

CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

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CHAPTER 1: INTRODUCTION AND LITERATURE REVIEW

1.1 Introduction

High-power microwave (HPM) sources are prominent in the microwave community due to technological advances and device developments in various civilian and military applications. HPM sources are operated in the millimeter-wave frequency range (30-300 GHz), which can produce at least 100 MW of RF output power. The idea of HPM sources originated from the high energy lethal radiation generated after a nuclear explosion, which causes an electronic blackout [1], [2]. As solid-state devices (SSDs) are limited to high RF output power at millimeter-wave frequencies, HPM technologies are being developed with high RF output power as a trend of using traditional microwave equipment by improving high power efficiency at higher microwave frequencies in the vacuum electronic devices (VEDs) community. VEDs can generate higher microwave power with a higher threshold breakdown electric field, as compared to SSDs and despite fabrication difficulties exist at higher frequencies; VEDs can generate high power per unit volume, as compared to SSDs. In VEDs, the energy of electrons is converted into RF wave. In the early days of 1960, most of the development studies of conventional VEDs were based on Cherenkov and transition-based devices such as klystron, travelling wave tubes (TWTs), and backward wave oscillators (BWOs). With an increase in operating frequency, the practical fabrication and operational realization of conventional VEDs is become difficult to operate with high power in the order of megawatt (MW). The performance of VEDs is measured by RF power and operating frequency, *i.e.* Pf^2 , which is called a figure of merit. HPM devices can generate up to Gigawatt (GW) of power level up to Ku-band of operation [2], [3], however, they are suffered from breakdown problems, which can cause pulse shortening in RF output. In General, the power handling capability of VEDs is limited by their

frequency of operation, as their dimensions are proportional to wavelength (λ) and power is proportional to square of the wavelength (λ^2). However, increasing the cross-sectional dimensions of the device can increase its power handling capacity. This technique is called overmoded technique. This technique allows the device capability to operate in a low external guiding magnetic field and can also overcome the pulse shortening to some extent.

The development of modern tube technology has a strong synergetic relationship with its applications. These new technologies are constantly being embedded for HPM device development, for both military as well as civilian applications. The research efforts in the field of HPM sources have generated a technology motivated attention towards the HPM directed energy weaponry (DEW). DEW attacks can disturb the system in two ways: (i) Hard kill- In this case, the electronic devices and components are physically damaged. It is caused by the induction of high current by an HPM pulse in an electronic circuit, which results into a flashover of electronic and semiconductor components. (ii) Soft kill- In this case, the electronic devices and components are deactivated. Soft kill distresses the digital circuit when the HPM pulses enter the system at a rate equal to the operating voltage of the electronic or semiconductor components [4] ,[5]. Apart from these applications, HPM sources are extensively used for particle accelerator, HPM Radar, Power Beaming, Plasma Heating, etc., [2], [6] and these applications require a high microwave power at high frequency, which is a major challenge to the vacuum electronics technology. Different HPM sources available with specific advantages and disadvantages, which will be explained in detail in the further section of this chapter. The various HPM sources are Relativistic Klystron Amplifier (RKA), Virtual Cathode Oscillator (Vircator), Relativistic Magnetron (RM), Magnetically Insulated Line Oscillator (MILO), Reltron, and Relativistic Backward

Wave Oscillator (RBWO), and Free Electron Laser (FEL). The present study focuses on a device named RBWO, which is one of the most promising HPM sources as it has got numerous advantages over other HPM sources. This has the sole disadvantage of the need for an external guiding magnetic field, which makes this device bulky. However, various researchers have done to reduce the external magnetic field and operate the device in a permanent magnets. This helps to reduce the size of the device and become compact [6-8]. RBWO can generate ~6 GW of RF power in S-band and ~3 GW in X-band with a maximum efficiency of 40 %. It has an advantage of high pulse repetition rate (PRR) up to 500 Hz and frequency tuning around 300 MHz [2, 3]. RBWO may be one of the most promising sources for aviation applications in Defense and Military. The main objective of this thesis is to contribute research work for performance improvement and output mode pattern of single-frequency RBWO and Dual-band/dual-frequency RBWO.

1.2 Overview of High-Power Microwave Sources

Over the past few decades, high-power microwave (HPM) has become popular in the microwave community due to its technological advances in various civil and military

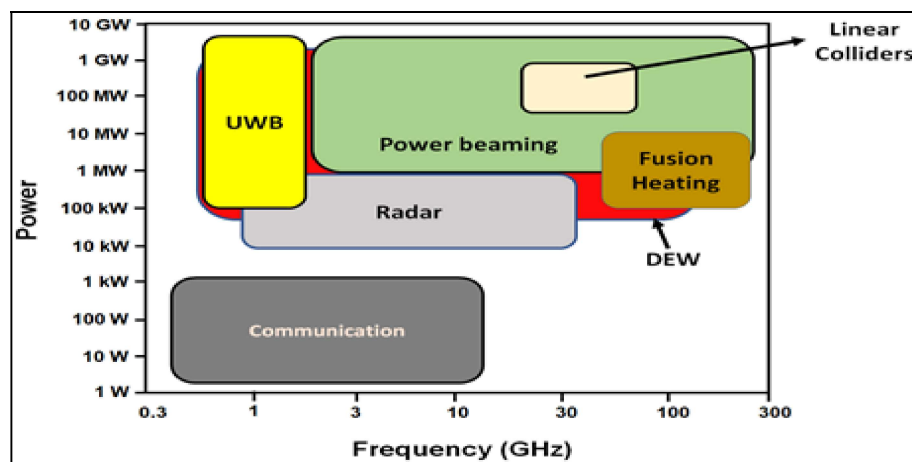


Figure 1.1: Application domain of HPM at a different frequency and Power level [3].

applications and device development. The HPM domain has dragged the attention of researchers and academia around the world by generating the RF output power at single-frequency and dual-frequency by a single HPM device within the millimeter-wave ranges. HPM, by convention, includes both the microwave and millimeter-wave frequency ranges (1-100 GHz) generating peak power more than 100 MW and refer to (i) the long pulse duration, high-pulse repetition frequency (PRF), or continuous wave (CW) or (ii) the high-peak-power, short-pulse duration, low-PRF, or single-shot sources and amplifiers. The domain of the application of HPM devices at a different frequency and power level is given in Figure 1.1.

HPM system can also be used as a non-lethal weapon for humans. These applications require a Gaussian RF pulse to target the enemy's assaults, as it has a maximum on its center and the radiation pattern is formed by the combination of TE_{11} mode (85%) and TM_{11} (15%) mode for Gaussian pulse [9]. Most HPM sources (O-type) generate azimuthally symmetric transverse magnetic (TM_{0n}) mode. Therefore, switching the output TM_{0n} mode into Transverse Electric (TE_{11}) mode requires a mode converter at the end of the device. The use of an external mode converter increases the overall length and also reduces the overall efficiency of the device, hence extensive

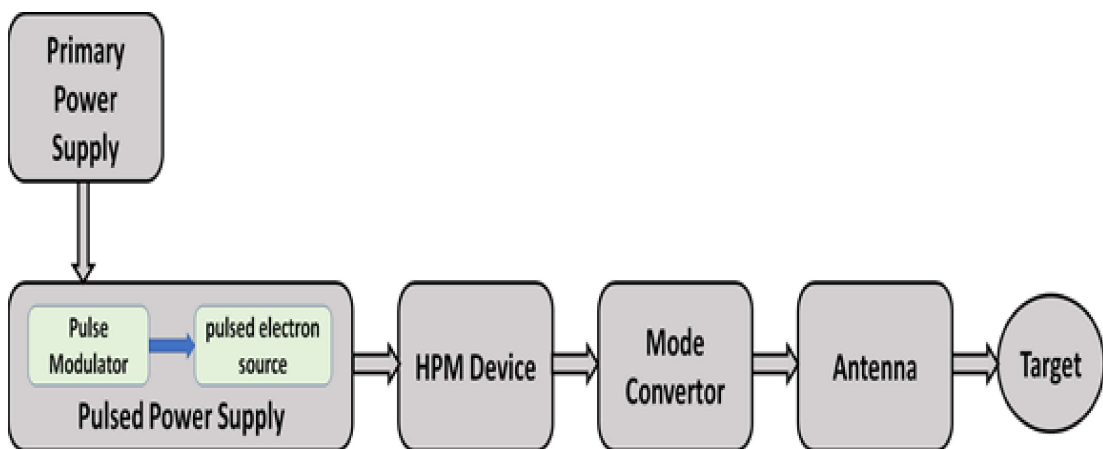


Figure 1.2: Block diagram of an HPM system [3].

research is being done now-a-days on devices that can directly generate TE₁₁ mode.

The basic block diagram of HPM system consists of Prime Power Supply, Pulsed Power Supply, HPM source, HPM antenna, and Antenna as shown in Figure 1.2.

1.2.1 Prime Power Supply

The prime power supply is used to generate a low power long pulse (or continuous mode) electrical input. To link the prime power to the pulse power supply, the important parameters are repetition rate, average power, which together define the output voltage and the energy per pulse. There are several technological options for prime power. One option for many pulse power options is to use continuous prime power output, which eventually drives the HPM source. A common choice of primary power supply is to use a generator powered by an internal combustion engine, such as a diesel generator or turbo generator, but it is also possible to run a long-term pulse power supply with batteries. In either case, a common feature of the subsystem options is that an alternating current (AC) internal combustion generator or direct current (DC) battery provides long-pulse or continuous power, which is converted to a DC output, which acts as an input for Pulse power supply.

