be easily produced even by the permanent magnetic systems (PMS). However, efficiency decreases with the harmonic number, hence; there is considerable interest in the second harmonic gyro-TWT amplifiers. However, higher harmonic modes are also difficult to excite because of mode competition from the nearby higher harmonic competing modes as well as the fundamental harmonic modes [Brand *et al*. (1992), Liu *et al*. (2000)]. Therefore, the study of the multimode interaction becomes important for the gyro-TWT amplifiers operating at its harmonics.

1.4. Significant Contributions

The development of overmoded amplifiers is more difficult than in the oscillator case because they must be kept stable in the absence of a drive signal. Furthermore, performance parameters such as bandwidth, gain, phase stability, and noise, which were not applicable to oscillators, become of crucial importance in the case of an amplifier. For a single mode analysis, the final equations for the starting current and detuning are independent of both time and RF field amplitude, which is consistent with the linear analysis. However, in a multimode analysis, the cross-terms associated with the interaction of two separate modes will be functions of both time and relative amplitude of the two modes. The mode competition problems in a gyro-TWT can also be appreciated by examining the dispersion relation for the gyro-TWT.

In the present work, the non-linear equations are obtained in the slow time scale for the motion of each individual particle and for the evolution of the amplitude and frequency of each individual waveguide eigenmode. The calculation of multimode effects in waveguide is complicated by the unequal coupling impedances and irregularly-spaced frequencies of the transverse modes. The key step in the derivation of the reduced description is the description of the fields as a superposition of (relatively few) eigenmodes of the waveguide where the interaction takes place. In the self-consistent nonlinear analysis, the equations of motion for the electrons are solved simultaneously with the field equations. Maxwell's equations are reduced to a set of coupled partial differential equations (time and axial coordinates), and the fields are locally computed as a superposition of the eigen functions with the calculated amplitudes.

To maximize the RF output power level of stable gyro-TWT amplifiers, marginal stability theory and design criterions are applied. It was asserted that a second harmonic gyro-TWT amplifier is more stable to spontaneous oscillation than a fundamental harmonic gyro-TWT amplifier. For the stable operation of a gyro-TWT amplifier, the electron beam current must be reduced below the absolute instability threshold value at which the operating mode is excited at the cutoff frequency due to the interaction bandwidth extending into the backward wave region. The interaction length of the amplifier must also be kept shorter than the start-oscillation length for the strongest competing interaction, which limits the gain of the device. Since cyclotron harmonic interactions are, in general, weaker and therefore allow higher levels of electron beam current, harmonic gyro-TWT's can stably yield significantly higher output power than a fundamental gyro-TWT. The circuit of a gyro-TWT usually is loaded with the wedge shaped lossy ceramic rods, operating in the circular azimuthally symmetric TE_{02} mode in order to suppress the instability competition. The thermal conductivity of the lossy material and related fabrication technology also compose the bottleneck to the system average power. Mode-selective interaction circuits were applied to suppress backward wave oscillations. The study presents a nonlinear analysis of typical oscillations, including absolute instability, gyro-BWO and reflection oscillation.

1.5. Objective and Scope of the Present Work

Depending on the nature of the RF interaction structure, an electron beam can support a space-charge mode, and different RF operating modes. The coupling between electron beam mode and electromagnetic modes can be easily studied using dispersion diagrams. Dispersion diagram which indicates the variation of the phase velocity of the RF wave with frequency is also known as ω-k_z plot, or Brillouin diagram. It describes the operational characteristic of the device, and the device synchronism condition between an RF mode and a fast electron cyclotronmode (fundamental or harmonic) can be obtained at the grazing intersection between the beam mode and waveguide mode dispersion curve. Based on the nature of interaction of fast waveguide mode with an electron beam, a device could be either an oscillator or an amplifier.

Analysis and design of the gyro-TWT is presented to study its RF behaviour. The analysis is reviewed here to observe the features that are essential for the design of a gyro-TWT amplifier. The generalized nonlinear analyses incorporating the presence of single mode as well as multimode are presented to study the beam-wave interaction mechanism. These analyses include arbitrary cyclotron harmonics operation of the device. The electrons motions are represented by the equations for its phase and energy which results in simplified and reduced number of equations. In this approach, waveguide excitation equation in beam absent case is determined and then the influence of the beam on the RF structure field profile has been derived and subsequently the calculations of the output power and efficiency for a given set of beam parameters have been done. In the analysis, the provisions of beam spreading effects are included. The nonlinear single-mode analysis predicts the existence of single mode inside the waveguide which is a major approximation for the case of over-moded operation. To incorporate the effect of the nearby modes present in the waveguide, a nonlinear time-dependent multimode analysis is also presented. The results obtained from these analyses are discussed and their utility in the gyro-TWT design, optimization and performance evaluation are demonstrated. In order to design a gyro-TWT amplifier, a systematic procedure is presented owing to various constraints.

