CHAPTER 6

SUMMARY, CONCLUSION, AND FUTURE SCOPE

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6.1. Summary and Conclusion

Among the variety of electronic devices available, microwave tubes (electron beam devices) still find its dominance for delivering high power at microwave to millimeter-wavelength, and this is an area where their solid-state counterparts are not able to compete. There exists a technological gap in the millimeter and sub-millimeter wave frequency; no matter whether it is filled up by decreasing the frequency of quantum-mechanical devices, like, laser or by increasing the frequency range of the conventional microwave tubes. 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. Whereas, the rapid miniaturization of the conventional microwave tubes at the millimeter-wavelengths results in decrement of the power handling capability of such structures. 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 microwave tubes at low frequencies and the extent of lasers at high frequencies. Gyro-oscillators and gyro-amplifiers are well recognized as the high power sources of coherent electromagnetic radiation in the millimeter and sub-millimeter wavelength. Such devices have important 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. In both the conventional slow-wave and fast-wave gyro-devices, the RF interaction structure decreases with the increase in frequency. But in case of conventional slow-wave devices, wavelength is determined by the circuit dimensions, while the wavelength in case of a gyro-device is determined by the cyclotron resonance condition, or more specifically, by the applied magnetic field strength. Thus, for the higher-order waveguide or cavity mode operation in the interaction circuit, the circuit dimensions of gyro-devices can be significantly larger than the operating wavelength. The drawback, of course, is that gyro-devices require high magnetic field strength for high-frequency operation. Furthermore, in the fast-wave circuits, the electron beam is placed in the region of high electric field, resulting into minimum beam interception from the cavity walls. Such arrangement results in larger structure dimension, and hence increased power handling capability of the gyro-device. In the category of gyro-devices, gyrotron has been most extensively studied, and are commercially available for applications like plasma heating. However, from the standpoint of application in the information carrying systems, like millimeter-wave radar and communication, the gyrotrons amplifiers are far from being mature, still requiring much improvement with respect to signal coherence and spectral quality. For such applications, gyro-amplifier would be a more appropriate choice than an oscillator. The gyrotron devices, such as, the gyromonotrons (gyrotrons), the gyroklystrons, and the gyro-TWTs, are based on the phenomenon of cyclotron resonance maser (CRM) instability.

Out of the family of gyro-devices, gyroklystron is the most important member today as a millimeter and sub-millimeter wave amplifier. The gyroklystron consists of a series of cavities separated by a region called as drift tube like a conventional klystron. The input signal is fed into the input cavity and the field excited in this cavity energy modulates the electrons that lead to orbital phase bunching which grows as the electrons proceeds along the interaction length. This modulation and bunching process causes an appearance of high frequency components at the signal frequency and its harmonics which in turn excite oscillations in other cavities, results in improving the quality of electron bunches and hence gain and efficiency of the device. Finally, the RF power is extracted out through output cavity. Another important issue which is important for gyroklystron is to avoid the leakage of microwave energy into the drift section. Therefore, the drift section should be made cut-off for the operating mode and secondly, these sections contain some lossy materials for absorbing the leaked microwave energy.

Mode purity is another important factor that affects the interaction of input RF signal and electron beam in the development of high power and high frequency gyroklystron amplifier. The gyroklystron operation at higher order modes can surmount the problem of miniaturization of RF interaction structures at the higher frequencies, but at the same time, results in the dense RF spectrum which can cause probability of switching of modes to the unwanted modes. This results into the serious problem of mode-competition which affects the performance of the device, such as, efficiency, and RF power in the desired operating mode. Additionally, for such high frequency fundamental mode of operation, the magnetic field requirement becomes high which further require a bulky superconducting magnet and makes the system bulky. So, to overcome these problems, the device can be designed to operate at a harmonic of the operating frequency so that the magnetic field requirement is reduced by a factor of the harmonic number. Such magnetic field can also be easily produced by the permanent magnetic systems. However, higher harmonic modes are difficult to excite because of the mode competitions from the nearby higher harmonic competing modes as well as the fundamental harmonic modes. So, tackling the mode competition issue at higher frequencies and higher harmonics is the main research objective of the present thesis.

