CHAPTER 7

SUMMARY, CONCLUSION, AND FUTURE SCOPE

7.1. Summary and Conclusion

7.2. Limitations of the Present Work and Further Scope

7.1. Summary and Conclusion

The regime of millimetre and sub-millimetre waves encompasses a wide range of applications, such as, high resolution radar and high information density communication, deep space and specialized satellite communication, advanced high gradient RF linear accelerators, plasma diagnostics and chemistry, material processing, waste remediation, ceramic sintering, laser pumping, power beaming and electron cyclotron resonance (ECR) heating of fusion plasmas, radar and imaging in atmospheric and planetary science, and nonlinear spectroscopy etc. However, there is a lack of millimetre and sub-millimetre waves devices to meet the systems requirement for these applications. There exists a technology gap due to (i) the limitation of conventional microwave tubes caused by the reduction of their sizes, and (ii) the limitation of optical devices, like, laser caused by the reduction of quantum energy as well as by the difficulty of retaining the population inversion. This has led the researchers to work in the area of fast-wave gyro-devices which provides high-power broadband operations in this frequency regime.

Considerable interest in the research has been aroused in recent years in the theoretical, analytical, simulation, as well as in the development of the gyro-TWTs which is a gyro amplifier in view of their potential capabilities in terms of producing high power with high gain, wide bandwidth, associated good efficiency as well as spectral quality. Fast-wave interaction in the gyro-TWT has many features in common with slow-wave interaction in the conventional TWT. These two interactions do differ in many respects. Both these tubes are growing-wave tubes in which a signal grows with distance as a result of distributed beam-wave interaction. However, a conventional TWT derives RF energy from the axial beam kinetic energy, whereas a gyro-TWT does it from the azimuthal beam kinetic energy. Further, relativistic azimuthal bunching of the electrons takes place in a gyro-TWT, unlike in a conventional TWT where the electrons bunching are axial and non-relativistic. Both the TWTs operate under near-synchronism-between the DC beam velocity and the RF circuit phase velocity whereas between the RF frequency and the cyclotron frequency in the gyro-TWT. Near synchronism causes the electron bunch to move to the RF decelerating phase and thus ensure a net transfer of energy from the electron bunch to RF waves in both the conventional and gyro-TWTs over a larger interaction length. The conventional TWT belongs to the Cerenkov radiation type and the gyro-TWT belongs to the bremsstrahlung radiation type of microwave tubes in which electrons move with acceleration or deceleration in a magnetic field or electric field; here, in helical paths in a DC magnetic field. Further, in a gyro-TWT, the fast cyclotron wave on the electron beam couples to the forward wave of the interaction waveguide supporting fast waves, unlike in a conventional TWT in which the slow space-charge wave on the electron beam couples to the forward circuit wave of the slow-wave structure. The cross-sectional areas of the interaction structures of both the conventional and gyro-TWTs reduce with the increase of the operating frequency. However, the reduction of the size of the structure is more for the latter than for the former. In other words, at high frequencies, the size of the structure can be made greater for a gyro-TWT than for a conventional TWT, and more so if the former is operated under over-moded condition. This makes the power capability of a gyro-TWT greater than that of a conventional TWT at the millimeter and submillimeter wave range. Further, for effective interaction with RF fields, the electron beam in a gyro-TWT need not be placed close to the interaction structure unlike in a conventional TWT in which the beam has to be located close to the interaction structure calling for strict beam confinement. In a conventional TWT, the role of a DC magnetic field is only to constrain the electrons to move in the longitudinal direction or focus the beam, whereas, in a gyro-TWT, the magnetic field is an essential interaction parameter. Higher the operating frequency, larger would be the required magnetic field for a gyro-TWT in order to nearly synchronise the wave frequency with the cyclotron frequency. The beam harmonic operation would however reduce the required magnetic field in proportion to the harmonic.

The analytical expression for studying the cold (beam absent) EM characteristics of the structure, like dispersion characteristics has been developed. These characteristics have been numerically appreciated by making use of MATLAB and have been validated against commercial available simulation software “CST Microwave Studio”. The shape of dispersion characteristics depends on the structure parameters. In order to widen the bandwidth of a gyro-TWT one has to widen the frequency range of the straight-line portion of the structure dispersion characteristics to ensure its grazing interaction with the beam-mode dispersion line of the gyro-TWT. For widening the grazing bandwidth preferably near the waveguide cutoff, one has to optimise the structure parameters. Accordingly, the present thesis has been divided in seven chapters.