A nonlinear analysis has been presented for the RF behaviour of a gyro-TWT. In the analysis, a single mode excitation by the electron beam has been considered. However, in high over-moded gyro-TWT amplifiers, the mode spectrum is very dense and electron is likely to interact several modes in the gyro-TWT which leads to unstable the device and lower the efficiencies. Hence, for a high efficiency gyro-TWT, it is a challenging task to avoid the mode competition. However, the single mode operation is indeed possible if the design of interaction structure is appropriate and the start oscillation current criteria are properly analysed for the designed waveguide. To study the performance of the over-moded cavities in the presence of several nodes, a time dependent multimode analysis is presented here extending the formulation outlined by Fliflet [Fliflet *et al.* (1991)].

The time-dependent multimode analysis has been presented to investigate the effect of all nearby competing modes on the gyro-TWT performance which provides a more realistic scenario. With this analysis, the actual output power and efficiency of the gyro-TWT can be determined. The independent codes have also been developed for the single-mode and multimode analysis to predict the output power.

The coupling coefficient provides the beam guiding centre radius selection for a particular mode of operation. In order to get optimum beam-wave interaction, it is important to position the electron beam at the place where field is the maximum. The start-oscillation current is also studied for the selection of the critical length of the device which is essential for the convective instability ($k_z > 0$). The beam-wave interaction mechanism is explained with the help of bunching of electrons. The output power and efficiency are dependent on the bunch quality. The selection of appropriate value of axial magnetic field is important for the proper beam-wave interaction in order to get optimum saturated power.

Simultaneously, particle-in-cell (PIC) simulations are also being performed to investigate the beam-wave interaction mechanism in the gyro-TWT. PIC simulations offer an insight into the EM behaviour of the device. Simulations also provide the validation and optimization of the design parameters without fabricating the actual device. The device performance can be observed to realize more reasonable scenario by incorporating straightforward various practical constraints.

In the CST particle studio, presence of all modes in the RF waveguide of the gyro-TWT can be observed in terms of the signal amplitudes which provide a more reasonable scenario. The field values are recorded in the time domain and its Fourier transform provides the device frequency of operation. The electron particle beamlets at different time intervals with in one cycle are shown to understand the bunching mechanism. The energy distribution of all the particles along the interaction length is demonstrated to understand the energy transfer phenomena. The effect of velocity or energy spread on the device performance is described. Beam-wave interaction yields the temporal RF power growth at the output end of the interaction structure. The stability of device operation is also discussed. It is observed that the presence of competing modes affects the gyro-TWT performance. The overall device performance of the waveguide as its RF interaction structure is observed in terms of output power, and efficiency.

Interactions in the backward-wave region are absolute instabilities which grow locally in time from the noise level by way of an internal feedback mechanism. Intersections in the forward-wave region are normally, but not always, convective instabilities which grow in space along the path of the electron beam. The gyro-TWT is a complicated case because it exploits a convective instability near the cutoff frequency, which turns into an absolute instability at sufficiently high beam current when the unstable spectrum extends into the backward-wave region. The absolute instabilities can easily be the dominant sources of oscillations in the gyro-TWT.

A marginal stability analysis [Lin *et al.* (1992)] is introduced to maximize the power level and gain of stable gyro-TWT amplifiers. First, the electron beam current is reduced below the threshold value at which the operating mode is excited at the cutoff frequency due to the forward-wave bandwidth extending into the backward-wave region. The interaction length of the amplifier is then chosen to be shorter than the critical oscillation length for the strongest competing interaction. The marginal stability analysis also predicts that harmonic gyro-TWT's are capable of significantly higher power than at the fundamental, because the stronger fundamental-harmonic interaction restricts the beam current to low levels for stability. Harmonic gyrotron devices are also valuable because they significantly reduce the strength of the required magnetic field.

Interaction at harmonics of the cyclotron frequency is due to the presence of higher-order multipole components in the electric field. For example, interaction at frequencies near the second harmonic of the cyclotron resonance depends upon the presence of a quadrupole component in the transverse waveguide field [Symons and Jory (1981)]. Interaction near the third harmonic depends upon a sextupole component etc. because the transverse waveguide fields can be represented by solutions of the Laplace equation; it is possible to represent the forces on the electrons by an infinite series of multipole components around the axis of the electron system.

