CHAPTER 6

SUMMARY, CONCLUSION AND FUTURE SCOPE

6.3. Summary and Conclusion

6.4. Future Scope

6.1. Summary and Conclusion

The horizon of microwave tubes continues to expand in the microwave and millimetre-wave frequency range encompassing various applications in communication, radar, electronic warfare, missile tracking and guidance, directed energy weaponry, remote sensing, industrial heating, material processing, plasma heating for controlled thermonuclear energy research, and so on.

Since various conventional microwave tubes, like TWT, klystron, magnetron, BWO, etc., have limitation of high power at millimeter-wave frequency band, gyro devices can overcome this limitation and deliver large RF powers. The gyro-devices fill the technology gap in millimeter-wave frequency band that cannot be done by conventional microwave tubes, which have limitations at higher power levels in the millimetre-wave range due to factors like DC power dissipation, RF losses, attainable electron current density, heat transfer, material breakdown, etc., nor by quantum mechanical devices, which have energy reduction limitations at lower frequencies as well as in millimeter frequency band, also the difficulty of sustaining population inversion.

In gyro-devices, based on CRM instability, like the gyrotron, the gyro-TWT,gyro-klystron and gyro-twystron, higher operating frequencies can be attained by increasing the magnetic field which in turn causes an increase in the cyclotron frequency to make it resonate with the waveguide-mode frequency. The required magnetic field can, however, be reduced by cyclotron harmonic operation of the device. The transverse dimension of the interaction structure of the fast-wave devices like the gyrotron and the gyro-TWT decreases with the operating frequency, however, not to the extent in which the transverse dimension of the slow-wave devices like the TWT decreases. The gyrotron (gyro-source), the gyro-klystron (gyro-amplifier) and the gyro-

TWT (gyro-amplifier) have received the maximum attention in the family of gyro-devices in their development. The gyro-klystron and gyro-TWT are effective amplifiers at high frequencies. However, they still suffer from various limitations, such as the microwave breakdown problem in gyro-klystron due to the output cavity section and mode competition constraints in gyro - TWT due to the short output waveguide section. A hybrid amplifier known as a gyro – twystron is introduced to address these problems and combine the benefits of the two devices into one. The gyro- twystron, analogous to a conventional twystron is constituting one or more input cavities followed by an output waveguide section. provides a significant gain-bandwidth improvement over other gyro amplifier. The gyro-twystron merging the merits of two gyro amplifiers (gyro klystron, gyro – TWT), it has aroused considerable research interest in widening the bandwidth with sufficient power level for applications such as in high-resolution radar and high information density communication systems in the millimetre-wave frequency band. This urge for increased device bandwidth led to the investigation of various methods, including the stagger tuning technique and the cluster cavity approach. Since the gyro-twystron is a hybrid device that utilizes both cavities and waveguide, the two methods of increasing the device's bandwidth; stagger tunning and cluster cavity, are perfectly applicable to it.

The gyro-twystron is able to meet the bandwidth requirements for millimeter-wave radar applications by employing a number of techniques for enhancing bandwidth. Nonetheless, it is susceptible to the same parasitic instability and backward wave oscillation issues as the gyro-TWT, as both employ the waveguide as the beam wave interaction region.

In order to investigate the beam-wave interaction mechanism in a gyro-twystron, a literature review of the well established linear and nonlinear analyses have been presented. The linear analysis has been used to predict the start oscillation condition which is crucial for the design of a stable amplifier in terms of beam current, DC magnetic field, along with the information regarding nearby competing modes. On the other hand, nonlinear analysis is used to predict RF output power, efficiency, and saturation gain, hence provides complete analysis of the overall structure. To investigate the instability problem, a steady state nonlinear analysis has been carried out on the fundamental stagger tuned W-band gyro-twystron with a periodic dielectric loaded (PDL) RF interaction circuit. The analytical finding using the existing linear and nonlinear theory have been validated through the numerical simulation using "CST Particle Studio". Along with this performance studies, the different subassemblies of gyro-TWT such as electron gun, input coupler, beam collector, and output window have also been designed and simulated. The design and simulation studies of single and double anode magnetron injection gun, undepressed and single stage depressed collector, RF output window have been carried out by using 2D electron optics (EGUN) for their beam trajectories and 3D simulation by using "CST Microwave Studio".

