CHAPTER 7

SUMMARY, CONCLUSION AND FUTURE SCOPE

7.1. Summary and Conclusion

The potential uses of Vacuum Electron Devices (VEDs) in the microwave and millimeter-wave frequency range are endless, and they include a wide range of fields such as communication, radar, electronic warfare, missile tracking and guidance, directed energy weapons, remote sensing, industrial heating, material processing, hyperthermia, waste remediation, plasma heating for controlled thermonuclear energy research, and so on. However, there exists a technological gap in the millimeter and sub-millimeter wave frequency range. That cannot be accomplished either by conventional Vacuum Electron Devices or by quantum mechanical devices. Because traditional VEDs have limitations at higher power levels in the millimeter-wave range with respect to the factors like DC power dissipation, RF losses, attainable electron current density, heat transfer, material breakdown, etc., and the quantum mechanical devices have limitations at lower frequencies, also in the millimeter-wave range, with respect to the reduction in energy of each quantum as well as the difficulty of sustaining population inversion. Therefore, during the past few decades, considerable research interest has been aroused in the development of gyro-devices to bridge the gap between the domain of conventional VEDs at low frequencies and the extent of lasers at high frequencies.

Gyro devices such as gyrotron, gyroklystron, gyro-TWT, and gyro-twystron are based on the phenomenon of cyclotron resonance maser (CRM) instability. In these devices, based on CRM instability, higher operating frequencies can be achieved by increasing the magnetic field, which in turn causes an increase in the cyclotron frequency to make it resonate with the cavity or waveguide-mode frequency. The required magnetic field can, however, be reduced by the cyclotron harmonic operation of the device. The transverse dimensions of the RF interaction structure in both conventional slow-wave and fast-wave gyro-devices reduce as frequency increases. However, the wavelength of traditional slow-wave devices is dictated by the circuit dimensions, whereas the wavelength of a gyro device is governed by the cyclotron resonance conditions or, more particularly, by the applied magnetic field strength. So dimensions of the gyro devices structure does not decrease with frequency as much as that of a slow-wave structure. In the family of gyro-devices, gyrotron, gyro-klystron, and gyro-TWT have received the maximum attention in their development. Even though gyro-klystron, gyro-TWT were rewarded as the successful amplifiers for millimeter radar systems, they have its own drawbacks. For example, gyro-klystron amplifier cannot sustain at higher levels of power. This is because poor output coupling of high quality factor output cavity present in gyro-klystron. Similarly gyro-TWT has the drawback of maintaining its stability against backward wave oscillations (BWO) in the interaction circuit. Also there are competing modes propagating in the forward direction due to the long output waveguide section. The presence of forward and backward propagating competing modes, power fluctuates between the desired mode and the competing modes in the gyro-TWT. This causes frequency and power instability in the device. A hybrid device, comprised of a klystron followed by a TWT known as a gyro – twystron is introduced to mitigate these problems and combine the merits of both these devices. One may look upon it as a device that is derived from the gyroklystron by extending the length of the drift section and replacing the output cavity with a waveguide section as in a gyro-TWT. The combination of the chain of resonators and the short output waveguide makes gyro-twystrons attractive as wide band, high efficiency, and high gain amplifiers. The gyro-twystron combining the advantages of two gyro amplifiers (gyro klystron, gyro – TWT) has ignited significant research interest in broadening the bandwidth with sufficient power level for applications such as high-resolution radar and high information density communication systems in the millimeter-wave frequency band.

In the present thesis work, comprehensive theoretical investigations of Ka-band gyro-twystron were carried out in order to investigate the new potentials and capabilities of gyro-twystron. The present work focused mainly on design, nonlinear analysis, and 3D PIC simulation. The potential capabilities of the single-cavity gyro-twystron were studied using nonlinear multimode analysis, which predicted that unwanted spurious oscillating modes cause instability in operation. To suppress unwanted spurious oscillating modes using the short periodic dielectric loading in the output waveguide section was made, and multimode analysis was carried out to investigate the behaviour of multiple modes in PDL gyro-twystron, which predicted that spurious oscillating modes was well suppressed. Furthermore, a stability analysis of the PDL gyro-twystron was performed. An intermediate cavity was introduced to single cavity PDL gyro-twystron to improve the performance metrics of the hybrid gyro amplifier. The gyro-twystron potentially achieves millimeter-wave radar bandwidth requirements by applying a variety of bandwidth enhancement approaches, including the stagger tuning technique and the cluster cavity approach. A multi-cavity Ka-band stagger-tuned gyro-twystron was designed to improve the bandwidth, and its beam-wave interaction behavior was explored. The various gyro-twystron subassemblies, including the input coupler, electron gun, beam collector, and output RF window, have also been designed and studied for their propagation characteristics. The following section discusses the present thesis's theoretical improvements and research findings.

