Abstract

Time-Dependent Multimode Analysis and Simulation Studies of Gyroklystron Amplifier

THESIS

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By

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ABSTRACT

The horizon of microwave tubes still find its dominance in delivering high power at the millimeter and sub-millimeter wave frequencies, and this is an area where their solid-state counterparts are not able to compete. Miniaturization of the conventional microwave tubes due to wavelength reduction at the millimeter waves result in decrement of the power handling capability of such devices. On the other hand, 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, considerable research interest has been aroused in the development of fast-wave devices to bridge the gap between the domain of conventional microwave tubes at low frequencies and the extent of lasers at high frequencies.

In the category of gyro-devices, the 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 are far from being mature, still requiring much improvement with respect to signal coherence and spectral quality. For such applications, gyro-amplifiers such as gyroklystron or gyro-TWT would be a more appropriate choice than an oscillator. In recent years, considerable research and development interest has been aroused in the area of gyroklystron amplifier. The capability of gyroklystron amplifiers to provide high gain and moderate bandwidth are making them attractive as high-power millimeter-wave amplifier. These amplifiers have potential for applications such as millimeter-wave radars, particle accelerators, RF plasma heating systems, etc. The gyroklystron consists of a series of resonant cavities separated by a region called as drift tube like a conventional klystron except that instead of reentrant cavities, overmoded cylindrical cavities are used. Electron beam and RF wave interaction mechanism in the gyroklystron is based on cyclotron resonance maser (CRM) instability similar to that in gyrotrons, instead of Weibel instability as in conventional klystrons.

The high frequency gyro-device requires higher magnetic field which is in order to synchronize the frequency of oscillation with the cyclotron frequency. The magnetic field requirement can be reduced through higher cyclotron harmonic operation. Due to higher

order mode operation of the RF interaction circuit, fast-wave devices offer the larger size of the interaction structure in the millimeter-wave frequency range as compared to slow-wave devices and hence handle higher power. Additionally, the electron beam location will also be far from the wall of RF interaction structure. At higher frequencies, the gyroklystron operation at higher order modes results in the dense RF spectrum which can cause probability of switching 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 etc. Additionally, at higher frequencies, the device operation at higher harmonic modes also results in the mode competition from the nearby higher harmonic competing modes as well as the fundamental harmonic modes. These important aspects of mode competition have motivated the author of the present thesis to take up the multimode analysis and simulation studies of higher harmonic gyroklystron amplifier as her research problem. The research work has been organized into six chapters.

In Chapter 1, the fundamentals of microwave tubes and the status of development of both conventional and fast-wave tubes for the generation and amplification of millimeter and submillimeter waves have been presented. The operating principle of gyro-devices has been studied. An overview to gyroklystron amplifier including its key elements and working mechanism has been discussed. The various applications of the gyroklystron has been reviewed and found it as an attractive device for millimeter and submillimeter waves' amplification. The state of the art of the gyroklystron is presented with their scope and limitations. Different configurations of the device for its performance improvement are also highlighted. The motivation of the present work has been illustrated in which the problems due to higher frequency and higher harmonic operation of the gyroklystron has been described along with the possible solution to surmount these problems has been proposed.

In Chapter 2, a review of the well-established generalized linear and nonlinear analyses have been presented to explore the beam-wave interaction behavior of a gyroklystron amplifier. In the present work, a self-consistent, time-dependent, multimode nonlinear analysis has been developed to investigate the beam-wave interaction behavior in an overmoded cavity operation of the gyroklystron amplifier. The developed analysis incorporates the effect of all nearby competing modes on the device performance, hence provides a realistic scenario to determine the accurate output power and efficiency in each mode. This analysis is generalized and incorporates the device operation at arbitrary cyclotron harmonics employing any arbitrary shape of interaction structures. 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 gyroklystron analysis development has been carried out by combining the time-dependent multimode nonlinear formulation as followed for gyrotron oscillators with those of the time-independent nonlinear approach followed for the gyroklystron amplifier. 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. The field-profile in each of the cavities is calculated self-consistently using the modified Vlasov equation. Coupled time-dependent equations are solved to calculate the mode amplitude and phase in each cavity at each time step. A numerical code has been written based on the developed analysis and further benchmarked for the performance evaluation of the reported experimental three-cavity Ka-band second harmonic gyroklystron amplifier. The linear analysis has been used for calculating the initial device design parameters, like coupling coefficient, start oscillation condition which provides the device design in terms of the beam radius, beam current and magnetic field corresponding to the operating mode along with the other possible competing modes. From the developed analysis, the temporal evolution of the RF output power in all the modes is plotted and it is observed that the saturated RF output power of 319kW is obtained in the operating TE_{02} mode. The mode competition is mainly due to fundamental harmonic TE_{01} mode. The analytical results obtained are then compared with the reported experimental values which are found to be in close agreement. The gain and bandwidth of the device has been obtained as ~26.3dB and 8MHz respectively. The analysis developed here will be further used in the subsequent chapters for the design and performance improvement studies of the gyroklystron amplifier.

