CERTIFICATE

This is to certify that the thesis entitled "**Design and Simulation Investigations of Single/Dual Frequency Relativistic Backward Wave Oscillators**" being submitted by **V Venkata Reddy (17091028),** to the Indian Institute of Technology (Banaras Hindu University), Varanasi, for the award of the Degree of Doctor of Philosophy in the Department of Electronics Engineering is a record of bonafide research work carried out absolutely by him under my supervision and guidance. The thesis has reached the standard; fulfilling the requirements of the regulations relating to the nature of degree. The results embodied in this thesis have not been submitted to any other university or institute for the award of any degree or diploma.

M. Thottappan 19/07/2022

(Dr. M. Thottappan)

Supervisor

19.07.22

(Prof. V. N. Mishra)

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I, **V Venkata Reddy**, certify that the work embodied in this thesis is my own bonafide work and carried out by me under the supervision of Dr. M. Thottappan from **25/07/2017** to **19/07/2022**, at the Department of Electronics Engineering, Indian Institute of Technology (Banaras Hindu University), Varanasi. The matter embodied in this thesis has not been submitted for the award of any other degree/diploma. I declare that I have faithfully acknowledged and given credits to the research workers wherever their works have been cited in my work in this thesis. I further declare that I have not willfully copied any other's work, paragraphs, text, data, results, etc., reported in journals, books, magazines, reports, dissertations, theses, etc., or available at websites and have not included them in this thesis and have not cited as my own work.

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(Dr. M. Thottappan)
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Signature of Head of Department

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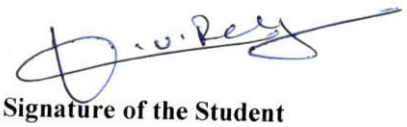

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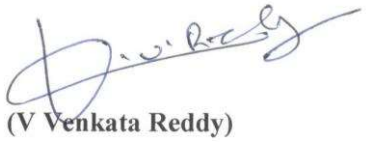

Date: 19/07/2022

(V Venkata Reddy)

Dedicated

To

My Family

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LIST OF ABBREVIATIONS

Abbreviation	Full Form
2D	Two Dimensional
3D	Three Dimensional
A	Ampere
AC	Alternating Current
A-K	Anode-Cathode
CRM	Cyclotron Resonant Maser
CARM	Cyclotron Auto-Resonance Maser
CST	Computer Simulation Technology
DC	Direct Current
DEW	Directed Energy Weapon
EEE	Explosive Electron Emission
EM	Electromagnetic
EMP	Electromagnetic Pulse
EWF	Electronic Warfare
FCG	Flux Compression Generator
FDTD	Finite Difference Time Domain
FEM	Finite Element Method
FIT	Finite Integration Technique
FEL	Free Electron Laser
FFT	Fast Fourier Transform
GHz	Gigahertz
HEE	High Electric field Emission

HFSS	High-frequency Structure Simulator
HPEM	High Power Electromagnetic
HPM	High Power Microwave
Hz	Hertz
IREB	Intense Relativistic Electron Beam
J	Joules
κA	Kilo Ampere
K.E.	Kinetic Energy
κV	Kilo Volt
LINAC	Linear Accelerator
MA	Mega Ampere
MHz	Mega Hertz
MILO	Magnetically Insulated Line Oscillator
MITL	Magnetically Insulated Transmission Line
MPM	Medium Power Microwaves
MW	Megawatt
NRL	Naval Research Laboratory
NS	Nanosecond
PIC	Particle-In-Cell
PCHI	Positively Charged Hydrogen Ions
P.E.	Potential Energy
PFL	Pulse Forming Line
RWO	Relativistic Backward Wave Oscillator
RKA	Relativistic Klystron Amplifier

RKO	Relativistic Klystron Oscillator
RM	Relativistic Magnetron
RF	Radio Frequency
RR	Resonant Reflector
SCO	Split Cavity Oscillator
SEE	Secondary Electron Emission
SSD	Solid-State Devices
SWS	Slow Wave Structure
OSWS	Overmoded Slow Wave Structure
TRR	Trapezoidal Resonant Reflector
TE	Transverse Electric
TM	Transverse Magnetic
TWT	Travelling Wave Tube
UNM	University of New Mexico
μs	Microseconds
VC	Virtual Cathode
VED	Vacuum Electronic Devices
VIRCATOR	Virtual Cathode Oscillator