1.2.2 Pulse Power Supply

In general, HPM sources require drivers capable of supplying short, intense electrical pulses of 1MV or more with durations of 1 μ s. This can be achieved by pulse compression or by using capacitor banks that can convert a low-voltage, slow-rising signal into a high-voltage, fast-rising signal. However, it must be ensured that the driver provides a well-matched signal in terms of voltage and impedance. Conventional microwave sources typically operate at low voltage and high impedance, whereas HPM sources require significantly higher voltage levels and very different impedance levels.

This is illustrated in Figure 1.3. A mismatch between the impedance of the driver signal and the HPM source results in poor energy transfer to the HPM source. This is especially true if the impedance of the source is lower than the impedance of the driver. The choice of power supply and driver section is largely determined by the type of source to be used.

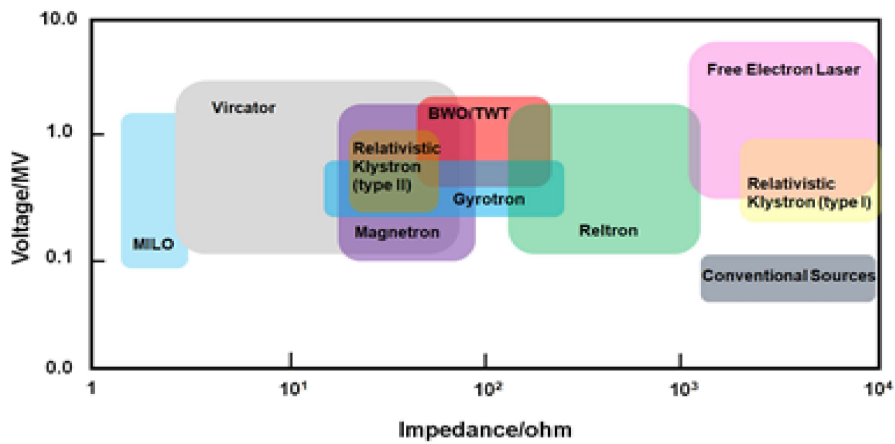


Figure 1.3: Comparison of HPM sources and conventional microwave sources with respect to optimal impedance and voltage [3].

A common configuration that consists of a Marx bank in which a row of capacitors is charged in parallel and then later quickly switched into a series circuit, allowing the voltage to be multiplied by the number of capacitive stages in the Marx. This can serve as an initial current generator for a flux compression generator (FCG). In an FCG, a magnetic coil is compressed either by explosive or magnetic forces so that the current level rapidly increases. Another common option is to replace the FCG by a Pulse Forming Line (PFL). A third option is the Swedish viricator [10], which directly generates the electrical pulse for the HPM source from a large Marx generator charged through a charging aggregate.

1.2.3 HPM Sources

The basic process behind all vacuum electron beam sources is the conversion of kinetic energy in the electron beam into electromagnetic (EM) radiation. This exchange is made possible by resonant interactions between the cavities and/or waveguides and the natural oscillating modes in the electron plasma. Sources are divided into slow-wave and fast-wave type devices, where the eigenmodes of the waveguide have phase velocities that are smaller or larger than the speed of light, respectively. In the case of slow-wave devices, Cerenkov radiation is produced when electrons move faster than the phase speed of EM waves. In the latter case, radiation is produced by the transfer of electrons from one medium to the other, where the two mediums have different refractive index, or by perturbations in the medium, such as a grid or perforated plate. As an alternative strategy, radiation sources are classified into three: linear beam (O-type), cross field (M-type) and space charge type as shown in Table 1.1. In the first case, the electrons move

Table 1.1: Classifications of HPM Sources [3]

Classification	Slow-Wave	Fast-Wave
O-Type	Relativistic Backward Wave Oscillator (RBWO) Multi-Save Cherenkov Generator (MWCG) Relativistic Diffraction Generator (RDG) Surface-Wave Oscillator (SWO) Relativistic Klystron Relativistic Transit Time Oscillator (TTO)	Free Electron Laser (FEL) Gyrotron Gyro-BWO Gyro-TWT Gyro Klystron Gyro Twystron Cyclotron Auto-Resonance Maser (CARM)
M-Type	Relativistic Magnetron Magnetically Insulated transmission Line Oscillator (MILO)	
Space-Charge Type	Virtual Cathode Oscillator (VIRICATOR)	

parallel to the strong magnetic field. In the second case, one exploits the fact that charged particles experience drift normal to E and B when these two fields are not parallel. The last case depends on the formation of so-called virtual cathodes when the current exceeds the space-charge limit. In this case no external magnetic field is required.

1.2.4 Mode Converter

Mode converter is used for tailoring the spatial distribution of EM energy to optimize the transmission of RF power and coupling to the antenna. High Power Microwave (HPM) sources such as the Relativistic Backward-Wave Oscillator (BWO), gyrotron, and Vircator (virtual cathode oscillator) generate RF power in cylindrically symmetric transverse electric TE_{0n} or transverse magnetic TM_{0n} modes. In particular, TM_{01} mode is widely used in all HPM sources due to high power capacity and easy realization. However, from the viewpoint of antennas for high power, TM_{01} mode gives rise to doughnut configuration for a radiated pattern of the main lobe between E- and H-planes. The side lobe generation, gain reduction, and inefficient power loading on the antenna aperture, makes these modes unsuitable for driving conventional antennas. This gave an idea of using mode converters at the output of these sources to convert these modes into a plane-parallel linearly polarized beam. Vlasov antenna is one of the most popular mode converters. Therefore, for more effective illumination of microwave energy, the antenna needs a TE_{11} mode circular waveguide, which provides an easily optimized radiation pattern where the major lobe contains maximum RF power and side lobes carry very less power. Therefore, mode converter is required between the HPM source and antenna.

1.2.5 Antenna

The microwave radiator, like the antenna acts as an interface between the HPM source and the rest of the space. The antenna that radiates the microwave EM energy output from the mode converter and spatially compresses the output as a high-intensity beam. An HPM source represents a challenge to conventional antenna technology due to its high-power levels and short pulse lengths. The most important characteristics of an antenna are how well it can restrict signals to propagate in a particular direction and how effective is the coupling between the antenna and the surrounding space. The shape of the antenna affects whether a phenomenon known as air or dielectric breakdown is a problem when operating at high power levels. This phenomenon occurs if the local E-field is strong enough. More specifically, the E-field is necessary to transfer enough energy to the electrons so that the molecules in air are ionized after collisions with high-energy electrons. At atmospheric pressure level, this occurs at a critical field strength of ~ 24 kV/cm. For pulses longer than 100 ns, ionospheric "plasma mirrors" form at high altitudes that reflect relatively low-frequency microwaves (1GHz). The most common type of antenna for HPM sources is the rectangular horn antenna. Recently, antenna arrays have been demonstrated as good alternatives.

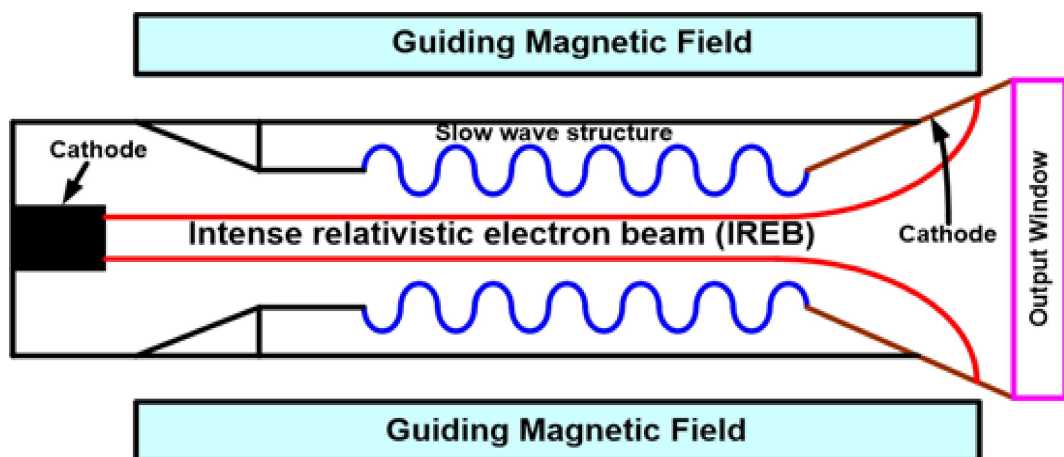


Figure 1.4: Generalized block diagram for linear beam microwave tubes.

The work is mainly concentrated over one of the relativistic versions of slow-wave devices generating HPM radiation. The generalized principle of operations for these HPM microwave tubes oscillators and amplifiers are the same and can be easily understood by Figure 1.4. Every microwave tube device consists of a DC power supply source to drive electron gun, an electron gun to provide electron beam, a focusing magnetic field to guide an electron beam, a microwave interaction circuit (Slow-Wave Structure (SWS)) to carry RF wave and a beam collector as a beam dump. The electron gun is driven by using an electron beam accelerator that produces a very high DC voltage pulse for the excitation of electron beam. The solenoid (permanent magnet provided low magnetic field) generates the focusing magnetic field to traverse the electron beam in one direction. The phase velocity of RF wave is reduced by the SWS to axial beam velocity and the phenomena like velocity modulation of electron beam, bunching and transfer of decelerated electrons energy to RF wave occurred in microwave interaction circuit. Finally, the beam collector is used to dump the electrons at the end of device structure.

1.3 Overview of different HPM Sources

High power microwave (HPM) sources are generally classified in two different ways: one is on the basis of its frequency band generation, which is ultra-wideband EM radiation and narrowband HPM sources and another on the basis of beam-wave interaction mechanism [11], [12].

Narrowband HPM sources generate coherent radiation with the expense of mono-energetic electron beam's kinetic energy in pulses ranges from 10's-100's ns in duration, whereas ultra-wideband sources use no electron beam but uses a high voltage spike with a very short rise time. An antenna radiates this high voltage spike through a

coupling in the wide frequency range. Ultra-wideband is considered analogous to flashbulbs.