The chapter 1 outlines the background of the problem undertaken, 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 electron beam devices and their applications have been described. The classification of microwave tubes, various instabilities in electron beam devices, CRM interaction and phase bunching mechanism in a gyro-device have been elaborated. Operating principle of gyro-devices including gyrotron has been described and the concepts relevant to the gyro-TWT problem undertaken. Present scenario of the gyro-TWT has been reviewed with their scope and limitations.

For the analysis of a gyro-TWT, both small signal and large signal analyses are in vogue. Small signal analysis based on the linear theory is used to predict start oscillation conditions, linear gain provide base for the device understanding and its design. On the other hand, the large signal analysis based on the nonlinear theory is used to predict output power, efficiency, saturated gain, and phenomenon of electron cross-over and debunching thereby providing better understanding of the beam wave interaction and saturation mechanism. Accordingly, in chapter 3 of the thesis, a generalised time independent nonlinear analysis of the gyro-TWT amplifier operating at arbitrary cyclotron harmonics of the interaction structure under single mode consideration has been presented. The electron motion has been represented by equations for its phase and energy which results in simplified and reduced number of equations. In order to get optimum beam-wave interaction, the electron beam is positioned at the radius where the RF electric field inside the cylindrical waveguide is maximum. Accordingly, the electron beam guiding centre radius selection for a particular mode of operation has been presented with the help of form factor variations for the RF structure parameter which decides the beam wave coupling. An optimum value of the beam guiding centre radius is chosen for the set of parameters. The RF power flowing through the structure cross-section is described by the norm factor. This nonlinear analysis results have also been compared with the linear analysis results. The beam wave interaction mechanism has been explained with the help of bunching of electrons along the axial position and also in Larmor radii. The RF output power and efficiency reduces as the bunch quality degrades. So, the selection of appropriate value of axial magnetic field is very important for the proper beam-wave interaction in order to get optimum RF saturated power.

For the numerical appreciation of the device performance, the electron beam formulations have been presented by considering the electron beam to be composed of a large number of macro particles (an ensemble of electrons). The set of coupled differential equations describing the electron energy, phase and RF amplitude have been solved by using Runge-Kutta-Verner fifth order method an efficient and fast method to solve ordinary differential equation with very small local and global errors. Finally, the calculation for gain, efficiency and output power has been performed using a self consistent loop.

In order to study the complex electron beam and RF wave interaction mechanism, particle-in-cell (PIC) simulation of the gyro-TWT device has been performed. In Chapter 4 of the thesis, 3D PIC simulation procedure of the gyro-TWT, reconfiguring the commercially available CST Studio Suite has been described in detail. CST Particle Studio is an electromagnetic particle-in-cell code which is based on finite-difference time domain method for the processes that involves interactions space charge and electromagnetic fields, simulates the interaction between charge particles and electromagnetic fields as they evolve in time and space from some defined initial configuration. Two typical gyro-TWT amplifier employing fundamental mode operation one in the Ka-band and other in the W band with heavily loaded RF interaction structure, reported in the literature have been selected for the PIC simulation. These gyro-TWTs using the smooth wall and the heavily loaded cylindrical waveguide have been simulated for both the beam absent (cold) as well as the beam present (hot) conditions. In the case of beam absent simulation, the desired mode of operation at desired frequency has been identified and field patterns have also been observed. The cold simulation results reveal explicitly the TE_{02} mode of operation at the central frequency of 92GHz in the device. In the case the PIC simulation under the electron beam present situation, the spatial growth of the RF signal has been observed. Simulation strongly supports the design goal of the gyro-TWT and attains the required specification of the device performance, e. g., the field profiles, phase bunching, RF output power, frequency obtained analytically shows close similarity with those obtained from the simulation. The bunching mechanism along the axial length and in Larmor radii has also been shown and compared with the analytical plots obtained in the earlier work reported in Chapter 3. The PIC simulation results of the gyro-TWTs are also validated against those obtained through the large signal analysis as well as the beam wave interaction phenomena were also verified. The beam present simulations for gyro-TWT employing smooth wall cylindrical waveguide Ka-band gyro-TWT resulted in ~140kW output power with ~23.7% efficiency and gain ~41.4dB which is within ±3% to the analytical results. For a heavily loaded W-band gyro-TWT, the beam present case, the PIC simulation predicted ~135.2kW output RF power with ~27% efficiency and gain ~49.8dB which also shows a fair agreement with analytical values.