In order to investigate the beam-wave interaction mechanism in a gyroklystron, a literature review of the well established linear and nonlinear analyses have been presented and it is inferred that both the analyses are supposed to perfectly verify each other in the linear interaction regime. 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. However, as per the state of the art, the existing nonlinear theories for the analysis of gyroklystron amplifiers mainly focused on the time-independent single-mode operation of the device and do not take into account the concept of mode competition. Thus, to incorporate the effect of all nearby competing modes on the performance of the device, a time-dependent, multimode nonlinear analysis of the gyroklystron amplifier has been carried out in the present work. Hence, in order to obtain more practical performance, multimode analysis has been revisited and described in detail that determines the actual output power and efficiency in the operating mode of the gyroklystron amplifier. In addition, the self-consistent approach has been adopted for analyzing the electron beam and RF interaction in which axial structure of the field is modified by the high frequency component of the electric field density. Thus, the purpose of our work in Chapter 2 is to develop and apply a self-consistent, time-dependent multimode formulation for the gyroklystron which is simultaneously adoptable for efficient numerical computations. This analysis is generalized and incorporates the device operation at arbitrary cyclotron harmonics employing any arbitrary shape of interaction structures.

In 1986, Salop and Caplan developed the time-independent nonlinear analysis of the gyroklystron amplifier by extending the basic theoretical approach as followed for gyrotron oscillators. By following the similar procedure, the author developed the time-dependent multimode nonlinear analysis for the gyroklystron amplifier by extending the time-dependent multimode nonlinear formulation as carried out for gyrotron oscillators by Fliflet *et al*. The analysis is governed by the time-dependent description of the electromagnetic fields and the electron motion expressions. In addition, the field profile in the cavities has been computed self-consistently. The generalized coupled nonlinear equations of motion of electrons are typically analyzed for the calculation of momentum and phase of the particles by considering the cumulative effect of all possible modes in the cavity. These equations are then solved self-consistently for each cavity and drift space by satisfying the appropriate boundary conditions for the particle momentum, phases and the field profile. The field profile inside the input cavity is taken as simple sinusoidal profile by assuming that “the interaction between the RF wave and beam particles in this cavity is small enough and the particles are uniformly distributed”. Since the beam-wave interaction becomes stronger as the beam particles proceeds from input cavity, the axial mode profile is modified. Hence, in the succeeding cavities the field profile is computed self-consistently using the modified Vlasov equation. The mode amplitude and phase in each cavity at each time step are calculated using coupled time-dependent equations. A flowchart explaining the step-by-step procedure for the multimode analysis of the gyroklystron amplifier is also shown. Using the expression of time-dependent RF output power, the temporal evolution of output power in all the possible modes has been plotted.

A code has been written based on the developed analysis and then has been used to numerically benchmark the analysis validity. A 32.3GHz, three-cavity, second harmonic, experimental gyroklystron amplifier operating in TE_{02} mode has been taken for this validation. It is assumed that all electrons have the same transverse velocity so that effects due to spreads in the spatial and velocity distribution are neglected. For simplification, space-charge effect is also neglected. The start oscillation current is calculated for the operating TE_{02} mode which ensures the stable operation of the device as an amplifier. Further, it also indicates that the possible competing modes are suppressed over the entire possible range of the DC magnetic field. The temporal evolution of the RF output power in all the modes is plotted and it is inferred from the figure that the RF output power corresponding to the TE_{02} mode eventually dominates all competing modes, and the mode competition is mainly due to the fundamental harmonic TE_{01} mode. The saturated RF power of ~319W is obtained in the operating TE_{02} mode. The analytical results obtained are then benchmarked with the reported experimental values and found to be in close agreement. This justifies the validity of the analytical approach adapted as well as computer codes developed. The parametric effects have been presented to show the device sensitivity in terms of output power with the beam parameters which further helpful in optimizing the design parameters. The effect of frequency and gain variation on the RF output power has been studied to estimate the bandwidth and gain of the device. The gain and bandwidth of the device has been obtained as ~26.3dB and 8MHz, respectively.