There are basically three kinds of EM radiation, which are any HPM sources that support on the basis of interaction mechanism between the relativistic electron beam and RF structure:

- (i). **Cherenkov Radiation:** HPM sources in which electrons propagate in a medium having the refractive index, $n > 1$ and the electron velocity, v_e exceeds the phase velocity, $v_{ph} = c/n$ of EM waves supports Cherenkov radiation. If the refractive index is so large (*i.e.*, $n > c/v$) then only the interaction can produce this radiation. The different HPM sources which are based on Cherenkov radiation are travelling wave tube (TWT), relativistic backward wave oscillator (RBWO), relativistic magnetron, and MILO. Cherenkov HPM sources can produce several GW of RF output power in 1-10 GHz frequency range for a very short period (*i.e.*, 10-100 ns) and also operated at a repetition rate of several 100 Hz.
- (ii). **Transition Radiation:** HPM sources in which the transition radiation occurs are having some kind of conducting grids or plates for perturbation of electron beam. Whenever electrons pass through a border between two media having different refractive indices, transition radiation occurs. The different HPM sources which can produce the transition radiation are: relativistic klystron oscillator (RKO), relativistic klystron amplifier (RKA), and Reltron [2]. These devices can produce RF output power up to 10's of GW with a pulse duration of 100 ns at lower microwave frequencies.
- (iii). **Bremsstrahlung Radiation:** HPM sources in which electrons oscillation occurs in external magnetic and/or electric field, generates Bremsstrahlung radiation. If Doppler-shifted frequencies coincide with either electron frequency of oscillation,

Ω or with its harmonics through $\omega - k_z v_z = s\Omega$, then electrons radiate EM waves, where, $k_z v_z$ is the Doppler-shift and s is the resonant harmonic number. The radiated wave can be fast or slow as the expression satisfies for all wave phase velocity. The HPM sources, which are based on Bremsstrahlung radiation are: Cyclotron resonance masers (CRM) and Free Electron Laser (FEL). Bremsstrahlung radiation-based sources can produce EM radiation across a very broad frequency range that extends well above 100 GHz and are tunable in nature. Vircators or virtual cathode oscillators are considered as the special type of Bremsstrahlung devices in which electrons oscillations occur in an external EM field [11]. This device can be considered an extreme case of intense beam relativistic klystron amplifiers (RKAs) in which space-charge causes voltage depression that significantly enhances velocity modulation and bunching.

1.3.1 Relativistic Klystron Amplifier

The relativistic klystron is a popular HPM device that is widely used in charge particle physics and RF linear accelerator (LINAC) applications. The typical schematic view of the relativistic klystron is shown in Figure 1.5. A cathode of klystron generates beam, and it travels through two or more pillbox cavities separated by a drift tube, extraction waveguide, and RF output window. As the electron beam enters between grids of the buncher cavity, some of the electron's group are accelerated, while others get decelerated; thereby forming electron bunches with different velocities. At the catcher cavity of the device, the electron bunch releases their kinetic energy to the RF waves. Finally, the unused electrons are collected at the collector subassembly of the klystron. The operation of relativistic klystron is similar to that of the conventional klystron. In the relativistic klystron, both high energy of electrons and relativistic effect change the modulation process as compared to the conventional klystron. These high-energy

electrons in the form of thin annular electron beam that propagates near the outer wall of the structure and carry much higher current at a given DC voltage [2]. There are two variants of RKA depending upon the beam impedance: high-impedance klystron and low-impedance klystron. High-impedance klystron amplifiers having impedance in the order of 1 k Ω , which are operated in a similar to conventional klystrons at higher voltages.

It gets further divided into two sub-classes as mildly relativistic klystron with operating voltage around \sim 500 kV and fully relativistic klystron with operating voltage around \sim 1 MV. The low-impedance klystron amplifiers having annular electron beam and impedance around \sim 100 Ω or less possess higher space charge forces, which provide unique power full bunching mechanism [3]. RKAs are widely used in the charged particle physics and RF linear accelerator (LINAC) applications and apart from this it is also used as high energy drivers for free-electron lasers, directed energy weaponry and colliders [3].

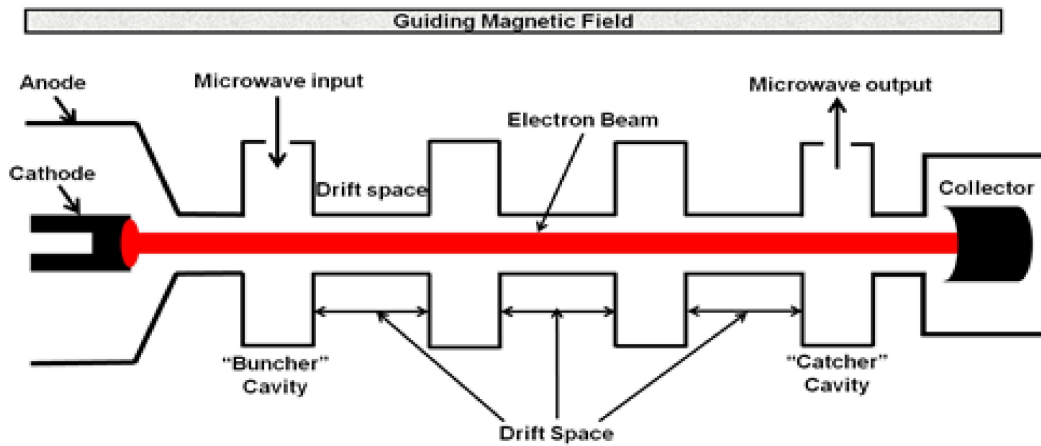


Figure 1.5: 2D Schematic of HPM source relativistic klystron amplifier (RKA).

Generally, the relativistic klystrons are categorized into three different types [13]. The first type is low-perveance relativistic klystrons with a solid beam, which was developed by Chodorow *et al.* [14] at Stanford University in 1949. The second type is relativistic multi-beam klystron, which was also designed at Stanford University and

generated Giga-watt power level having 10-beam in L-band [15]. Finally, the third type of relativistic klystrons is mildly relativistic tube with an annular beam, which was operated with an explosive emission magnetically insulated diode, and coaxial cavities at the Naval Research Laboratory (NRL) [16]. In the early 1970s, the first high power klystron was demonstrated by Friedman [17] and studied the modulation process of IREB, as it passes through the number of pillbox cavities separated by drift tubes. Its experimental test predicted an RF output power ~ 500 MW at ~ 2.9 GHz with an efficiency of ~ 20 % [17]. A decade after Friedman *et al.* [18] have developed the relativistic klystron oscillator resonating at ~ 1.3 GHz with a feedback mechanism like Reflex klystron. Later they kept the beam current close to the threshold value to form a virtual cathode and applied input RF signal ~ 4 MW to develop relativistic klystron amplifier [19]. The relativistic klystrons are widely used as high energy drivers for free-electron lasers, directed energy weapons, colliders, and accelerators [3].

1.3.2 Relativistic Magnetron

The relativistic magnetron originated due to the development of cold cathode and pulsed power technology. It is a high current, and high voltage conventional magnetron. Conventional magnetrons reached power up to 10 MW, while the first relativistic magnetron produced 900 MW power [20], [21]. This source was developed as a direct extrapolation of a cavity magnetron driven at high currents produced by pulsed-power and cold-cathode technology. A relativistic magnetron is a high-current extension of conventional magnetrons, where a ‘relativistic’ voltage is required to produce high currents [20]. The relativistic magnetron is operated in the frequency range of 1-10 GHz. The typical schematic view of relativistic magnetrons is shown in Figure 1.6. The cathode is surrounded by the anode cavity structure as seen in Figure 1.6. The area between the cathode and anode is called the interaction region, or the A-K gap, where

the conversion of input electrical power into RF power takes place. A negative voltage is applied to the cathode with respect to an anode block held at ground potential and an axially oriented magnetic field is applied additionally. From the mathematical relations known as the Buneman-Hartree condition and the Hull cut-off condition, the approximate operating voltage and magnetic field can be calculated. These values are applied to a properly designed magnetron, electrons are emitted from the cathode, and their energy is converted to microwave energy, which is extracted out utilizing a loop through one of the cavities.

In 1976, Bekefi *et al.* [22] experimentally demonstrated the relativistic magnetron that showed the RF output power ~ 1.7 GW with an efficiency of ~ 35 %. A model of relativistic magnetron using a diffraction coupling method was tested experimentally, which generated an RF power of ~ 4 GW at ~ 9.2 GHz [23]. Levine *et al.* [24] have connected the seven relativistic magnetrons through phase-locking to generate an RF power in the range of 400 - 600 MW in the frequency range of 1-3 GHz. In parallel a tunable relativistic magnetron was also demonstrated by Levine *et al.* [25], and achieved ~ 400 MW RF power at 1.21 GHz with a tuning range of ~ 24 % and ~ 500 MW at 2.82 GHz with a tuning range of ~ 33 %. Fuks and Schamiloglu have extracted

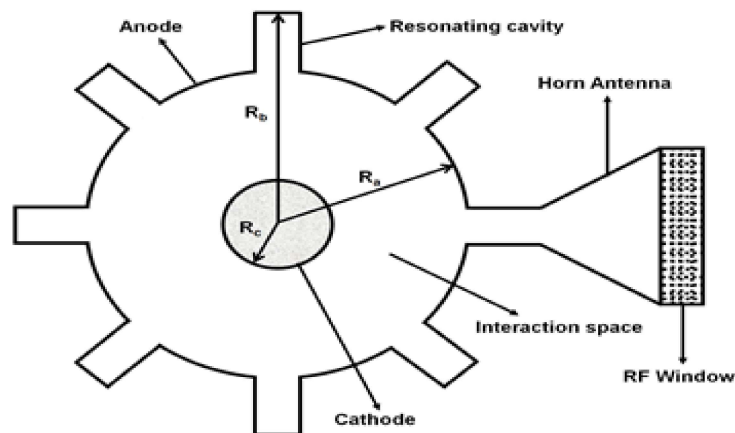


Figure 1.6: 2D Schematic of HPM source relativistic magnetron (RM).

the RF power axially by using a horn antenna from the relativistic magnetron that produced ~70 % efficiency [26].