The difference between the PIC simulation and analytical results of gyro-TWT has been accounted for the assumptions taken in the large signal analysis, like, single mode of operation, single particle approach in which the perturbation due to nearby particles (electrons) are also ignored. One of the major constraints is also the resolution of mesh, which can maximum affect the results accuracy. The effect of different beam parameters on the gain-frequency and spatial power growth has also been investigated. The positioning of the electron guiding centre is extremely important since it changes the relative interaction strength of all the modes. A properly placed electron beam will interact with the RF wave and would result in the maximum energy transfer for the desired mode and less or minimum energy transfer for the competing modes. Further, it has been chosen to place the electron beam at the maxima of the azimuthal electric field for maximum interaction between RF wave and electron beam. A search for high gain for the ratio of electron beam guiding centre radius to waveguide wall radius has resulted in the position of the electron beam. The effect of beam current showed that increase in the beam current results in increased growth rate and bandwidth. The impact of beam voltage is very low on the gain-bandwidth and spatial power growth so it is recommended to operate the device at lower operating beam voltages. The increase in bandwidth is obtained at the cost of reduced gain. The effect of electron beam velocity spread is very dominant in the gyro-TWT operation because deviation in the electron trajectories, i.e., loss of synchronism, caused by finite spreads will result in loss of gain and output power. The optimization of the structure parameters for the maximum bandwidth or gain without causing any change in centre frequency has been done. Furthermore, the optimization of the waveguide radius has been done by accounting its loading effects through azimuthal periodic dielectric wedges (fins), its dielectric property, thickness and periodicity, etc. The lossy dielectric fins azimuthal periodic radially projecting out from the interaction waveguide wall provides the mode selectivity. It has been observed that the size of the waveguide cross section can be increased for lower RF power loss density and enhanced power handling capacity of the structure. However, with the increase in the waveguide size, the structure becomes over-moded.

In the present Chapter 5, design aspects and stability study of W-band second harmonic wedge shaped gyro-TWT amplifier has been described. The stability of the gyro-TWT has been investigated against the spurious oscillations including the reflective oscillation, gyrotron backward oscillation (gyro-BWO), and absolute instability. The transmission loss for the operating mode has been calculated as ~19dB /cm at 1.4GHz for achieving the stability. Further, the gyro-TWT using the distributed loaded RF section has been investigated for its nonlinear behavior using a self-consistent nonlinear analysis. The saturated RF output power of ~450 kW at 91.4GHz with ~18 % efficiency, ~30 dB saturated gain, and 3dB bandwidth of ~3% has been achieved for an electron beam of 100 kV, and 25 A. Further, 3D particle-in-cell (PIC) simulation of a W-band, second harmonic gyro-TWT amplifier has been presented to study its transient behaviour. Its RF interaction circuit is loaded with the wedge shaped lossy ceramic rods arranged azimuthally symmetric in the axial direction to make the device operation stable by suppressing the parasitic modes including $TE_{01}^{(2)}$, $TE_{02}^{(3)}$ and $TE_{03}^{(4)}$. Through PIC simulation, the transmission loss for the desired $TE_{02}^{(2)}$ mode of the device has been found to be ~19dB /cm at 91.4GHz with saturated RF output power of ~435kW. The conversion efficiency has been obtained as ~17% for the gyrating beam of 100kV, 25A with a pitch of 1.2 and an axial spread of 5%.

Further, the saturated gain of the amplifier has been calculated as ~30dB with an instantaneous bandwidth ~3%. The PIC simulation values have also been validated with the nonlinear analytical results and found in agreement within 3%. The present study should be helpful in the design and stability study of gyro-TWTs.