To further validate the developed multimode analysis, Chapter 3 deals with the PIC simulation of the same experimental three-cavity Ka-band second harmonic gyroklystron amplifier as considered in Chapter 2. The 3D PIC simulation procedure of the gyroklystron amplifier, reconfiguring the commercially available "CST Studio Suite" has been described in detail. In the PIC simulation, cold (beam absent) and hot (beam present) electromagnetic behavior of an all metal cylindrical interaction structure (RF section) have been demonstrated. Cold simulation has been performed using eigenmode solver of ‘CST

Microwave Studio' to examine the cavity operation in the specific mode and frequency. Using cold simulation, a well-defined TE_{02} mode has been observed in the cavity at 32.3GHz resonant frequency. Further, beam-present (hot) simulation has been performed using PIC solver of "CST Particle Studio" 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 behavior of electrons along the interaction length has been also observed which indicates the energy transfer phenomenon and bunching mechanism. The signal growth of the desired mode along with nearby competing modes have been observed to realize their relative strength, and it has been shown that power grows only in TE_{02} mode with small power in the other modes. A stable output power of 315kW has been obtained in the desired TE_{02} mode. Finally, simulation results are benchmarked with the previously reported experimental results and the analytical results obtained in Chapter 2 which are found to be in close agreement.

In Chapter 4, a detailed design procedure of the second harmonic, cylindrical four-cavity gyroklystron amplifier operating at 140GHz frequency has been presented. A simple and comprehensive design methodology for designing the gyroklystron amplifier is developed following the analytical approaches. Firstly, essential design constraints for the choice of operating mode are explained. After this, different parameters of the RF section and electron beam such as cavity geometry, drift tube dimensions, beam voltage, beam current, magnetic field, etc. are calculated analytically based on the operating mode, frequency and power. The mode competition is severe problem in the gyroklystron operation and is thoroughly analyzed using start oscillation current criteria. The start oscillation current and coupling coefficient curves also 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. TE_{02} mode has been chosen as the operating mode in each cavity because it ensures the benefit 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 have been obtained which are well within the limit.

Since, the higher frequency and higher harmonic device leads to the problem of mode competition, the developed design methodology has been numerically appreciated by carrying out the time-dependent multimode analysis of the typically selected gyroklystron amplifier and has been validated through multimode PIC simulation using a commercial code ‘CST Particle Studio’. For the designed parameters, a well above of 1kW of RF output power has been obtained in the desired TE_{02} mode at 140GHz operating frequency from both the approaches. The analytical results and PIC simulation results are found in close agreement ~ 5%. Sensitivity analysis has also been carried out to make the present study of more practical useful.

In Chapter 5, the gyroklystron amplifier has been explored further for the performance improvement of the device. To overcome the narrow bandwidth problem associated with the existing gyroklystron amplifiers, an attempt has been made towards the broadening of the gyroklystron amplifier by making use of a modified interaction circuit called the clustered-cavity. The generalized formalism for the clustered-cavity gyroklystron amplifier has been studied and is then numerically appreciated to the gyroklystron amplifier for its bandwidth improvement. A 35.12GHz, second harmonic, two-cavity gyroklystron amplifier is considered for this purpose. A peak output power of ~ 269kW 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 show that the bandwidth of gyroklystron is 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 is also studied briefly. The analytical results obtained here have been verified with the help of the PIC simulation results, and a close agreement between the results (< 5%) obtained from both the approaches have been found.

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, such as, implementation of scattering matrix technique for the complete design of gyroklystron amplifier, including the space-charge and velocity-spread effects in the analysis to make the present study more practically feasible, inclusion of input coupler in the simulation model, and study of effect of tapered magnetic field on the gyroklystron performance.

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