1.3.3 Virtual Cathode Oscillators (VCO or Vircator)

Virtual Cathode Oscillator (VCOs or Vircator) is a different kind of HPM source based on the concept of space charge effect and microwave radiation is not generated due to the interaction of electrons and RF generated inside the interaction circuit as occurred in other HPM devices. Vircator has got few advantages like very simple design consideration, no slow-wave structure, no external magnetic field required and no frequency tuning. It has the only disadvantage of low power generating efficiency about 1 to 3 % [3], [20]. It works on the principle of electron beam retardation due to the self-generated space charge force, which causes the formation of virtual cathode and the mode of operation in Vircator is transverse magnetic (TM) mode. There are generally three variants of Vircators available: Cavity Vircator, Tunable Vircator, and Coaxial Vircator. The basic schematic of Vircator is shown in Figure 1.7, which consists of an Explosive Electron Emission (EEE) cathode, high voltage pulse power supply, anode foil, and RF window. The cathode is driven by a high DC voltage and the electron beam is emitted by the EEE process and forms a layer of plasma around the cathode. The high current density electrons will come out through this plasma layer and accelerated by the transparent anode foil which allows these electrons to pass out. These electrons are then injected into a cylindrical drift space where no external magnetic field is applied. The operational mechanism is based on the space charge limiting current which is also called as threshold current. As the electron beam current crosses this threshold value of current, the potential energy (P.E) of electrons becomes more than the kinetic energy (K.E) of electrons and as a result, electrons will not allow moving in the forward direction. Now these electrons will form a negative potential cloud termed as virtual

cathode. After the formation of virtual cathode, those electrons having sufficient K.E. to cross the virtual cathode are called escape electrons while the remaining electrons start oscillating back and forth between the physical cathode and the virtual cathode, hence the generation of EM radiation in Vircator [3].

Vircator generally required very voltage and current and its performance is mainly dependent over the cathode material. The cathodes having a dielectric material, such as velvet, electrons are emitted through FFE while in carbon fiber cathodes, electrons are emitted from the plasma layer formed on the cathode surface [20], [27-29]. However, the vacuum quality and hence performance of the device is highly degraded by the generation of high plasma layer inside the Vircator. To overcome this problem emitting materials like carbon velvet are used, in which the emission process is carried out through field emission [30-32]. More recently, the performance of the Vircator is improved by using a multistage axial Vircator developed by Champeaux *et al.* [33, 34].

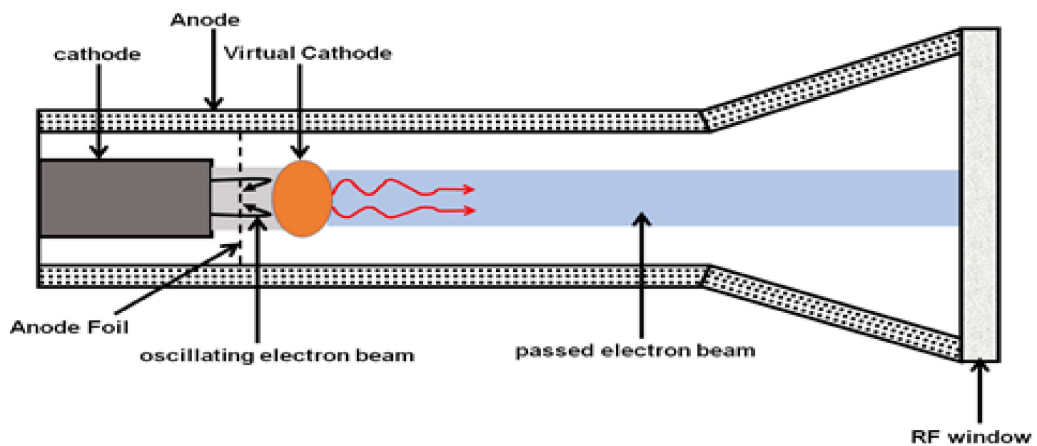


Figure 1.7: 2D Schematic of HPM source virtual cathode oscillator (VCO).

1.3.4 Magnetically Insulated Line Oscillator (MILO)

Magnetically Insulated Line Oscillator (MILO) is a kind of cross-field (M-Type) device which is nothing but a linear version of the RM as it has an axially periodic slow-wave structure (SWS) instead of azimuthally periodic SWS. It also does not require any

external guiding magnetic field to guide the electron beam. MILO generally requires a very high operating current to generate its own axial magnetic field to prevent the electrons from short-circuiting at anode-cathode (A-K) gap and to generate self-insulating magnetic field it required an input DC voltage more than 500 kV. MILO found potential applications in the field of military and Defense applications as non-lethal Direct Energy Weaponry (DEW) to either permanently damage or disturb the enemy's assaults [3]. It has got a disadvantage of no frequency tunability and low power conversion efficiency because of self-magnetic insulation. MILO consists of coaxially loaded metal disc as a SWS with inner conductor as explosive emission cathode, first few discs towards input side as a filter or choke cavity, one extractor cavity towards output side, inductive stub, and collector as shown in Figure 1.8. A high DC pulse voltage (kV) is applied between anode and cathode to initiate the EEE and forming plasma at cathode surface. When the current at the load side (charging current) becomes equal to critical current (Alfven Current), magnetic insulation takes place near SWS and electron beam drifts parallel to the cathode surface. Beam wave interaction takes place near the SWS structure when drift velocity becomes equal to the phase velocity of RF wave and energy stored in the form of standing wave in SWS cavity. The stored energy coupled out through extractor in TM_{01} mode. The operating frequency of the MILO is decided by the design of SWS. The extractor vane is used to extract the RF power and couple to the mode converter and the design of extractor vane determines the efficiency of the device. The collector/beam dump is used to provide a path for insulating current, which also bend the electron trajectory parallel to the cathode. A MILO with three or more cavities oscillates readily in its fundamental π -mode. In this mode, each cavity in the SWS behaves as a quarter-wave oscillator shifted in phase by approximately π from its neighbors. The quarter-wave oscillations have maximum magnetic field at top of the

cavity, and a maximum electric field for the electron flow in the MILO, which develops a spoke like structure as the electrons give up their potential to the EM field. Hence high power microwave is generated in TM_{01} mode at the desired frequency [3], [35].

The theory of magnetically insulated transmission line (MITL) was developed by Mendel *et al.* [36] and suggested the operation of large pulsed power system with magnetic insulation. Later Clark *et al.* [37] explored the concept of magnetically insulated line oscillator (MILO) quite similar to the linear magnetron and also experimentally tested the device at US Air Force Weapons Laboratory. Lemke *et al.* [35],[38, 39] did the theoretical investigation for the calculation of dispersion relation, critical current, maximum efficiency and load length for Load-limited MILO with axial power extraction. In 2001, Haworth *et al.* [40] studied the effect of pulse lengthening in MILO by using separate improvements in cathode segment and choke insertion. The new MILO design proposed by Eastwood *et al.* [41] named “Tapered MILO” with axial load current generation for the magnetic insulation, which overcomes the problem of mode competition. In 2009, Chen *et al.* [42] proposed the concept of Bi-frequency MILO (BFMILO) and validated it through preliminary experiments. Zhang *et al.* [43] investigated a dual-band HPM source by merging MILO and Vircator in the same

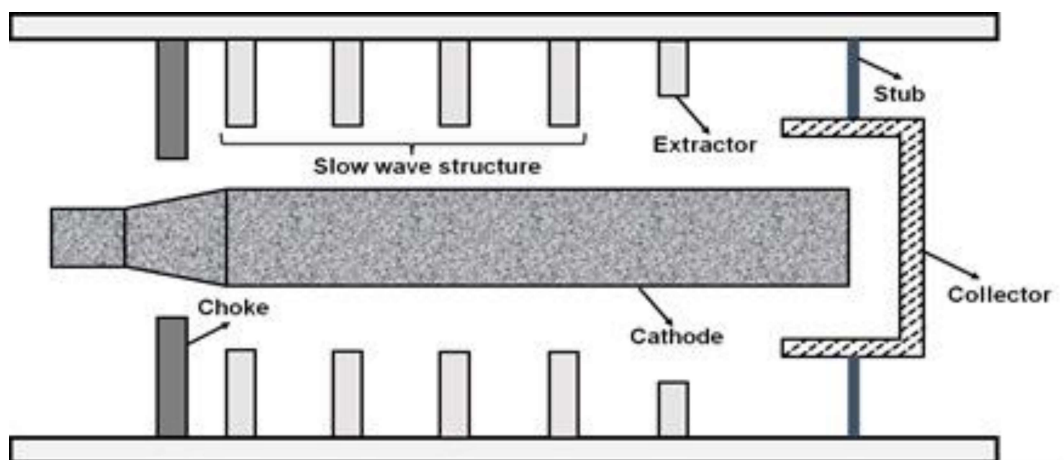


Figure 1.8: 2D Schematic of HPM source MILO.

device generates the overall efficiency $\sim 13.4\%$ at S- and C-bands.