The second harmonic cyclotron interaction with an axis-encircling electron beam is found to be more stable to oscillations and can yield significantly greater power than the fundamental harmonic gyro-TWT. The strong beam wave interaction at the fundamental cyclotron harmonic is the cause of unwanted oscillations which limit the output power. There are various ways to increase the oscillation threshold, such as (i) lowering the beam $\alpha(v_t / v_z)$ to reduce the interaction strength, (ii) increasing the beam voltage to move away from the cut-off frequency of the operating mode, and (iii) employing a severed interaction waveguide. While all of these methods have proved effective in improving the stability and power, additional measures are required if still higher power is desired. Harmonic interaction is much weaker, but it offers the important advantage of a reduced magnetic field requirement [Lin *et al.*]. However, the brute-force remedy of increasing the electron beam current may be the most suitable for high power operation. It offers the dual merits of moderate voltage and smooth waveguide structure. The efficiency of the final state depends strongly on the final detuning (as well as on the presence of parasitic modes).

1.6. Methodology

The analysis starts with the Maxwell's equation leading to express field components of a circular cylindrical waveguide excited in the TE_{mn} mode. In order to include the effect of the electron beam, a source present term in the wave equation is considered. For a waveguide mode both sides of the appropriate wave equation may be integrated over the waveguide cross section. The current or charge density needed on the right hand side of the equation is usually found by solving the relativistic Vlasov equation in order to find the perturbed part of the electron distribution function [Sirigiri (1999)]. Linear analysis shows that the growth rate maximizes when the axial beam velocity coincides with the axial wave group velocity of the excited electromagnetic wave. Further, in order to obtain the wave equation in terms of the slow time scale variables, the transformation of the coordinates from the cylindrical system to guiding center system is required. Graf's summation theorem for Bessel's functions is used to incorporate this transformation [Winternitz and Gazeau (2001), Basu (1996)]. Finally, the circuit equations govern the evolution of amplitude and phase of electromagnetic fields. The electron beam dynamics, which govern the motion of the RF wave and electrons in the presence of a static axial magnetic field (assuming the space charge fields to be negligible), is explained with the help of relativistic Lorentz force equation for an electron interacting with a TE_{mn} waveguide mode. In the present approach, certain assumptions are made. The space-charge effects on the electron beam are ignored. Here, in this nonlinear theory, it is assumed that all the electrons have the same kinetic energy. A quasi-static system is assumed in the sense that the particles, entering the interaction region separated by integral multiples of a wave period, will travel along similar trajectories [wang (1995)]. With this assumption, the slow-time scale formalism can be followed where fast scale phenomena such as the electron cyclotron motion, and the sinusoidal variations of the RF field are eliminated through averaging over a period while the more important slow-time scale spatial variations of the fields are retained. In this procedure, the dynamics of a single wave is determined in terms of ensemble average over the nonlinear electron trajectories.

Since, gyro-TWT operates in circular transverse electric (TE_{mn}) modes near grazing point, i.e., $\omega/c = k = \sqrt{k_t + k_z}$ with, $k_t >> k_z$. In this case, we take $\omega/c = k \approx k_t = \nu_{mn}/r_w$ for TE_{mn} modes, where k_t is transverse wavenumber, k_z is axial wavenumber, r_w is the cavity radius and v_{mn} is the n^{th} zero of Bessel function $J'_m(x)$. The combination of this condition and cyclotron condition, $\omega = s\omega_c$ determine the operating mode of a gyro-TWT.

The generalized nonlinear analysis for a harmonic gyro-TWT can be developed in the form of generalized pendulum equations used for the gyrotron, as the RF interaction structure of a gyro-TWT is quite similar to a gyrotron [Fliflet *et al.* (1991)].

Beam current is usually fixed by the power requirement and the magnetic field must be fine-tuned for maximum efficiency, hence wall resistivity provides the most effective means for stabilization.Wall resistivity reduces the gain, but this can be easily compensated by a lengthened lossy section.

With the advent of high speed computers, simulation and modeling techniques have been widely used for the design and performance evaluation of the device. These simulation techniques offer useful insight in understanding device behavior as well as supporting the analytical models. Particle-in-cell (PIC) simulation method is found to be useful and handy to investigate the beam-wave interaction behavior of the gyro-devices and also to optimize their performance. Eigenmode analysis is carried out in the absence of electron beam using eigenmode solver to ensure the device operation in the desired mode and frequency. The exact operating mode is confirmed by observing electric and magnetic fields patterns and their variations along radial as well as axial directions. Further, electron beam present analysis is performed for the performance evaluation of the gyro-TWT amplifier in all respects.

For an accurate and self-consistent simulation, one must include the electrons as the source of the electromagnetic fields, and the fields as part of the forces driving the electrons. In time-dependent numerical simulations, which are essential for electron-beam systems to describe the interaction between the electron and the electromagnetic wave. There are several working codes in which the fields are calculated using the finite-difference time-domain (FDTD) scheme, and the particles are described by the particle-in-cell (PIC) scheme. In these codes the field components are assigned to a spatiotemporal grid, calculated each time step, and used to “push” the particles. The sources are then prepared and the field is recalculated. Therefore, at each time step, a set of trajectories are calculated and used as current sources for the fields. In order to resolve the high-frequency portion of the electromagnetic fields, the time step for advancement of the FDTD scheme needs to be small compared with the wave period. Accordingly, the code must be run for a relatively large number of time steps to get to steady state. Furthermore, the spatial resolution usually requires storage of field value on very large matrices. As a direct result, these codes require extensive computing resources.