Chapter One of This Thesis provides a thorough literature overview of the development, limitations, and future possibilities of the VEDs. The fundamentals of conventional VEDs and the discoveries of the CRM mechanism motivate the development of gyrotron devices, which are mainly discussed in the literature review. Fast-wave gyro amplifiers were reviewed thoroughly, and the scientific advancements of gyro-klystron and gyro-TWT were discussed along with the gyro-twystron amplifier. The possibility of the gyro-twystron amplifier as a millimetre wave radar source has been discussed. Finally, its limitations and scope for further performance improvement have been discussed. Various solutions for improving gyro-twystron performance, such as gain, bandwidth enhancement, and stability analysis, have been thoroughly investigated.

In chapter 2, the design approach of the Ka-band gyro-twystron amplifier has been developed along with the beam wave interaction theory. Each component of a gyro-twystron amplifier, such as the cavity, drift tube, and waveguide, has its design issues addressed. A steady state self-consistent nonlinear multimode analysis was used to investigate the complete RF wave-electron beam interaction behaviour. The potential capabilities of the single-cavity gyro-twystron have been studied, which provides a broader bandwidth over the gyroklystron and provides better gain and moderate bandwidth as compared to the gyro-TWT.

In Chapter 3, analytical studies of gyro-twystron is discussed in chapter 2 is validated through the PIC simulation results. A single cavity *Ka*-band gyro-twystron has been modelled and studied for its beam-wave interaction behaviour using a commercially available 3D electromagnetic simulation tool, "CST Particle Studio". A single anode MIG was designed using EGUN code, that able to generate a good quality gyrating electron beam having a 4% velocity spread and 1.4 velocity ratio. The PIC simulations predicted an RF output power of ~240 kW at 35 GHz with ~37 % efficiency, ~53 dB gain, and a 3-dB bandwidth of ~2 GHz. As an output section, a collector was designed to collect the spent electrons with a wall loading of 0.116 kW

/cm^2, and also a single-disc RF window was designed and studied for its good propagation characteristics for the collection of generated RF power.

In Chapter 4, a short periodic dielectric loading (PDL) output waveguide section of a single cavity millimeter wave gyro-twystron was designed with a high beam velocity ratio to suppress the parasitic modes and improve the performance. Using a short high thermal conductivity lossy dialectic material has reduced the generation of parasitic TE_{11}, TE_{21}, and TE_{02} modes. As a result, the hybrid amplifier's high-power handling performance has significantly improved, and the device has become more compact. The stability and beam–wave interaction behaviour of the millimeter-wave PDL gyro-twystron amplifier were investigated using the linear and nonlinear multimode theory. Moreover, the analytical findings were validated by using a commercially available FIT-based 3-D electromagnetic code. Furthermore, a triode-type MIG has been designed to generate a good quality gyrating electron beam with a ~ 4% velocity spread and 1.4 velocity ratio. A *Y*-shaped input coupler has also been designed and studied for its propagation characteristics. As an output section, an undepressed curved collector was designed to collect the spent electrons with a wall loading of 0.044 kW/cm2. Finally, a double-disk RF window was designed and studied for its good propagation characteristics for the collection of amplifier RF signal.