1.3.5 Reltron

Reltron is a very compact HPM source, which can achieve power conversion efficiency around 40 % and can be operated in a wide range of frequency of operation (0.7 GHz to 12 GHz). It is quite like relativistic klystron in the sense that microwave power is extracted out from the set of cavities. However, Reltron differs from relativistic klystron in two aspects; firstly the bunching mechanism is different from klystron and secondly the bunched electron beam is re-accelerated by higher DC voltage in the post-acceleration voltage gap to freeze the bunching and increase the energy withdrawn in the output cavities [3], [44]. The Reltron does not require external guiding magnetic field to guide the electrons and it can generate long RF pulse up to microseconds that enable this device to produce high energy microwave radiation. Reltron uses cold velvet cathodes that are readily available and very cheap, as compared to thermionic cathodes. This cathode can generate current densities $>1 \text{ kA/cm}^2$. The tube performance is independent of the load impedance [5].

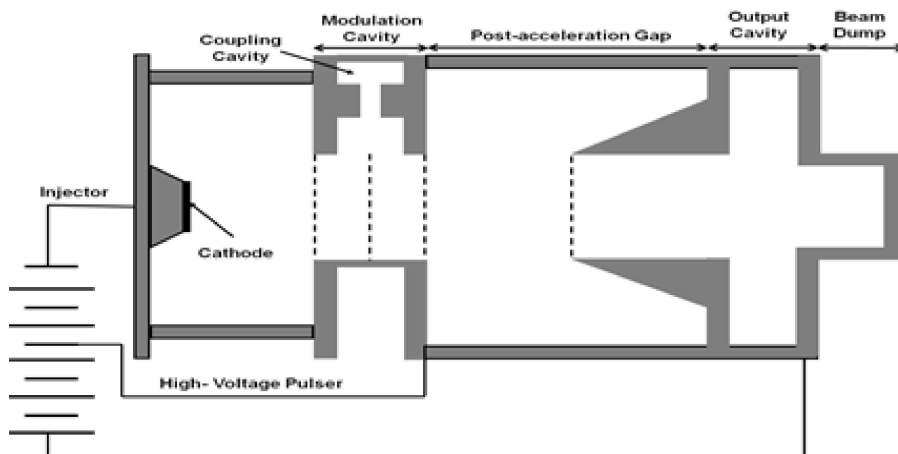


Figure 1.9: 2D Schematic of HPM source Reltron.

The principle is quite similar to a two-cavity klystron instead in place of second cavity a post acceleration gap is placed in Reltron, as shown in Figure 1.9. The RF

electric field inside the modulation cavity causes the velocity modulation, which leads to the axial bunching of electrons. The bunched electrons injected into the post acceleration gap, where the accelerating voltage causes the bunched electrons to move nearly with the speed of light gained very high K.E. and this will freeze the temporal bunching of electrons. Finally, the K.E. of the electron beam can be extracted by the output extractor cavities in the form of RF wave without breakdown, because the relativistic electron beam would not debunch until most of its K.E. had been converted into RF energy. The RF wave is extracted directly in TE₁₀ mode which is the dominant mode for rectangular cavities [3], [44].

The first experimental version of Reltron was developed in 1992 by Miller *et al.* [44] at Titan Spectron. The experimental results showed an RF output power 400 MW at ~1 GHz with an efficiency of about 50 % for the beam parameters 800 kV and 1.2 kA. Similarly, a 3 GHz Reltron showed the experimental results with 235 MW of RF power and an efficiency nearly 40 %. Later, Miller *et al.* [45] developed the Reltron that produced an RF power of 600 MW at 1 GHz with 250 J energy per pulse. In parallel, they reported another Reltron at 1.25 GHz having frequency tuning range ~1.18-1.30 GHz and an RF power ~400 MW. The gridless Reltron was also tested for the RF output power 20 MW at 2.86 GHz up to 5 μ sec with repetition rate of 100 Hz and efficiency ~40 % [46]. In 2002, Choi and Schamiloglu presented the compact HPM Reltron with low operating voltage at the University of New Mexico (UNM) [47]. Soh *et al.* [48] proposed the dual cavity Reltron to enhance the bunching. They studied different types of Reltron with interaction cavity and output waveguide that used two different types of mode simultaneously or separately to enhance the generation efficiency. The results showed the RF power 81 MW with TM₀₁₀ mode excitation, 74

MW with TM_{110} mode excitation and by exciting both modes simultaneously, they were able to generate 128 MW microwave power with 35% efficiency.

1.3.6 Free Electron Laser

Free-electron laser (FEL) is the most flexible of all HPM sources, although they are arguably the most complex. They provide an almost unlimited frequency range, at the expense of higher beam energies as the frequency increases. In a remarkable series of experiments, the FEL has been operated at repetition rates above one kilohertz with one gigawatt power levels at frequencies above 100 GHz. The original FELs were referred to as ubitrons developed in the 1950's. Like gyrotrons, FELs operate in the millimeter wave regime. The schematic of the FEL is shown in Figure 1.10. The external force causes the transverse acceleration of the beam is usually alternating transverse magnetic field lines called the wiggler field. FEL beam quality requirements are similar to those of gyrotron. Therefore, they use high-quality relativistic beams produced by accelerators. Linear accelerators, electrostatic accelerators, and microtrons have all been used in the low beam density, high beam voltage (Compton) operation. Induction accelerators are used in the high-beam density, lower voltage (Raman) regime [20]. The FEL can be continuously tuned by varying the beam energy. Radiation in the far IR is produced by 1-2 MV beams. 10 to 1000 MeV beam produce radiation in the IR to UV range. Peak powers of more than 1 GW have been reported. The intrinsic efficiency of the FEL is very low. In the Compton regime it was a fraction of a percent; in the Raman regime it is a few percent. Tapered undulators (wigglers) produce reasonably with high efficiency ~ 40% reported.

The history of FEL (long-wavelength) began in the 1960's [49]. In the 1970's, extend this work to high-peak-power levels using IREB [50], [51]. The interesting applications of FELs are in biology and biomedicine [52].

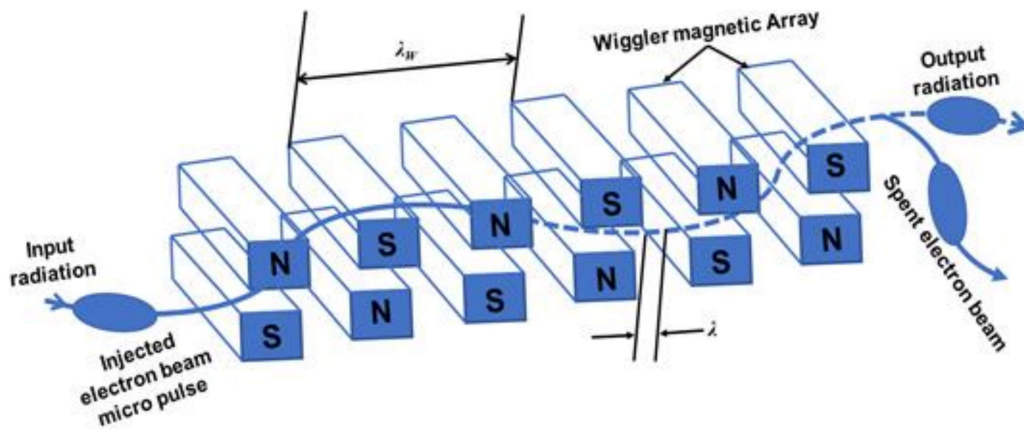


Figure 1.10: Schematic of a FEL with planer wiggler.

1.3.7 Relativistic Gyrotron Devices

Gyrotron is also known as the ‘electron cyclotron resonance maser’ and it is a high-power high-frequency source. In gyro-devices, the phase velocity of the EM wave in the interaction circuit is greater than or equal to the speed of light. Gyrotron comprises of magnetron injection gun, which produces an annular gyrating electron beam that is guided in an open cavity resonator by a high external axial DC magnetic field produced by a superconducting magnet. The magnitude of the applied DC magnetic field and the microwave frequency that can be generated from the device are closely related to the synchronism condition. The beam wave interaction inside the cavity uses the cyclotron motion of the electrons present in the beam and the transverse kinetic energy of the electrons is converted into the RF wave resulting in the formation of a Gaussian wave. The spent electrons, after losing their energy, flow out of the beam cavity and propagate to the collector where it is finally collected. The particular variation of the gyro-device based on the interaction circuit falls into several categories as per their conventional device counterparts, like, gyrotron oscillator also known as gyro-monotron, gyro-TWT, Gyro-klystron, gyro-BWO, gyro-twystron, etc. Figure 1.11 shows different types of gyrotron devices for their slow-wave and fast-wave.

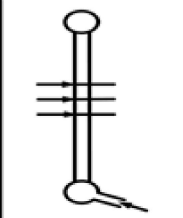
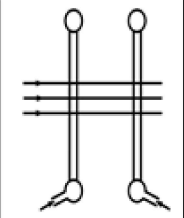
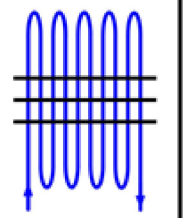
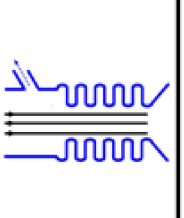
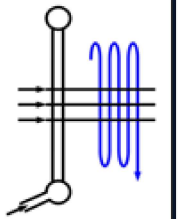
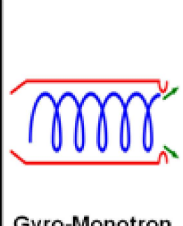
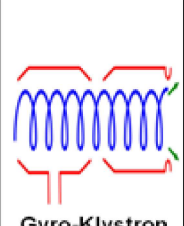
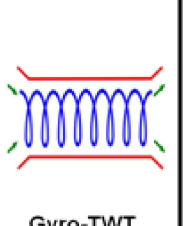
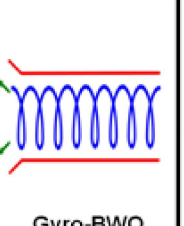
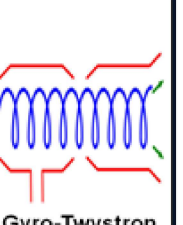
Linear Beam Device	 Monotron	 Klystron	 TWT	 BWO	 Twystron
Type of Gyrotron	 Gyro-Monotron	 Gyro-Klystron	 Gyro-TWT	 Gyro-BWO	 Gyro-Twystron

Figure 1.11: All types of Gyro devices [11].