In order to understand the complex electron beam and RF wave interaction mechanism as well as to predict the physical phenomena happening at different places at different intervals inside the device, 3D particle-in-cell (PIC) simulation are often used. In Chapter 3 of the thesis, 3D PIC simulation procedure of the gyroklystron, reconfiguring the commercially available "CST Studio Suite" has been described. CST Particle Studio is an PIC code which is based on finite-integration method for the processes that involves interactions between space charge and electromagnetic (EM) fields, simulates the interaction between charged particles and electromagnetic fields as they evolve in time and space from some defined initial configuration. This PIC simulation offers an insight into the EM behavior of the device by integrating the practical design constraints and provides the validation and optimization of the design parameters without fabricating the actual device. The basic steps followed for the PIC simulation of a gyroklystron amplifier has been discussed in detail. Firstly, RF interaction structure of a gyroklystron amplifier has been modeled for simulation using the relevant design parameters. Then, the simulations have been performed in both the beam-absent and beam-present cases. The desired mode of operation at desired frequency has been selected by simulating the structure in the absence of beam (cold analysis) using eigenmode solver. Then, using the PIC solver, the performance of the device in terms of RF output power and gain has been obtained by simulating the structure in the presence of beam (hot analysis). To have insight of the electromagnetic field distribution inside the interaction structure, field monitors such as *E*-Field monitor, and *H*-Field monitor are defined. The phase space monitors are defined to have the information about the perturbation of the particles in terms of energy or phase, and bunching phenomena. A waveguide port is defined at the output section of the cavity to determine the signal amplitude corresponding to the different modes.

In order to validate the analysis developed in the present work, the PIC simulation has been performed for the same experimental second harmonic Ka-band gyroklystron amplifier as considered in Chapter 2. The RF interaction structure modeling has been done using the experimental parameters for PIC simulation. The material property of the cavity walls of the RF interaction structure has been taken as pure copper to reduce the ohmic losses in the structure. The input cavity and buncher cavity has been loaded with a lossy material (lossy alumina (96% lossy)) to achieve the desired quality factor. The drift tubes have been loaded with lossy ceramic rings (BeO-SiC) to avoid the complete isolation between the adjacent cavities. Using eigenmode simulation, a well defined TE_{02} mode has been observed in the cavity at 32.3GHz resonant frequency. Field distributions obtained in terms of vector and contour plots along the cavity dimensions confirm the operating TE_{02} mode of operation. Further, beam-present (hot) simulation is performed to study the beam-wave interaction behavior in terms of RF output power and electronic efficiency. In order to facilitate the simplicity of the simulation process, the space charge effect on the electron beam has been neglected. The DC emission model which includes the beam voltage in terms of relativistic mass factor, beam current, and pitch factor has been defined. The trajectory of electron beam along the interaction length has been observed which indicates that the presence of RF field perturbs the momentum of electron-beam resulting in the bunch-formation. 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. The contour plot of the electric field pattern clearly indicates that the TE_{02} mode is propagating along the axial length of the interaction circuit. In the present PIC code, the temporal growth of the field amplitude for the operating TE_{02} mode and the other nearby competing modes present inside the RF interaction circuit can be observed. Hence, this simulation tool also provides a reasonable picture similar to the multimode analysis. It has been demonstrated that the interaction circuit takes some time to settle in the TE_{02} mode due to the competition from the nearby modes. From the PIC simulation, the RF output power has been obtained as ~315kW at 32.3GHz. The gain of the device has been calculated as ~26dB with an efficiency of ~22.5 %. Finally, simulation results are benchmarked with the previously reported experimental results and the analytical results obtained in Chapter 2 which have been found to be in close agreement within 5%.