In Chapter 5, a gyro-twystron performance improvement investigation was carried out. An intermediate cavity was incorporated in a single cavity PDL gyro-twystron to enhance the gain and efficiency. A periodically dielectric loaded output waveguide section was used to suppress spurious modes to improve the stability and gain of the amplifier. From this study, a significant RF output power and gain improvement has been achieved using an additional intermediate cavity. From the analytical and simulation results, it is observed that pre-bunched electron beam provides better growth and saturation of RF power in the short PDL waveguide section. A study on double anode MIG suggested that at the optimum value of modulating anode voltage of 25 kV, the electron beam with a 1.4 pitch factor and ~3 % spread is achieved. The device's efficiency is further improved by using a single-stage depressed collector (SSDC). The efficiency of the SSDC is 57%, which increases the overall efficiency of the gyro-twystron from 46% to 66.5%. Furthermore, a triple-disc RF output window is designed and simulated to extract the amplifier RF signal over a broad frequency range.

In Chapter 6, the gyro-twystron amplifier has been explored further for the performance improvement of the device. Gyro-amplifiers are to find widespread use in radar systems, particularly in the Ka-band (26.5-40 GHz) and W-band millimeter-wave bands (75–110 GHz). Radars frequently employ atmospheric windows in these bands. Gyro-amplifiers for radar applications must typically have high average power and bandwidth. Gyro-twystron amplifier is one of the viable candidates for use in millimeter-wave high-resolution radar applications. But the gyro-twystron bandwidth is primarily limited by the quality factor of the pre-bunching cavities. The stagger tuning approach has been used to avoid this limitation and widen the bandwidth of the gyro-twystron. The stagger-tuned multi-cavity *ka*-band gyrotwystron amplifier has increased by two times when compared to without a stagger-tuning amplifier while exhibiting minimum gain degradation. Furthermore, a double anode MIG has been designed to generate a high-quality electron beam with a velocity spread of ~2% and a pitch factor of 1.4. To increase the efficiency of the amplifier, a three-stage depressed collector was designed as the output system. The current amplifier's overall efficiency rises from ~ 43% to ~78%. Finally, a Meta surface output window for collecting amplifier RF signal with wide bandwidth was designed, and its propagation characteristics were explored.

7.2. Future Scope

A *Ka*-band gyro-twystron is designed and studied in the present thesis. The main focus of the thesis is on the beam wave interaction mechanism in various RF structures of gyrotwystron amplifier, along with the study of various approaches to improve gain, bandwidth, and efficiency for various millimeter wave radar applications. The present work also includes the design and simulation studies of electron guns, RF input couplers, beam collectors, and RF output windows. To increase efficiency and gain, a periodic dielectric loading technique is introduced in the output waveguide section of a single cavity and two-cavity gyro-twystron amplifier. The stagger tuning technique has been investigated to improve the bandwidth further, but at the same time, less degradation in gain is observed. It is hoped that the present design analyses and simulation investigations of various sub-assemblies would be useful in designing the gyrotwystron amplifier of any frequency and power. However, the author is aware of the limitations of the present work and the 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 multimode analysis presented for the beam-wave interaction studies in gyrotwystron amplifiers has some limitations. In the analyses, an important aspect of the space charge effects has not been considered, which provides a more realistic scenario.

The current beam wave interaction investigation is limited to fundamental beam mode harmonics. However, a higher harmonic is preferable for increasing the gyrotron amplifier's figure of merit. The second harmonic action of the gyro-twystron can improve the figure of merit; however, a stability analysis is required since the higher harmonic operation is susceptible to oscillations. In addition to the electromagnetic analysis, the implementation of distributed loading to second harmonic gyro-twystron will be an extension of the existing work. Furthermore, a Cusp gun can also be designed for the second harmonic operation of a gyro-twystron amplifier.

The efficiency of beam-wave interaction depends on the electron beam quality, and this electron beam has an unavoidable velocity spread, which will be challenging to minimize. Therefore, a helical waveguide can be used as a velocity spread tolerant interaction structure in the output part of a gyro-twystron amplifier.

In the present work, the stagger tuning technique has been investigated to improve the bandwidth with minimum gain degradation. To enhance the bandwidth without compromise with the gain, a cluster cavity technique can also be done.

In the present analysis, one of the practical aspects of gyro-twystron, like thermal analysis, has not been considered. The thermal analysis of the electron gun, interaction region, beam collector, and output window can also be done. The effect of secondary electron emission from the depressed collector can also be studied.