CHAPTER 6

SUMMARY AND CONCLUSION

6.1 Limitations of the Present Work and Scope for Further Studies

Generation and amplification of RF waves in the millimeter wave and submillimeter wave frequency range is of importance to applications in 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. However, there exists a technology gap in this frequency range. The conventional microwave tubes are not capable to generate high power at millimeter and submillimeter wave frequencies due to shrinking of their cross-sectional dimension with frequency. For quantum-optical devices, like, lasers, it is difficult to sustain the population inversion with the reduction of the energy of each quantum in the lower frequency region. Therefore, during the past few decades, intensive research and development efforts have been made towards high power coherent gyro-sources and gyro-amplifiers in this range of frequencies. In gyro-devices, the problem of miniaturization of transverse dimensions with frequency can be easily tackled by using overmoded RF circuits, such as cavities and waveguides, thereby dramatic increase in the transverse dimension due to their operation in the higher order modes.

Fast-wave devices like gyrotrons, gyroklystrons, gyro-TWTs come under the category of the bremsstrahlung radiation type devices. In bremsstrahlung type of devices, the radiation occurs when electrons move with an acceleration or deceleration in electric and/or magnetic fields. These electronic motions are most of the time oscillatory in nature. The electrons radiate coherent waves when the Doppler-shifted frequency of the wave coincides with the frequency of oscillation of electrons or with one of its harmonics. In gyro-devices, bremsstrahlung of electrons is realized by making relativistic electrons to move in helical trajectories in a background DC magnetic field in a cavity or waveguide. In such devices, it is the background magnetic field rather than the characteristic size of the interaction structure, unlike in conventional slow-wave microwave tubes that decide the operating frequency. The size of a fast-wave structure does not decrease with frequency as much as that of a slow-wave structure. Furthermore, in a fast-wave tube, the placement of the electron beam away from the wall of the interaction structure reduces the problem of beam interception by the structure. These results in larger structure dimension, increased power handling capability of the gyro-device. In the category of these devices, the gyrotron has been most extensively studied, and are commercially available for applications like plasma heating. However, from the standpoint of application in information carrying systems, like millimeter wave radar and communication, the gyrotrons are far from being mature, still requiring much improvement with respect to signal coherence and spectral quality. For such applications, an amplifier would be a more appropriate choice than an oscillator.

In recent years, extensive renewed interest has been aroused in the research and development of the gyroklystron amplifier in view of its potential capabilities of producing high RF power with larger gain and moderate bandwidth, along with better efficiency and spectral quality in the millimeter wave and submillimeter wave frequency range. Such devices are having applications in high energy particle accelerators (supercolliders), and high-resolution, long range millimeter wave radars. Gyroklystron amplifier is a fast-wave device which is based on the principle of the cyclotron resonance maser (CRM) instability. In the CRM interaction, phase bunching of electrons occurs due to the change in their relativistic mass as they lose or gain energy from the transverse electric field in the circuit. The azimuthal RF electric field interacts with the electrons in the transverse plane. The relativistic cyclotron frequency of electrons gets varied due to the change in the relativistic mass factor in this interaction mechanism. The cyclotron frequency of some electrons will increase, whereas for some, it decreases causing energy transfer and consequently, results in the phase bunching of the electrons.

In gyroklystron, electron beam having strong transverse velocity component gyrate at the cyclotron frequency. RF signal to be amplified is coupled through an RF cavity which imparts velocity modulation to the gyrating electrons. Azimuthal electric field of desired *TE* mode modulates the transverse velocity of the electrons and causes CRM instability. This results in azimuthal electron bunching which grows as the electrons travel towards output RF cavity through a drift tube of certain length. The drift tubes are designed to operate within cutoff. The bunching process and the gain of the gyroklystron can be increased by adding more number of RF cavities separated by the drift tubes. In the output RF cavity, the azimuthally bunched electron beam is continuously decelerated and transfers energy to the RF field in the operating *TE* mode and coupled out to the external circuit.

Though gyroklystron possess many potential qualities of a millimeter wave amplifier but still at present the design of a gyroklystron amplifier remains a critical issue for its developers. As the design of a gyroklystron amplifier is more complex than its oscillator counterpart gyrotron. Since, the performance parameters such as gain, bandwidth, noise and phase stability, which are not applicable to oscillators become of vital importance here. The device must be kept stable in the absence of a drive signal. Also, overmoded input couplers must be needed to inject the drive signal. The gyroklystrons are capable of high-gain and high efficiency amplification of RF waves in a relatively narrow bandwidth due to resonating nature of their interaction structure. These performances related issues along with the criticality in the design of the gyroklystron amplifier have motivated the author of the present thesis to take-up the design and electromagnetic wave and electron beam interaction studies of the gyroklystron amplifier in the present thesis and accordingly; the thesis has been organized into six chapters.