The first chapter of this thesis provides a comprehensive literature review on the history, evolution, limitations, and future prospects of the microwave tube. The stagnation in developments of conventional microwave tubes and discovery of CRM mechanism ignites the development of gyrotron devices, which were dominantly discussed in the Literature review. Gyrotron amplifiers were reviewed thoroughly, and the research advancement of gyro-klystron and gyro-TWT were discussed along with slow-wave twystron amplifier. Finally, a detailed discussion of the gyro-twystron amplifier's potential as a millimeter wave radar source has taken place. Various solutions for improving gyro-twystron performance, such as bandwidth enhancement and stability analysis, have been thoroughly investigated.

In Chapter 2, The design methodology of different sub sections, i.e. the cavity, the drift tube and the output waveguide section of the gyro-twystron was developed. For the stability analysis, a single-mode nonlinear theory of gyro-twystron was studied. This theory is then extended to the study of stagger tuning analysis. These theoretical advancements of the stagger tuning mechanism predicted a significant increase in bandwidth, approximately 2.5 times greater than the synchronously tuned gyro-amplifier.

In Chapter 3, the analytical finding of the chapter 2 is validated through the PIC simulation results. The gyrating electron beam source, MIG is designed using the 2 D EGUN code and optimized this MIG for the velocity spread of 4% and the pitch factor of 1.6. The stagger tuned cavities and the drift tubes are designed in the absence of beam (cold analysis) using the eigenmode solver and optimized according to the required operating mode and isolation between adjacent structures. The 3D PIC simulation has performed in beam presence condition to simulate the beam wave interaction mechanism and extract the RF output power at the predefined output port. The PIC simulation predicted an output power of 83 kW with a gain and efficiency of 37 dB and 22.5, respectively, for a 20 W input power. The stagger tuning mechanism has a 3 dB bandwidth of 1.5 GHz, which is approximately 2.5 times the synchronous tuned gyro-twystron bandwidth. The simulation output is validated against the analytical finding , obtained through nonlinear theory . To collect the spent electron beam after the beam wave interaction, an undepressed collector is designed using 2D electron optics (EGUN). The amplified RF output power is extracted through the single disc RF window having a bandwidth of ~ 3 GHz.

The Chapter 4 of the thesis explore the method of broad banding a gyro-twystron at relatively large gains by loading the circular waveguide by axially periodic dielectric loading while accruing the advantage of stagger tuning as well as the loading of the cross-sectional structure dimensions. For this performance advancement purpose, chapter 4 has included the development of the cold or beam-absent analysis of a disc-loaded circular waveguide for optimum dispersion control as required for wide bandwidths of a gyro-twystron as well as the appreciation of the device performance in the gain-frequency response of the device with the help of the hot or beam-present analysis of the device. Out of the various analytical techniques to the problem of the disc-loaded waveguide reported in literature, the field matching technique has been identified as the one suitable for the study of a disc-loaded waveguide considering higher order travelling-wave space harmonics in the disc-free region as well as higher order stationary-wave modal harmonics in the disc-occupied. The effect of the dielectric loading has observed in the dispersion diagram, and the operating point of the PDL gyro-twystron is chosen based on this dispersion. Linear theory used identify the attenuation rate, the start current, and the start length of the interaction section. The dielectric ring is made of BeO-SiC, which soaks up the sporous mode that is developed in the interaction region, and the size of the ring is chosen so that produce the maximum output. The PIC simulation of the PDL gyro-twystron predicted 120 kW in fundamental TE_{01} mode at 94 GHz. The conversion efficiency, 3-dB bandwidth and saturated gain were calculated as ~34 %, ~2.2 GHz and ~51 dB, respectively. A triode magnetron injection gun was designed for 60 kV and 6A gyrating electron beam and optimized for the velocity spread of ~2.2 % with a velocity ratio of 1.6. A single-stage depressed (SSD) collector has also been designed to enhance the efficiency of the amplifier to ~57 %. A double-disc window was designed and optimized for the broader bandwidth of ~8 GHz.