LIST OF SYMBOLS

Symbol	Details
B	Guiding Magnetic Field
B_1	Cerenkov Absorption
B_2	Cyclotron Absorption
c	Speed of the light
d, P	SWS Period Length
e	Charge of the electron
E	RF electric field
E_z, E_r, *and* E_ϕ	Axial, Radial, and Azimuthal RF Electric Field
f_r	Resonant frequency
f_c	Cut-off frequency
f	Frequency
I_b	Beam current
I_{st}	Start current
I_{scl}	Space charge limiting current
I_{mn}^J , I_{mn}^Y	Fourier integrals of the Bessel functions of the first and second kind
k	Wavenumber in free space
k_z	Longitudinal wavenumber
K_P	Power reflection coefficient
L_c, L_{dr}, L_{cut}, L_{dr1}, L_{dr2}	Cavity/Drift section/Waveguide Length
m	Mass of electron
P_1, P_2, P_3	Axial, Radial, and Azimuthal electron momentum
P_b	Beam Power

r_b	Beam radius
r_c, r_w, R_c, R_{cut}, R_{dr1}, R_{dr2}	Cavity/Waveguide Radius
r_0, R_0	Mean Radius
r_1, R_1	Corrugation Depth/Ripple amplitude
s	Resonant Harmonic Number
v_e/ v_b	Electron Velocity/Beam Velocity
v_{ph}	Phase Velocity
v_z, v_b	Longitudinal velocity of electron/beam
V	Electrostatic Potential
V_b	Beam Voltage
z, r, and ϕ	Axial, Radial, and Azimuthal axis
θ	Phase
δ	Coupling coefficient
α	Space charge factor
β_o	Normalized beam velocity
γ	Relativistic Factor
γ_0	Initial Relativistic Factor
γ_b	Relativistic Factor under the influence of Space Charge
λ	Wavelength
λ_r	Resonant wavelength
ω	Angular frequency
χ_{mn}	Eigen Value of operating mode

PREFACE

In recent years, the development of High-power microwave (HPM) sources has been very popular in the microwave community due to its various civilian and military applications. The main purpose of HPM sources is to deliberately disrupt or destroy electronic equipment without harming the infrastructure or harming the humans. The generation of RF power by HPM sources from KW's to GW's in the frequency range from GHz to THz with single and dual-frequency by a single HPM device has drag the attention of researchers and academia around the world for R&D in this domain. There are many HPM sources to generate high power using Relativistic electron beam such as Relativistic Klystron, Relativistic Backward Wave Oscillator (RBWO), Relativistic Magnetron, Magnetically Insulated Line Oscillator (MILO), fast wave devices such as gyro devices and space-charged devices such as Vircator and FEL and these devices are still in active research in many countries. Above all, Relativistic Backward Wave Oscillator (RBWO) is one of the most prominent slow-wave relativistic device used in many applications like E-bomb and Directed Energy Weapons (DEW) applications, and it is more promising HPM source in terms of design, efficiency, repetition rate, and frequency tunability. The only drawback is that it requires a strong external guiding magnetic field. This makes this device cumbersome and can be overcome. Since most applications are used with the help of ground-based stations, I chosen S- and C-bands frequency of operation for my research work.

In the present thesis, the author has designed and simulate the S-band RBWO by considering an experimentally demonstrated S-band overmoded RBWO and the Trapezoidal resonant reflector has been replaced with resonant reflector to enhances the pre-modulation during electron beam propagation, thus increasing the generated RF

signal overall efficiency and coherency. In addition, the pulse shortening study is analyzed by considering its various mechanisms in MAGIC-PIC simulations. Authors tried to develop the look-alike environment causing RF breakdown which leads to the pulse shortening of RF wave. Further, significant use of the helically corrugated cylindrical waveguide named Bragg structure is made to directly generate the HE_{11} / TE_{11} mode from an RBWO for the Gaussian output. The Bragg structure is used as an integral part of a device that performs many functions, such as reflectors, mode converters, and RF interaction structure. It eliminates the requirement of external mode converter to convert outputted TM_{01} mode to Gaussian-like TE_{11} mode which increases the overall length and reduces the overall efficiency of the RBWO device. A single band and dual-band RBWO device are designed and simulated using Bragg structure to achieve high power conversion efficiency. A dual-band relativistic backward wave oscillator (RBWO) with sectional slow-wave structures (SWSs) also has been designed to generate a long high-power microwave (HPM) pulse at two different frequencies.

The author present work has been partially reported in national and international conferences, as well as in reputed journals, in the IEEE Transactions on Electronic Devices, and in the Defence Science Journal. If it useful in the designing, developing, and experimenting with single and dual frequency RBWO, the author would consider his efforts a success.

CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

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