In Chapter 1, the theme of the present research work is described in detail. An overview of fast-wave devices with a brief discussion of high power gyro-amplifiers like, gyroklystrons, gyro-TWTs, and gyro-twystrons have been given. Potential applications of gyro-devices, with a detailed literature review of the gyroklystron amplifier have been presented. The state-of-the-art, improvement and advancement of the gyroklystron amplifier, its limitations, and scope for the further performance improvement have also studied. Chapter 1 finally concludes with the discussions regarding the need, plan and scope of the present thesis work.

In Chapter 2, a self-consistent nonlinear signal formulation of the gyroklystron has been developed considering electron velocity spread effects to study the beam-wave interaction behavior of a gyroklystron amplifier under the time independent single mode consideration. Small signal analysis based on the linear theory could be used to study the device behavior in the linear regime whereas, the large signal analysis based on the nonlinear theory could be 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 mechanisms.

In the earlier reported gyroklystron analysis, the results are presented in terms of normalized parameters through graphical analysis based on contour plots which has been extended here in terms of the mathematical model. Earlier the momentum and phase expressions were solved only for the output RF cavity to optimize the orbital efficiency of the device by arbitrarily choosing the normalized parameters. Thus, it was not providing the comprehensive scenario of the amplification process taking place in each stage of the device as one move from input cavity to the output cavity. Also, the variation of efficiency with frequency was not carried-out to estimate the device bandwidth. Therefore, in the present paper the work has been extended and the momentum and phase have been obtained for each RF cavities of the gyroklystron amplifier by considering actual parameters of the device instead of arbitrarily chosen parameters to estimate the efficiency in each cavity. The bandwidth of the device is estimated by studying the effect of frequency variations on RF output power.

The electron beam velocity spread always present practical device due to the non-uniform electrons emission from the cathode caused by the its non-uniform heating, surface roughness, and electrons repulsions due to space charge. 2 to 4% electron velocity spreads are usually found in the practical devices and this degrades the tube performance, both RF output power and efficiency. The nonlinear analysis has been modified to include this effect by making the normalized parameters: field amplitude, momentum and electron phase terms velocity dependent.

For the numerical benchmarking of the developed analytical model, the performance of typical 35GHz, cylindrical two-cavity and four-cavity gyroklystron amplifiers operating at the TE_{01} mode, reported experimental work in the literature has been investigated as well as validated. The results obtained through the nonlinear analytical model developed here have been found in agreement of ~5% with those of the reported experimental values. The effects of the various device parameters, such as, variations in the beam current, quality factor, beam voltage, and velocity spread on the device electronic efficiency, bandwidth and RF output power are explored and discussed. This sensitivity studies will help this device developer to analyze their device under practical conditions.

PIC simulation is an established tool to supplements the analytical results, sees the device behavior at different locations inside the device as well as also reduces the device development time and efforts. Gyroklystrons have also been investigated through PIC simulations but mostly in-house custom built simulation codes were used, which are not available in public domain. Also, detailed investigation of PIC results are not reported in the literature. The work reported in Chapter 3, a commercially available particle-in-cell code 'MAGIC' has been used for 3D simulation of gyroklystron amplifier. 3D PIC simulation has been performed both for the beam absent and beam present cases using this commercial code. The simulation procedure and beam-wave interaction investigation have been described. Electromagnetic simulation of RF cavity structure has been performed to examine the cavity operating mode, frequency as well as electric and magnetic field profile which also confirms the device operation in the desired mode. After the cold cavity simulation the beam-wave interaction analysis has been carried out for the estimations of the RF output performance of the device in the presence of the electron beam.

In Chapter 3, the electromagnetic and PIC simulations have been carried out for the same two-cavity and four-cavity Ka-band gyroklystron amplifiers whose parameters were typically selected and fixed previously in Chapter 2, as simulation techniques offer useful insight in understanding the device behavior as well as supporting the analytical models. Using eigenmode simulation, a well defined TE_{01} mode has been observed in the cavity at 35GHz resonant frequency. Field distributions obtained in terms of vector and contour plots along the cavity dimensions confirm the operating TE_{01} mode of operation. Further, the beam-wave interaction analysis has been carried out for the estimations of the RF output performance of the device in the presence of the electron beam (hot condition). Particles energy and phase plots have been observed during the beam-wave interaction process of the gyroklystron amplifiers. These plots clearly demonstrate bunching of the particles in their Larmor radius of each beamlets and the energy transfer phenomena to the RF field. Electric field patterns have been also monitored during the whole simulation runtime, which confirm the operation in the desired TE_{01} mode during the beam-wave interaction process. Moreover, the gain and bandwidth of the device have been also estimated through parametric analyses using PIC simulation by studying the effect of variations of driver power and frequency on the device RF output power. Finally, the gyroklystron amplifiers simulation results have been validated with the analytical results obtained in Chapter 2 and with published experimental results. The simulated values have been found in agreement with the analytical results and reported experimental results within ~5%.

