CHAPTER 7

SUMMARY, CONCLUSION AND FUTURE SCOPE

7.1. Summary and Conclusion

In the last decade, high-power microwave (HPM) became very popular in the microwave community due to its emerging civilian and military applications and the new technological improvements in the microwave tube technology. The generation of RF in the microwave / millimeter-wave ranges and multi-frequency generation through a single HPM device drag the attention of researchers and academia around the world. Further, an extensive renewed interest has been aroused in the research and development of the HPM sources in view of their potential capabilities of producing high RF power in Giga-Watts (GW) level at microwave frequencies for non-lethal applications. In recent years, many HPM sources including relativistic magnetron, reltron, vircator, MILO, relativistic backward wave oscillator (RBWO), gyrotron, etc, have been competing to bridge the technological gap that could not be done by the conventional microwave tubes. MILO is a crossed-field high power microwave device that is similar in operation and theory of magnetron thus also known as a linear magnetron. It operates combining the technology of magnetically insulated electron flow and slow-wave tubes. Microwave oscillators that require an external magnetic field employ two DC power sources for exhibiting magnetic insulation and also give rise to electrical breakdown as higher voltages are approached. These oscillators are having a very high inherent impedance that severely limits the power level at which the oscillator will operate. Thus, for efficient operation at higher power levels, it would be desirable to have an oscillator that will operate at the lower impedance and also eliminate the problem of voltage matching. To overcome the above problems, MILO has been used, in which the required magnetic field is supplied by the electron-beam current itself, rather than by a separate magnet and thus makes the device more compact and lightweight. The dual-frequency generation through a single HPM device by using different design methodology and concept is one of the interesting research areas these days. The design improvements of the MILO to avoid some critical issues, like pulse shortening problem, asymmetric mode generation and mode competition, shot-to-shot reproducibility, the requirement of high pulse rate frequency and long life of cathode are still consider as a challenge for such device developments. These aspects motivated the author to associate, contribute, and enhance the knowledge for such important teething problems in the MILO device. This research work is embodied in the form of the present thesis which is organized in the seven chapters as follows.

First chapter "Introduction and Literature Review" an overall view of the research topic has been provided. In Chapter 1, an overview of HPM systems with a brief discussion of high power devices like, relativistic backward wave oscillator (RBWO), relativistic klystron, relativistic magnetron, relativistic gyrotron devices, Reltron, and virtual cathode oscillator (vircator) has been presented. A brief description of different sub-assemblies of the MILO device and the principle of operation has been presented in this chapter. A literature review for major breakthroughs achieved in the design and development of the MILO device has also been presented. Chronological development of the MILO device improvement has been presented in tabular form. Finally, the motivation and objective of the research work embodied in this thesis have been also described in this chapter.

In Chapter 2, the equivalent circuit approach has been used to investigate the beam wave interaction analysis for the axially periodic disc loaded coaxial structure used for the MILO device. For this, firstly, various analytical approaches that have been used in analyzing such structures so far have been reviewed. Then, the equivalent circuit analysis for MILO in the beam absent case has been discussed and various characteristics of periodic disc loaded coaxial structure, such as dispersion relation, phase velocity, and characteristic impedance have been derived using equivalent circuit line parameters. To derive these characteristics, the actual structure has been replaced by an equivalent transmission line in terms of its equivalent circuit parameters with the assumption of the loss-free conditions. The two-line parameters (i.e. the series inductance and shunt capacitance per unit length) of the equivalent line have been used for the analysis. These two parameters are derived independently and one has to deal with only half of the total number of the RF structure EM field expressions and boundary conditions at a time, which makes the analysis simpler and yields a relatively much simple form of the expressions. The dispersion characteristics obtained by the present equivalent circuit approach exactly pass to those expressions which were obtained through the field analysis. The characteristic impedance of the line in the beam absent case which is an important parameter while considering circuit matching condition has also be obtained through the present analysis. Furthermore, the equivalent circuit analysis for MILO in the beam present case has been discussed. The equivalent circuit approach has been developed in this chapter considering the presence of an electron beam in order to study the RF analysis of MILO. This approach has been used to investigate the device oscillation condition, dispersion relation, and temporal RF growth rate.

In Chapter 3, MILO device performance improvement and optimization studies have been explored by adapting the impedance matching approach of its different sub-assemblies. For this purpose, circuit impedances are evaluated in terms of their equivalent circuit parameters, e.g., equivalent shunt capacitance, and equivalent series inductance per unit circuit length. This approach is much easier and simple to handle compared to the field analytical approach. The standard reported characteristic impedance results of the MILO structure have been used for impedance matching at the input and output section of the MILO device and analyzed using an equivalent circuit approach. Input impedance matching depends upon cathode tapering length at the input side. The optimum tapering length was found to be an odd multiple of $\lambda/4$. Similarly, the output section impedance matching depends upon the extractor section by varying extractor gap. Further, the optimization of the stub position has been described. In order to validate the performance improvement of the MILO device, the first 3D PIC simulation has been carried out and compared with those for the reported experimental device. Further, the simulation is carried out for the device with an optimized design parameter obtained through analytical study.