Though gyroklystron possess many potential qualities at higher frequencies, but still at present the design of a gyroklystron amplifier remains a critical issue for its developers. The design of the gyroklystron amplifier is more rigorous at higher frequencies, and at higher cyclotron harmonic ($s > 1$) operation. Thus, the purpose of the Chapter 4 is to identify important design parameters and to develop a suitable device design methodology. The choice of higher frequency and higher harmonic gyroklystron design is motivated by the requirement of higher power for specific applications at reduced magnetic field. Certain steps have been followed for designing of gyroklystron amplifier. Firstly, the operating frequency and RF output power are fixed depending on the application. The design process initiates with the choice of the desired RF operating mode. The mode selection criterion includes the calculation of coupling coefficient, and main design constraints namely wall losses, voltage depression, and limiting current. The coupling coefficient has been obtained in order to get the optimum beam radius for a particular mode of operation so that the desired mode is excited and other competing modes are suppressed. Essential design constraints for the choice of operating mode are explained. Proper mode selection ensures that the design constraints are within the limits. Further, for the investigation of stable operation of a gyroklystron amplifier, the start oscillation current criterion has been studied. It ensures that the device is operating in the stable condition in the desired mode with maximum efficiency. It also helps to decide the operating beam current and DC magnetic field. The number of cavities and their dimensions are chosen based on the nonlinear analysis. Then, the various device input parameters are chosen with the help of its parametric analysis to achieve the desired efficiency and output power. One of the major issues that affect the device efficiency at higher frequencies and higher harmonics is the dense mode spectrum. Therefore, the self-consistent multimode nonlinear formulation and simulation of the device has been carried out further in this chapter to investigate the performance of the device due to mode competition.

As per the literature review, the second harmonic gyroklystron amplifier that can generate peak power in kW at D-band (110-170GHz). In the present work, a systematic design of a 140GHz, 1kW second harmonic gyroklystron amplifier with gain ~30dB has been carried out which can be used in spectrometers for Electron Paramagnetic Resonance (EPR) experiments. Further, the multimode behavior of the device is studied with the help of PIC simulation and is then validated with the time-dependent multimode analysis as described in Chapter 2. TE_{02} mode has been chosen as the operating mode in each cavity because it ensures the benefits of high coupling coefficient, lower wall loss, feasible cathode design, and an easier design of mode convertor. For the device design parameters, and chosen TE_{02} mode, the design constraints, i. e., wall losses, voltage depression and limiting current have been obtained which are well within the limit. The start oscillation current and coupling coefficient curves have been obtained which provide us a set of optimized operating parameters such as beam current, magnetic field, beam radius, etc., which will excite the desired mode in the resonator cavity. It also gives information about the nearby competing modes. The design values obtained by adapting the present methodology have been then used as input parameters for the beam-wave interaction study through time-dependent multimode analysis. The parameters have been optimized further through analysis for the optimum performance in terms of efficiency and RF output power. A stable RF output power of 1.03kW is achieved through the developed analysis in the designed TE_{02} mode. The device efficiency and gain are obtained as ~2.58% and ~30.13dB, respectively.

In order to validate the developed analyses further, PIC simulation has been performed. The modeling of the RF interaction circuit and the beam absent and beam present cases have been investigated. Using the beam absent simulation, a well defined TE_{02} mode has been observed at 140GHz resonant frequency. Field distributions along the cavity dimensions confirm the desired TE_{02} mode of operation. Particles energy and phase plots have been obtained which is used to study the energy transfer phenomenon and bunching mechanism. Electric field patterns have been monitored which confirm the device operation in the desired mode. In the present PIC code, the temporal power growth in all the modes present inside the RF cavity has been observed. A stable 1kW output RF power has been observed in TE_{02} mode. Thus, the analytical results and PIC simulation results have been found to be in in close agreement within 5%.

In Chapter 5, the gyroklystron amplifier has been explored further for the performance improvement of the device. The application of gyroklystron amplifier as high-resolution advanced imaging radar should fulfill a criteria of stable, high power and high bandwidth. But the existing simple cavity gyroklystron amplifier produces the higher power in a relatively narrow bandwidth and hence the performance improvement in terms of bandwidth has to be fulfilled. To overcome the narrow bandwidth problem associated with the existing gyroklystron amplifiers, an attempt has been made towards the broad banding of the gyroklystron amplifier by making use of a new gyro-device interaction circuit called the clustered-cavity. In this structure, the individual intermediate cavity of a multi-cavity gyroklystron is replaced by pairs or triplets of artificially loaded cavities which form a cluster. The Q-factor of each cavity in a cluster is reduced to one-half or one-third of the single cavity resulting in either doubled or tripled bandwidth of the device. The generalized formalism for the clustered-cavity gyroklystron amplifier has been studied Using this formalism a two cluster gyroklystron with two cavities in each cluster has been analyzed.