In Chapter 4, important design parameters for the design of gyroklystron amplifier have been identified and developed a suitable approach for its design. As, in most of the reported work, detailed description of device design methodology and beam-wave interaction mechanism at the different locations within the device of a gyroklystron amplifier are not available. Therefore, in the present work, a comprehensive device design methodology has been described and step by step procedure of device design has been explained using a flow chart.

In Chapter 4, for a typically selected 35 GHz four-cavity 200kW gyroklystron amplifier operating at the fundamental mode, a comprehensive analytical device design methodology has been presented. The results obtained from nonlinear time independent single mode analysis for the conceptually designed gyroklystron under investigation produces a stable output power of ~219kW at center frequency 35GHz with electronic efficiency 37% corresponding to ~45dB gain and 3dB bandwidth ~0.3% (105MHz). PIC simulation is also carried out for this device and found that the analytical values are in agreement of ~5% with the PIC results. Moreover, in this chapter, the practical case of misalignment which may occur during the assembling of the various components of the gyroklystron is studied in detail. A practical case of the misalignment of the cavities axis, drift tube axis and both the axes is also investigated and found that the RF output power is more sensitive to the misalignment in comparison to the device bandwidth.

In Chapter 5, the gyroklystron amplifier has been explored further for the performance improvement of the device. One of the major limitations of the gyroklystron amplifier is its limited bandwidth operation, since it uses resonant cavities as its interaction structure. Thus, in this chapter an attempt has been made towards the broadbanding of the gyroklystron amplifier using stagger-tuning technique. In stagger-tuning the resonant frequencies of different RF interaction cavities of a klystron amplifier are slightly detuned, due to which the enhancement in the bandwidth of the device occurs, but at the cost of its gain. This method is widely used for the bandwidth enhancement of the conventional slow-wave klystron and can also be applied to broadband the gyroklystron. For this purpose, in this chapter a tradeoff in gain and bandwidth alongwith the gain-bandwidth product have been studied in detail for the stagger-tuned gyroklystrons. First, the generalized formalism for multicavity stagger-tuned gyroklystron amplifiers has been developed. The developed formalism has been numerically appreciated by studying the effect of stagger-tuning on the designed gyroklystron amplifier. The analytical results obtained here have been validated by carrying out the PIC simulation of the designed gyroklystron amplifier for the stagger-tuning case. The agreement between the analytical and simulation results is found within the limits of 10%.

In Chapter 6, the work embodied in the present thesis has been summarized, and the significant conclusions have drawn from the major findings. The limitations of the present work have also been discussed, pointing out the scope for further work.

6.1 Limitations of the Present Work and Scope for Further Studies

In the present thesis, the performance study of a gyroklystron 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 for cylindrical two-cavity and multicavity gyroklystron amplifiers. It is hoped that the present study would be useful in designing the gyroklystron 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 gyroklystron amplifiers have some limitations. In the analyses, an important aspect of the space charge effects has not been considered, which provide a more realistic scenario.

PIC simulation offers a self-consistent behavior of RF interaction structures. Although a lot of simulation studies have been carried out related to performance evaluation and performance improvement techniques in a gyroklystron amplifier, several issues still remain to be addressed. In the simulations, an important aspect of the beam velocity spread has not been incorporated, which provide a more realistic scenario. Since the inclusion of velocity spread is not there with the commercial PIC code 'MAGIC'. In the present simulation input coupler is not modeled for exciting the input cavity of the gyroklystron amplifier. Here RF input is applied directly to the input cavity with the help of the DRIVER command in PIC code. However, to make the present simulation model more useful for the practical case the input coupler should be modeled and its effect on the cold cavity mode, the quality factor, etc. needs to be studied.

Though the gyroklystron 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 gyroklystron amplifier, these studies are very much needed.

In the present thesis the device has been designed and studied for the fundamental mode of operation, which requires high magnetic field. The requirement of magnetic field further increases with frequency for the fundamental operation of the device. The requirement of high background magnetic field can be reduced by high harmonic operation of the device. 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 gyroklystron amplifier posses all the qualities of a high power amplifier in the millimeter and submillimeter 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 gyroklystron amplifiers.