In Chapter 5, the gyro-twystron amplifier has been explored further for the performance improvement of the device. Gyro-amplifiers are envisaged to find significant radar applications, especially in the Ka-band (26.5-40 GHz) and W-band millimeter-wave bands (75–110 GHz). Radars typically use atmospheric windows at 35 GHz and 94 GHz in these bands. The gyro-amplifiers required for radar applications must usually be capable of high average power and bandwidth. This urge for wide bandwidth led to exploring various methods to improve the device output performance. Thus, considerable research is being conducted on developing various approaches for increasing the device's bandwidth. There are two basic strategies used for bandwidth enhancement. One is stagger tuning (discussed in chapter 2 and chapter 3) and other one is cluster cavity method. In chapter 5 the detail analysis of the cluster cavity method has performed to determine the complication of narrow bandwidth associated with cavity-related gyro amplifiers with minimum degradation of gain and efficiency. In this technique for enhancing the bandwidth, the structure of a single intermediate cavity is replaced by pairs or triplets of artificially loaded cavities with Q factors dropped to half or one-third, respectively, of the cavity they replace. The analytical finding of the cluster cavity based gyro-twystron is validated against the PIC simulation result. The PIC simulation developed the RF output power of ~ 82 kW at 94 GHz in operating TE_{01} mode with a gain of ~ 36 dB for the RF input of 20 W. The electronic efficiency of the present gyro-twystron is ~ 21 % corresponding to the beam voltage and current of 65 kV and 6 A, respectively. The measured bandwidth of the clustered cavity gyro-twystron is ~ 3 GHz, which is twice as large as the bandwidth (~1.4 GHz) reported in stagger tuned gyro-twystron.

6.2. Future Scope

In the present thesis the stagger tuned multi cavity gyro-twystron has been designed and studied. The main focus of the thesis to investigate the beam wave interaction mechanism of the amplifier along with the study of different methods to enhance the bandwidth, required for the various millimeter wave radar applications. To increase the amplifier's efficiency and for the wide band operation, the different sub assemblies, like, electron beam source (MIG), collector and output RF window are also designed and simulate. The stagger tuning technique, where the different cavities are tuned at slightly different resonating frequency, has investigate to improve the bandwidth but at the same time loss in gain is observed. To enhance the bandwidth without compromise with the gain, a cluster cavity technique has investigated and find a significant improvement in device outputs. It is hoped that the findings of this study will aid in the design of a gyro-twystron amplifier that can operate at any frequency and generate required amount of power. Nonetheless, the author is fully conscious of the limitations of the present work and the extent of the additional research required to improve it. Some of the limitations suggested for future work are the following:

In present thesis the two cluster was introduced in two cavities and each cavities was stagger tuned. It is worth to investigating the limits on the number of cavities used in the cluster and the effect of stagger tunning in each cluster.

To increase the amplifier's efficiency and gain, dielectric rings are introduced in interaction section. The device efficiency could also enhance by the proper optimization of the beam source (MIG) and spent beam collection system (collector). Beam source can be optimized to reduce the velocity spread which improves the RF power with large doppler upshifted operation. Beam collector system can be optimized as multistage depressed collector (MSD) to improve the device overall efficiency. The multidisc output RF window can optimize for different ceramic material for the broadening the operation bandwidth. Helical waveguide structures can be introduced to gyro-twystron amplifiers to achieve velocity spread tolerant operation.

In the present study the beam wave interaction studies of the gyro-twystron have performed for the fundamental mode operation, under the guidance of high magnetic field. For the investigation of higher frequency operation, requirement of magnetic field further increases 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 generation of sporous modes in operating range of the device.

Suggested future scopes can summarised as:

- Beam source can be optimized to reduce the velocity spread which improves the RF power with large doppler upshifted operation.
- Beam collector system can be optimized as multistage depressed collector (MSD) to improve the device overall efficiency.
- It is worth to investigating the limits on the number of cavities used in the cluster and the effect of stagger tunning in each cluster.
- Helical waveguide structures can be introduced to gyro-twystron amplifiers to achieve velocity spread tolerant operation.
- Subassemblies such as input coupler and RF window can be optimized to support the broadband operation of gyro-amplifiers.