A 35.12GHz, second harmonic, two-cavity gyroklystron amplifier is considered for its performance improvement. A peak output power of ~269kW, efficiency ~18.4% and gain ~17.14dB has been obtained in the clustered-cavity case. The bandwidth of the device has been achieved ~0.155% which is approximately doubles that of conventional cavity case i. e. 0.08%. The results showed that the bandwidth of gyroklystron has been enhanced with the small increment in the gain, and efficiency of the device. The effect of stagger tuning on the performance of clustered-cavity gyroklystron has also been studied. The analytical results obtained here have been verified with the PIC simulation values, and a close agreement (<5%) has been obtained.

6.2. Limitations of the Present Work and Scope for Further Studies

In the present thesis, the multimode beam-wave interaction behavior in a gyroklystron amplifier has been presented using time-dependent multimode analysis and multimode PIC simulation. The temporal growths of the RF output power in the possible competing modes have been evaluated to provide more realistic scenario. The extensive demonstration of the beam-wave interaction process has been presented for cylindrical multi-cavity gyroklystron. It is hoped that the present study would be useful in designing the gyroklystron amplifier of any frequency and power. Also, the performance improvement of the gyroklystron amplifier has been carried out in terms of bandwidth by employing the clustered-cavity in place of cylindrical cavity. 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:

i) Implementation of scattering matrix technique for the complete design of gyroklystron amplifier.

Scattering matrix method is an efficient technique and is widely used for the modeling and design of gyroklystron amplifier, where the exact, real-time cold field-profile is desired inside the cavities. These field profiles are computed non self-consistently and can be employed mainly for the experimental designing of the device. In addition, scattering matrix technique is also much helpful in the analysis of complex cavities i. e. stepped cavities, irregular cavities etc. There are several numerical codes, such as CASCADE to compute these field profiles on the basis of scattering matrix method.

In the present work, the scattering matrix technique can be implemented for the complete design of gyroklystron amplifier in which the cold-cavity RF electric field profile in each cavity can be evaluated using the scattering matrix formulation. The formulation follows the assumption that cavity field profile remains unaltered in the presence of electron beam. Hence, the approach is not fully self-consistent.

ii) Space-charge effects can be considered in the analysis which provides a more realistic-scenario.

In practical situations, the electron beam itself constitutes a significant amount of negative charge inside the gyroklystron body. This is called as space-charge which imposes a repelling potential on electrons that emerge at the cathode surface. The consequence is a decrease of the effective beam voltage with respect to cathode voltage due to which the applied accelerating voltage is not fully available to the beam and can also change the resonance condition in the interaction cavity. This effect is called as the space-charge effect.

In the developed multimode analysis, an important aspect of the space charge effect has not been considered which can be included in the further studies for achieving more accurate power.

iii) Inclusion of input coupler in the simulation model.

The input coupler, which provides a transition from the rectangular waveguide mode to the circular TE_{0n} mode, is a very important part for the gyroklystron amplifier. In experimental gyroklystron, the input driven signal is injected into the input cavity through the input coupler, which excites the RF field to modulate the electron beam.

In the present PIC 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. Hence, 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.

iv) The study of effect of tapered magnetic field instead of uniform magnetic field on the device performance.

The efficiency of the gyroklystron amplifier depends strongly on the magnetic field -profile which is in general, considered as Gaussian. The magnetic field is tapered down along the output cavity which in turn enhances the efficiency of the device by channeling more electrons into the decelerating phase.

In the present work, the performance of the gyroklystron amplifier has been improved in terms of bandwidth by using the clustered-cavity concept. However, the device performance can be further enhanced in terms of efficiency by employing the tapered magnetic field instead of uniform magnetic field along the interaction structure.

v) 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.

Author feels that the study carried out in the present thesis would certainly helpful and motivate the readers and other researchers working in the field of gyro-amplifiers.