In the Chapter 6, nonlinear time dependent multimode analysis has been presented to investigate the temporal RF interaction behaviour of the operating as well as all other competiting modes in the gyro-TWT amplifier. In a highly overmoded gyro-TWT waveguide RF interaction structure, the mode spectrum becomes very dense and electron beam is probable to interact several nearby modes simultaneously. In this approach, the transverse and longitudinal modal electric and magnetic field components are substituted in the Maxwell's equations. The differential equations thus obtained as a function of complex field amplitudes and induced AC current densities are time as well as position dependent. Then, the electron beam dynamics expressed in terms of Lorentz force with transformed coordinates from the waveguide center to the electron guiding center. Further, to transform the expressions into the slow time-scale domain, Graff's addition theorem for Bessel functions has been used. This provided us information about the electron momentum, phase angle and electron center motion equations. Hence, combining these obtained differential equations with the Lorentz force equation for electron momentum, phase angle, and electron guiding center motion equations gave a self-consistent equation which demonstrates the overall interaction process yielding information in time space taking all the modes into the simultaneous consideration.

Using this time dependent multi-mode analytical expressions, a W-band, second harmonic wedge shaped lossy ceramic gyro-TWT amplifier has been anlyzed and a saturated RF output power of ~438kW with conversion efficiency ~17% for the gyrating beam of 100kV, 25A with a pitch of 1.2 and an axial spread of 5% has been obtained. Further, the saturated gain of the amplifier has been calculated as ~30dB with an instantaneous bandwidth ~3%. The PIC simulation values have also been validated with the multi-mode nonlinear analytical results and found in agreement within 3%.

In Chapter 7, finally, the summary of the work and the conclusions drawn from the major findings of the work have been presented, pointing out the limitations of the work as well as the scope for the furtherance of the present study, such as those with respect to the gyro-TWT amplifier RF interaction structure has been characterized analytically and through PIC simulations in the present thesis and needs to be characterized experimentally. Moreover, in the present study, important aspects of thermal and structural analyses have not been considered. For the practical implementation of a gyro-TWT amplifier, these studies are very much important.

7.2. Limitations of the Present Work and Further Scope

In the present thesis, the performance study of a gyro-TWT amplifier has been carried out with the help of linear and nonlinear analyses. The extensive demonstration of the beam-wave interaction process has been presented by loading with ceramic. It is hoped that the present study would be useful in designing the gyro-TWT amplifier of any frequency and power. However, the author is aware of the limitations of the present work and scope of further research work for its improvements. The limitations of the work carried out here, and the scopes of its future extension are as follows:

The nonlinear analysis presented for the beam-wave interaction studies in gyro-TWT amplifiers have some limitations.

(a) In the analyses, an important aspect of the space charge effects has not been considered, which provide a more realistic scenario.

(b) In the present case, metal RF interaction structure under study has been considered with trapezoid sharp edges. But, in practical situations these sharp edges are not preferred. So, it is suggested to go for a circular waveguide loaded with metal fins of round edges and to extend the analysis for such a practical interaction structure.

(c) The harmonic interaction is relatively weak and leads to lower gain and requires a longer interaction length than the conventional fundamental gyro-TWT amplifier. It is suggested to go for a multi-stage gyro-TWT amplifier.

PIC simulation offers a self-consistent behaviour of RF interaction structures. Although a lot of simulation studies have been carried out related to performance evaluation and performance improvement techniques in a gyro-TWT amplifier, several issues still remain to be addressed. In the present simulation input coupler is not modelled for exciting of the gyro-TWT amplifier. Here RF input is applied directly to the input with the help of the particle source command in PIC code. However, to make the present simulation model more useful for the practical case the input coupler should be modelled and its effect on the cold cavity mode, the form and norm factor, etc. needs to be studied.

Though the gyro-TWT amplifier RF interaction structure has been characterized theoretically and through simulation in the present thesis and needs to be characterized experimentally also, this is kept outside the scope of the present work. Moreover, in the present study, an important aspect of thermal analysis has not been considered. For the practical implementation of a gyro-TWT amplifier, these studies are very much needed.

In the present thesis the device has been designed and studied for second harmonic mode of operation, which requires low magnetic field with respect to fundamental harmonic. However, at high harmonic operation, the multimode analyses are very much needed due to the polluted mode spectrum which causes the increase in the parasitic oscillations from the nearby competing modes.

Finally, through the present work, we conclude that the gyro-TWT amplifier posses all the qualities of a high power amplifier in the millimetre and sub-millimetre wave frequency range with attractive efficiency, gain and bandwidth. Author feels that the study carried out in the present thesis would certainly help and motivate the readers and other researchers in the field of gyro-TWT amplifiers.