In Chapter 4, an azimuthally partitioned axially periodic metal disc loaded coaxial structure has been considered to use as the MILO RF interaction structure for the bi-frequency HPM generation. This structure has been analyzed using the equivalent circuit approach which is found much simpler, less cumbersome, and yields equally accurate results that of the more involved and rigorous field analytical approach. Considering the azimuthally portioned metal RF interaction structure as loss-free, expressions for the equivalent series inductance per unit length and equivalent capacitance per unit length of its equivalent transmission line have been obtained. These series inductance and shunt capacitance expressions are then used for deriving the structure dispersion relation, phase velocity, and as well as characteristic impedance. Since the structure is azimuthally asymmetric, the symmetric TE and TM modes do not exist independently and the two modes excited in the azimuthally partitioned structure have been studied. To confirm the structure capable of supporting bi-frequency; the dispersion behavior of the azimuthally uniform structure of different radii has been studied through the developed analysis and verified through simulations. To find the structure operation region and the frequency bandwidth possible between the modes, the group and phase velocities have been analytically computed. EM fields excited in the azimuthally partitioned structure have been simulated which confirms the excitation of two modes as predicted by the present analysis. The parametric studies have also been made to analyze the crucial structural parameters which affect the operating frequency associated with the excited modes in the azimuthally partitioned structure. The dispersion values obtained by the developed analysis and simulation results were found within ±5%.

In Chapter 5, the electron beam present analysis has been performed for an azimuthally partitioned axially periodic metal disc loaded coaxial structure which can be used as the MILO RF interaction structure for the bi-frequency HPM generation. The expressions for the equivalent capacitance per unit length and equivalent inductance per unit length in the presence of an electron beam in the RF structure have been obtained considering the loss-free conditions. These series inductance and shunt capacitance expressions are used for deriving the structure dispersion relation, and the temporal growth rate along with the estimation of the RF output power and energy from the MILO device. The temporal growth rate associated with the two different modes has been computed analytically. Further, to confirm the structure capable of generating bi-frequency; the PIC simulation study has also been performed in the presence of an electron beam. The obtained results through analysis and PIC simulation have been compared with results reported in the literature. Furthermore, the effect of beam parameter variation on the temporal growth rate for two different modes associated with the different azimuthal sections has been studied numerically.

In Chapter 6, different bi-frequency MILO (i.e. L-band bi-frequency MILO and S-band bi-frequency MILO) along with dual-band MILO (i.e. MILO which generates RF power in S-band and Ku-band simultaneously through different interaction structures) has been designed and investigated using analysis and further the designed device is validated through PIC simulation using a commercial code. The design expressions have been derived for calculating the different design parameters for different bi-frequency MILO. The beam wave interaction process has been described and the temporal growth rate calculated numerically for dual-band MILO. The numerical calculation has been used to find the dispersion curve which further got validated through the Eigenmode EM simulation for the different interaction structures for *L*-band and *S*-band bi-frequency MILO and for *S*-band and *Ku*-band related to dual-band MILOs, respectively. Finally, the PIC simulations have been performed for different bi-frequency MILOs and found its results in close agreement with the expected designed values.

7.2. Limitations of the Present Work and Scope for Future studies

In the present thesis, MILO performance improvement studies have been performed using the equivalent circuit approach. Along with this, the basic study related to bi-frequency generation in the MILO devices has been carried out. The analytical investigations of the electron beam and RF wave interaction in the MILO devices and its validation through PIC simulations using commercial code have also been presented in this thesis. The current work has not been further carried out for use of a dual-frequency mode converter and antenna system. The experimental study related to bi-frequency generation has also been kept beyond the scope here which could have validated the theory and simulation work in more effective ways. The future scope for works related to the MILO device (which was not accomplished due to the limitation of the time and unavailability of experimental facility) are as follows:

- As MILO operates at very high voltage DC pulses, the pulse shortening problem and vacuum breakdown are still a topic to research.

- The thermal aspect of MILO, especially at its collector end also requires a detailed study.

- For bi-frequency generation through the MILO devices, the optimization and performance improvement have to be carried out more intensively since the achieved efficiency reported in the present thesis as well as literature is quire low.

- The effect of cathode misalignment on the MILO device performance can be taken as a point for detailed study.

- Dielectric loading inside the slow-wave structure cavity of the MILO device is a new design improvement to enhance the RF generation and performance improvement. There are very few literatures available on this topic and a detailed study related to this is required.