The theoretical and experimental version of the various gyro devices are: gyrotron with no resonant cavity [53], gyrotron with resonant cavities [54-55], plasma filled gyrotron [56], high voltage and high current gyrotron [57, 58], [59], gyro-backward-wave oscillator (gyro-BWO) configuration [60], gyro-klystron and gyro-traveling-wave amplifier configurations [11], [61], and third cyclotron harmonic gyrotrons [62] are developed by various researchers. Unlike the gyrotron, the frequency of the cyclotron auto-resonance maser (CARM).[35] also developed.

1.4 Relativistic Backward Wave Oscillator (RBWO)

Relativistic Backward Wave Oscillator (RBWO) is an O-type slow-wave device having TM_{mn} mode of operation that consists of an axial component of RF electric field (E_z) to provide velocity modulation and bunching is provided by the radial component of RF field (E_r). The RBWO consists of an IREB confined by a strong axial external magnetic field and traverse through a cylindrical waveguide consists of some type of SWS. The SWS provides a set of EM modes having a phase velocity slightly less than beam velocity. The transfer of energy from the beam to EM waves based on the absolute instability, and it is due to interaction of slow space charge waves associated with the

IREB and slow waves associated with SWS. The RBWO operates in the regime of negative group velocity regime provided by the periodic type SWS, which shows that wave is growing in backward direction. A reflection structure of the upstream section of the device is used to reflect the backward propagating microwave signal, earlier cut-off neck waveguide was used as reflection structure, but it has greatly limited the output power because of its insufficient power handling capacity [63]. Now-a-days, Resonant Reflector (RR) is an alternative reflection structure for RBWO, which enhances the efficiency and coherency of the source by providing pre-bunching of electrons [64]. The external guiding magnetic field guides the beam in axial direction and makes the transverse motion of electrons negligible, however for weak guiding magnetic fields, the transverse motion of electrons affects the interaction between the SWS and beam, which affects the electronic efficiency. The 2D-schematic of RBWO has shown in Figure 1.12, that consists of an annular cathode, a cavity resonant reflector, a waveguide section, followed by an SWS and a Tapered waveguide collector, where, r_0 , r_1 and d are the mean radius, corrugation depth and period of SWS, respectively, and r_b is the beam radius.

A hollow electron beam is emitted by the cathode. Hence the dominant slow

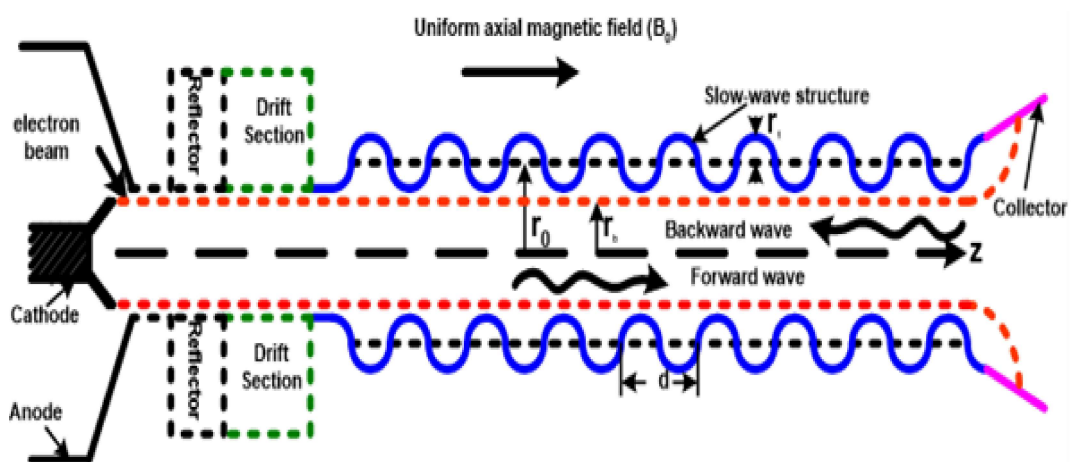


Figure 1.12: 2D Schematic of HPM source RBWO.

space charge wave associated with the beam is closer to SWS surface, in addition, the annular electron beam increases the space charge limiting current, *i.e.*, maximum current handling capability of the device [3]. The reflector at the upstream section cut-off the backward propagating operating mode (TM_{01}) wave and make it forward propagating mode (TM_{01}). The drift section length changes (called as mechanical tuning) the phase between the forward wave (fundamental) and backward wave (-1^{st} harmonic) that facilitates the frequency tuning. The next important section is the RF interaction circuit, also known as SWS, which reduces the phase velocity of the generated RF to equal the drift velocity of electrons. It can be like Disk Loaded, Trapezoidal Corrugated or sinusoidally corrugated cylindrical waveguide. The SWS is designed in such a way that the desired operating TM_{mn} mode has a higher growth rate than other modes. The decelerated electron beam must be absorbed in the tapered collector as shown in Figure 1.12, after the interaction through RF within SWS in order to prevent the damage by the electron beam.

1.4.1 Advantages of an RBWO

Among all HPM generators, the Relativistic Backward Wave Oscillator (RBWO), has been researched intensively in recent years and captured more and more attention due to the number of advantages over other HPM sources such as its ability of repetition rate operation, simple design and operation, coherent source of RF power, oscillating in single mode, high stability in repetitive or long pulse operation, high-power conversion efficiency, variation of electron adaptability to beam parameter, and high pulse repetition rate.. The comparison of various experimented HPM devices is shown in Table 1.1 [3].

Table 1.2: Comparison of various experimentally tested HPM Sources [3]

Parameters	MILO	Viricator	Reltron	Relativistic Magnetron	Relativistic BWO	Relativistic Klystron
Frequency Range (GHz)	1 to 10	1 to 10	0.7 to 12	1 to 10	1 to 12	2 to 14
Pout (GW)	~3.0	>1.0	~0.6	~5.0	~6.0	~0.3
Efficiency	~15% Up to S-band	1 - 3%	30-40% Up to S-band	30-60% Up to S-band	30-40% Up to X-band	35-50% Up to S-band
Mode	TE _{n1}	TM _{0m}	TE ₁₀	TM ₀₁	TM ₀₁ /TE ₁₁	TM ₀₁
Frequency Tuning (MHz)	No	No	~400	~900	~300	No
Pulse Width (ns)	50-150	50 -150	up to 1μs	30 - 100	30 - 100	~50
External Magnetic field	No	No	Grid-Yes, Grid less-No	Yes	Yes	Yes
Applied Voltage (MV)	>0.5	0.3 to 1.2	0.7 to ~1	>0.5 kV	0.5 to ~1	~1.0
Electrical Impedance (Ω)	~20	~20	~700	~50	~100	~2 k
Repetitive Operation (Hz)	Up to 100	Single shot	up to 10	up to 250	up to 500	N/A

1.4.2 Applications of an RBWO

RBWO has found potential applications in many different areas, such as in High Power Microwave (HPM) RADAR, Particle accelerator, Power beaming, Plasma heating and Space propulsion. Besides these applications, an RBWO is very potentially used in HPM weapons as an HPM source that can generate RF power in Giga-watt (GW) level up to X-band of operation with high power conversion efficiency and repetitive pulse operation. The HPM system consists of an RBWO as an HPM source can generate very high power and energy, which is also non-lethal to humans. The expected outcome of

an HPM weapon attack can be a hard kill, where the electrical components get permanently damaged, or a soft kill, where the components are disabled and malfunctioned. The RBWO makes the HPM weapon system more efficient and compact (provided at low magnetic field operation) for ground based as well as for airborne Defense applications. The Defense and Military applications are divided into two different categories: First is Electronic Warfare (EWF), which is quite similar to soft kill and radar jamming. It requires less power in the order of kW to oppose the enemy's effective use of communications and weapon systems and also protecting our own EM spectrum. It is widely used as an electronic countermeasure and also fight against such interference with electronic counter measures. EWF is an action to disturb or destroy the enemy's electronic systems, to delay the enemy's assault, to locate the enemy's combat electronic system using short-pulsed RADAR and also to protect own electronic systems. Second is Directed Energy Weaponry (DEW), which is very similar to hard kill used GW level of power to attack magnitudes of targets. The DEW shoot the pulsed EM energy directly from surface to surface, surface to air, air to surface, air to air, sea to air and air to sea also [3]. The difference between HPM directed energy and EWF can be seen in terms of trade-off between attack sophistication and power level [3], as

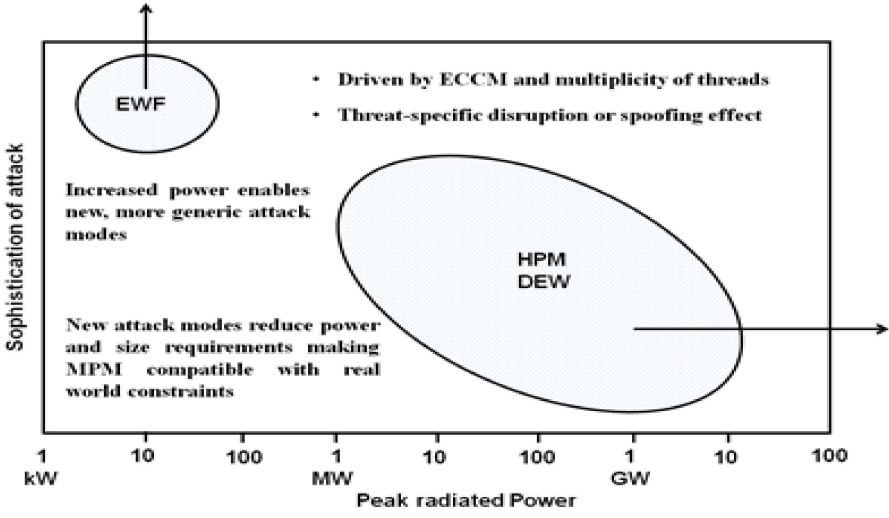


Figure 1.13: Trends and Domains of HPM [6].

shown in Figure 1.13. Now-a-days, technology is transformed to developed the intermediate alternatives having features of both DEW and EWF termed as Medium Power Microwaves (MPMs) [3]. The MPM generally reduces the damage level of enemy electronics combat system.