The analysis is self-consistent in that the particle and wave dynamics are treated as a unit. The input wave is injected at a point where the waveguide mode and the beam mode are strongly coupled into three modes-an unchanged mode, a growing mode, and a decaying mode [Kou (1991)]. Our parameter study indicates that the maser instability can be an efficient mechanism for the production of high-power radiation, particularly at millimeter and submillimeter wavelengths. Saturation efficiencies at the fundamental waveguide mode and cyclotron mode are obtained.

The strength of interaction depends upon the dc beam conductance and on circuit impedance. As a result, it can be concluded that small waveguides, for which the electric field is high when the power flow is low, give the strongest interaction but necessarily the highest output power capabilities. Very high power gyro-TWT usually have high dc beam conductance, therefore, high circuit impedance sacrificed for size and power capability in either device as the power level is raised. The electronic efficiency (η) is defined as the average electron energy loss divided by its total initial energy and the transverse efficiency (η_t) is the same quantity divided by the initial transverse energy.

1.7. Thesis Organization

The need of multimode operation of overmoded RF waveguide for higher frequency and higher harmonic gyro-TWT has motivated the author to carry out the work embodied in the present thesis. The present work explore the gyro-TWT using a ceramic fin waveguide structure as its RF interaction waveguide and present a detailed insight of the design and analysis of the ceramic fin structure and gyro-TWT including the nonlinear beam-wave interaction description of the gyro-TWT.

The chapter 1 is dedicated to outlining the background of the problem undertaken defined above, discussing the various issues such as the applications of millimetre waves at high power levels; the limitations of both the conventional microwave tubes and solid-state devices as well as those of quantum-optical devices in the high power regime, millimetre-wave frequency regime; the role of bunching (bremsstrahlung) gyro-devices in filling up the technology gap in the high power, millimetre-wave frequency regime; significance of the present work; significant contributions; objective and scope of the present work, adopted methodology to solve the giving problem; and the advantage of a gyro-TWT, with respect to its wide bandwidth potential, over its other gyro-device counterparts.

In chapter 2, basics of the microwave vacuum electronics devices and their applications are discussed. The evolution of microwave sources and their limitations are introduced. The classification of microwave tubes, various instabilities in electron beam devices, CRM interaction and phase bunching mechanism in a gyro-device are elaborated. Operating principle of gyro-devices including gyrotron is described and the concepts related to widening the bandwidth of a gyro-TWT as relevant to the problem undertaken. Present scenario of the gyro-TWT is reviewed with their scope and limitations.

In chapter 3, the time-independent single-mode non-linear analysis is presented in order to study the beam-wave interaction behaviour of a gyro-TWT. The results obtained through the non-linear analysis are benchmarked against the reported experimental W-band gyro-TWT results.

In chapter 4, the PIC simulation of a fundamental harmonic Ka band and W-band gyro-TWT amplifier is presented which helps to validate the analyses developed in chapter 3. In the PIC simulation, beam absent and beam present EM behavior of a metal cylindrical waveguide interaction circuit are demonstrated using ‘CST microwave studio’ in order to confirm the desired mode and frequency of operation of the interaction circuit. 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 time-independent nonlinear single mode analysis.

In the chapter 5, the use of wedge-shaped lossy ceramic rods symmetrically arranged on the inner wall of the cylindrical waveguide is proposed to investigate the design aspects and stability study of the gyro-TWT amplifier. Such an arrangement provides resistive loss to the azimuthally asymmetric modes while supporting an azimuthally symmetric operational mode as long as the lossy ceramic rods remains thin. By optimizing the lossy ceramic rods dimension, this type of structure ensures device stability by suppressing the backward wave oscillations (BWO) in gyro-TWT amplifiers. Further, the stability is verified by PIC simulation. In order to suppress the instability competition, the circuit of a gyro-TWT usually is loaded with lossy material. The thermal conductivity of the lossy material and related fabrication technology also compose the bottleneck to the system average power.

Mode competition is an important aspect of the stability analysis of a gyro-TWT amplifier. In chapter 6, time-dependent nonlinear multimode analysis is presented to describe the beam-wave interaction and mode competition in gyro-TWT amplifier.

In chapter 7, the conclusion of the thesis is explained. Also, the limitations of the present work are highlighted and the scope to overcome in the future work is proposed.