1.5 Literature Review of an RBWO

RBWO is one of the most promising HPM devices that has been intensively investigated recent years. In the early 1970s many experiments were conducted at Cornell University and this is when the HPM era began. An IREB technology is used first time to generate 10 MW of RF power with power conversion efficiency $\sim 0.05\%$ [65]. A few years later a team at the Institute of Applied Physics in Nizhny Novgorod, and the Lebedev Institute in Moscow demonstrated the first true HPM source, *i.e.*, RBWO that produced a single RF pulse up to 10 ns, 400 MW power with $\sim 10\%$ efficiency in X-band [66, 67]. A year after, a similar RBWO was demonstrated at Cornell University, and power was increased up 500 MW [68]. In the late 1970s, the energy conversion efficiency of uniform ultra-relativistic BWOs was limited to 15%. Since then, great progress has been made in both theory and experimental. J.R. Pierce [69, 70], G.N. Rapoport [71], Kovalev *et al.* [72], Ginzburg *et al.* [73], Swegle *et al.* [74, 75], Levush *et al.* [76, 77], Miller *et al.* [78] have developed independently both linear and non-linear theories of BWO that helped to understand the physics of interaction between IREB and EM modes in periodic structures. Swegle *et al.* have developed the beam present and beam absent dispersion relation for the sinusoidally corrugated uniform SWS and suggested the analytical calculation of growth rate for devices like BWOs and TWTs. In addition, the theory for intense relativistic electron beam (IREB) under high guiding magnetic field also presented [74, 75]. The start current for the devices having corrugated SWSs was developed by Levush *et al.* [76,

77]. They also included the end reflection within the structure for their start current calculations. It was suggested that the efficiency of an RBWO can be increased up to 40 % using a non-uniform SWS, which provides variable coupling impedance distribution within the device [79]. In 1980's, the RBWO efficiency of about 30 % was achieved using a non-uniform SWS with variable coupling impedance distribution [80]. Miller *et al.* [78] stated the theory for the operation of an RBWO near the cutoff region. The RBWO in GW level operation usually suffers from RF breakdown problem due to high electric field around conventional reflector and increase of SWS surface and edges inside the device. The remedy for RF breakdown due to high electric field was suggested by Paoloni *et al.* [81] and Valsov *et al.* [82]. They studied the EM properties of the overmoded SWS and indicated that the power handling capability of the overmoded SWS is higher than that of the conventional one.. However, the RBWO with overmoded SWS was being suffered from mode competition issue, but the issue was resolved by Kurkan *et al.* [6], Gunin *et al.* [63] and David *et al.* [83]. They suggested the theory for mode selection in an Overmoded RBWOs.

In 1996, RBWO with a cut-off neck section reflector was experimentally demonstrated by Moreland *et al.* [84] that produced ~650 MW RF output power at an 9.5 GHz with ~25 % efficiency. The uniform RBWO with a cut-off neck reflector demonstrated experimentally generated ~3 GW RF power at 9.4 GHz using a DC beam of 1 MV, 14 kA [63]. In parallel, the same RBWO with RR was studied for an output of ~0.8 GW at 9.4 GHz with an electron beam of 550 kV, 6 kA [63]. The S-band non-uniform RBWO with a Resonant reflector is demonstrated experimentally by Levush *et al* [77] and generated RF power ~1.0 GW at 3.6 GHz using the DC beam of 500 kV, 5.0 kA. In 2000, RBWO with variable coupling impedance is experimentally demonstrated by Wen *et al.* [85] and observed output power ~950 MW centered at operating

frequency 9.06 GHz with a efficiency of $\sim 38\%$. Chen *et al.* [86] experimentally tested a repetitive RBWO having a cut-off neck reflector that generate the RF power 1.1 GW with a efficiency of $\sim 33\%$. In 2002, an S-band RBWO with cut-off neck section reflector is demonstrated experimentally by Kitsanov *et al.* [87] that produced an RF output power of ~ 3.9 GW at 3.6 GHz with a efficiency of $\sim 22\%$. In parallel the same RBWO was studied for output of 5.3 GW at 3.6 GHz with DC input of 1.2MV, 15 kA [88]. Polevin *et al.* [89] have tested a S-Band RBWO to generate an RF output of 3 GW at 3.6 GHz for the DC input of 1.0 MV, 12 kA. A year after, Kitsanov *et al.* [7] experimentally studied a frequency tunable S-band RBWO to get (4 ± 1) GW output power at 3.6 GHz. They observed a frequency tuning of 12 % by mechanically shifting the RR about the SWS. In 2008, a multi-gigawatt RBWO using an overmoded non-uniform SWS with RR is experimentally demonstrated for ~ 4.3 GW of RF output power at ~ 9.4 GHz with efficiency $\sim 31\%$ [90]. In parallel, Qiao-sheng *et al.* [91] have experimentally studied a uniform RBWO with a RR in its upstream and an extractor cavity at its downstream section that produced an RF output of ~ 1.15 GW centered at 9.1 GHz for a DC input of 740 kV, 7 kA. The use of extractor cavity provides partial reflections and which in turn increases the Q-factor of the device. In 2009, a work proposed by Zhang *et al.* [92] introduced a drift region between SWS to enhance the density of electron bunching and coherency of generated RF power. This study results ~ 1.6 GW at operating frequency ~ 9.6 GHz for the DC input of 630 kV, 8.4 kA with $\sim 30\%$ efficiency. Subsequently, Xiao *et al.* [64] have tested an RBWO with modulation cavity in between the SWS and an extractor cavity at the end of SWS to enhance the efficiency. The 3D PIC simulation showed an RF output of ~ 5 GW at ~ 4.5 GHz for the electron beam parameters of 900 kV, 12 kA with $\sim 46\%$ efficiency. A dual-cavity extractor with an overmoded SWS is used for detuning the higher-order modes at the

output of the device [93]. Its PIC simulation gave an output power of ~ 10 GW at ~ 4.3 GHz with ~ 48 % efficiency. In 2012, Wu *et al.* [94] studied an overmoded nonuniform RBWO with RR that produced an RF power ~ 8 GW at ~ 8.48 GHz with a efficiency of ~ 40 %. It has been demonstrated that the probability of RF breakdown decreases as the power handling capability of the device increases. The reflection coefficient of non-uniform SWS is higher than that of uniform SWS, which comparatively reduce the strength of modulating electric field in RR and leads to better matching of the distributed fundamental harmonic current with the axial electric field [95]. The 3D PIC simulation showed the RF power of ~ 4 GW at the operating frequency ~ 9.7 GHz with a conversion efficiency of ~ 30 %. In 2014, an overmoded X-band RBWO is experimentally tested with trapezoidal cavity RR (TRR) that generated an RF power of ~ 3 GW with a conversion efficiency of ~ 36 % [96]. The TRR transforms the RF field towards the center of the cavity and also reduced the strength around the edges and surface of RR. A new reflector introduced by Elfrgani *et al.* [97] and simulated a nine-period RBWO with the twelve period Bragg reflector that produced an RF output power of ~ 340 MW directly in TE_{11} mode at ~ 9.84 GHz for the DC parameters 460 kV, 4.4 kA. The Bragg overcome the requirement of external mode converter but reduced the generating efficiency of the device. More recently, in 2016 Li *et al.* [8] have simulated a low magnetic field overmoded non-uniform RBWO with TRR that outputted an RF output power of ~ 1.8 GW at ~ 14.7 GHz for the beam 620 kV, 6.1 kA.

It has been more than a decade that researchers are extensively investigated dual-frequency and dual-band HPM sources. In 1999, Yang *et al.* [98] experimentally demonstrated two perpendicularly coupled RBWO and OROTRON are operating at X-band and Q-band. The experiment produced an RF output power of 10 MW in X-band for TM_{01} output mode (RBWO) and 1 MW in Q-band for TM_{13} output mode

(OROTRON) respectively [98]. However, this method has a disadvantage of synchronism of beam and RF wave generated and not suitable practically. In 2003, Ginzburg *et al.* [99] performed a theoretical study of dual-band RBWO with sectioned SWSs and suggested three regimes of operations named stationary, periodic auto modulation and stochastic auto-modulation regimes. These operating regimes can be realized within the sectioned SWSs RBWO by changing the device parameters. The PIC simulation results showed the stationary regime for the dual-frequency RBWO at 8.8 GHz and 10.3 GHz. The device outputted an RF power of ~ 1 MW with ~ 10 % efficiency. Ting *et al.* [100] have demonstrated two dual-band RBWO structures through simulations. The first RBWO structure consisting of two cascaded SWSs resonant at 5.48 GHz and 9.60 GHz respectively, produced 380 MW RF output power in TM_{01} output mode with a single IREB with ~ 11.7 % efficiency and external magnetic field of 2.0 T. The second RBWO structure consisting of two parallel SWSs resonant at 4.60 GHz and 8.40 GHz respectively, with IREBs produced a combined RF output power of 1.4 GW in TM_{01} and TEM mode with an efficiency of ~ 18.3 % [100]. In 2012, Tang *et al.* [101] have demonstrated an X-band Coaxial RBWO that outputted an RF power of ~ 700 MW at ~ 10.06 GHz and ~ 10.49 GHz with a conversion efficiency of ~ 16.1 %. A group at UNM worked for a direct generation of TE_{11} mode from an RBWO by using a Bragg structure. A Bragg structure can play multiple roles like a reflector, a mode converter, and it can also act as an interaction circuit resonating at some frequency. In 2014, Elfrgani *et al.* [102] a dual-band RBWO having an uniform 9 periods SWS and 12 periods Bragg structure as an interaction circuit and reflector cum mode converter, is also demonstrated by MAGIC simulation that outputted an RF power of ~ 150 MW and ~ 130 MW at ~ 10 GHz and ~ 7 GHz in TE_{11} mode for a DC parameter of 460 kV, ~ 3.3 kA and ~ 2 T magnetic field. A single fold two-way helically corrugated

Bragg structure is used as an interaction circuit for C-band and also converts the backward TM_{01} wave to forward TE_{11} linearly polarized wave at X-band. However, overall efficiency is reduced due to the asymmetric mode and helical corrugation [102].

1.6 Problem Definition

The motivation for the present research on HPM source, RBWO is led from its potential application such as, directed energy weapons, electronic warfare, EMP and HPEM simulators. Although RBWO has many advantages over other HPM sources and is being one of the promising HPM sources, there are still many issues related to its efficiency, RF output Power, magnetic field, output mode, and pulse width in an RBWO.

The prime objective of this thesis is to contribute research work for performance improvement and output mode pattern of single-frequency RBWO and Dual-band/dual-frequency RBWO. The foremost problem in RBWO is its higher power conversion efficiency at both low and high guiding magnetic fields, which is still being challenged to the research community. The RBWO power generation efficiency can be improved by utilizing the concept of trapezoidal resonant reflector [8, 96] in addition to concept of variable coupling impedance [79, 103], velocity tapering by reducing or increasing the SWS period length that will help in reutilizing the energy of unfavorable electrons [104], and a non-uniform SWS [80]). Second, at GW power level of operation the device is being suffered from the problem of RF breakdown that causes RF pulse shortening. The RF pulse shortening occurs due to the numerous reasons such as beam degradation, multiple mode excitation inside the interaction circuit, Secondary electron emission, High-field electron emission through various explosive emission centers, anode plasma and collector plasma formation [105-107] and the simulation studies for

the causes of pulse shortening are unaddressed. Third, mode converter is required to convert the outputted TM_{01} mode to TE_{11} mode for Gaussian output, which increased the overall length and reduce the efficiency. Gaussian output has maxima at the center axis unlike TM_{01} mode, which has a null at the bore sight and it is required for Defense and Military applications.

Gaussian output formed by the combination of 85 % of TE_{11} and 15 % of TM_{11} mode [108]. Therefore, device generating direct TE_{11} mode is of great interest for HPM weapons and studies for RBWO to directly generate TE_{11} mode with more efficiency are required. Fourth, limited research has been done on the Dual-band operation of RBWO during the past two decades [98-102] and there is big research gap found for the Dual-band operation of RBWO even with higher conversion efficiencies. Fifth, mode converter is also required in dual-band RBWO to convert the outputted TM_{01} mode to TE_{11} mode for Gaussian output. So, there is a need to fulfill this broad gap by doing a research study for high efficiency and long pulse single and dual-band RBWO to radiate the RF output power without using mode converter at the output section.

1.7 Outline of the Thesis

Relativistic Backward Wave Oscillator (RBWO) is a linear beam, compact HPM device that can generate gigawatts of RF output power at the microwave frequency range from L-to X-band. RBWO is a widely used HPM source for Defense and Military applications. The analytical and simulation investigation of an S-band RBWO is carried out and discussed in various chapters of the present thesis. The work is mainly concentrated to increase the efficiency of the device and also to examine the performance the device at high and low guiding magnetic field. The present work is also highlighted the RF breakdown causes the pulse shortening by various mechanisms

through MAGIC-PIC simulations. In addition, the direct generation of TE_{11} output mode from an RBWO for Gaussian output is also studied along with the single-band and dual-band operation of the device with TM_{01} output mode. The present work includes the detailed design aspects, rigorous analysis, and vast simulation results to understand the beam-wave interaction mechanism in S-band HPM source, RBWO and its performance enhancement studies are also presented. The proposed structures of the RBWO are modeled with the mesh size of $dz \approx d/24$ mm, $dr \approx d/48$, and $d\phi \approx \pi/12$ (where d is period of the SWS in mm) in a commercially available FDTD based “MAGIC-3D” simulation software.

In the present chapter, the development of HPM technology with its State-of-the-Art has been presented followed by its various applications in Defense and other sectors. The various HPM sources are studied and the RBWO is selected for its numerous advantages and very few laggings over other HPM sources. The literature survey for RBWO is done and State-of-the-Art is made along with the device shortcomings to find the research gap. The present thesis is structured into seven chapters and chapter organization is given, as follows.

In Chapter 2, the analytical background and mathematical model are recollected and presented as per the various linear and non-linear theories developed by the researchers in early 1990's. The operating principle of the device for sustained oscillations is explained theoretically and numerically. The design methodology for each subassembly of RBWO is introduced followed by the calculation of various analytical parameters like behavior of annular electron beam under external magnetic field, maximum DC power carried by the IREB, cold and hot dispersion relations, and finally the cyclotron resonance magnetic field. The numerical investigations are also validated by considering an experimentally demonstrated S-band overmoded RBWO,

and the Rectangular resonant reflector has been replaced with Trapezoidal resonant reflector to enhance the pre-modulation during electron beam propagation, thus increasing the generated RF signal overall efficiency and coherency.

In chapter 3, the design of both overmoded and non-overmoded S-band RBWO are presented and studied for beam-wave interaction behavior by using MAGIC-PIC simulations. In addition, the various pulse shortening mechanisms are formulated in PIC simulation environment to study their effects over the generation of high-power microwaves at low guiding magnetic field. The pulse shortening analyses showed that these causes do not influence the microwave generation time in the overmoded RBWO with TRR for the entire simulation time. The predicted simulation results of the overmoded RBWO with TRR have been justified by comparing with the performances of other RBWO configurations, including a non-overmoded RBWO with rectangular resonant reflector (RR) and TRR individually and an overmoded RBWO with RR provided the inclusion of some of the practical causes of RF pulse shortening.

Chapter 4 deals with the design and simulation of an S-band RBWO consists of a new type of reflector to get direct generation of TE_{11} output mode. The modeling of the device and PIC simulations are carried out to study the beam-wave interaction of an RBWO having Sectional Bragg reflector. Further, the parametric studies are performed to check the sensitivity of the device over structural and electrical parameters.

In Chapter 5, a relativistic backward wave oscillator (RBWO) with sectional slow-wave structures (SWSs) has been designed to generate a long high-power microwave (HPM) pulse at two different frequencies. The two slow-wave structures (SWS) are used to generate dual-band microwaves, and a rectangular resonant reflector (RR) is used to reflect the backward waves generated by both SWS's. The drift section-

It is separated by two SWS's also acts as a reflector, and it helps to enhance the pulse duration up to 100 ns of simulation time. Further, the parametric studies are performed to check the sensitivity of the device over structural parameters. Finally, a voltage tunability of the proposed dual-band RBWO device is presented to get the frequency tuning of the device about the center frequency and guiding magnetic field over dual-band frequency and RF output power.

Chapter 6 deals with the direct generation of TE_{11} output mode from an RBWO to obtain the Gaussian radiation intensity as it has maxima at its axis and found potential applications in Defense and Military sectors. The two ways helically corrugated single fold cylindrical waveguide named Bragg structure has opted which can act like an interaction circuit and reflector and mode converter. The design methodology for Bragg Structure and analytical formalisms like coupling coefficient, conversion or power reflection coefficient followed by cold dispersion relation is discussed in detail. The Bragg structure (twelve periods) is designed as an RF interaction circuit and simulated to get the HE_{11} output mode directly on the output port. Further, the dual-band RBWO with S-band Bragg structure and C-band SWS is modeled to obtain the direct linearly polarized TE_{11} mode with high efficiency. Finally, the chapter is concluded by the parametric studies to check the sensitivity of the device for various structural parameter variations.

Finally, Chapter 7 discusses the work done in the previous chapters to complete the dissertation, and the main findings are structured to provide as conclusion. The limitations of the present study are also discussed by pointing out the scope for further research work.

1.8 Conclusion

In the present chapter, the outline of high-power microwave (HPM) sources has been presented with their classifications and types. The development of the HPM era has been discussed from the beginning of the development of the VEDs. Various applications of HPM sources including Defense and Military have been highlighted for Direct Energy Weaponry (DEW) and Electronic Warfare (EWF). The literature survey showed the advantages and disadvantages of different types of HPM sources and the progress in HPM devices over time. The linear and non-linear theories developed by various researchers in the early 1970's were scanned to understand the physics and operating principle for Backward Wave Oscillators (BWOs). The State of the Art for the Relativistic BWOs has been reviewed to increase its scope, resistance, and performance in the field of HPM weapon systems.

The next Chapter deals with the analytical model of relativistic version of BWO, which is further validated by considering an experimental version of the S-band RBWO.