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Dr. M. Thottappan

Supervisor

Department of Electronics Engineering

IIT (BHU), Varanasi

DECLARATION BY THE CANDIDATE

I, Anshu Sharan Singh, 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 "23/07/2014" to "24/09/2019", at the Department of Electronics Engineering, Indian Institute of Technology (BHU), 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 will fully 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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Date: **(Anshu Sharan Singh)**

Dedicated

To

My Mother

Anju Devi

(1st July 1967 to 09th November 2017)

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ABBREVIATIONS

Abbreviation	Full Form
BeO-SiC	Beryllium Oxide-Silicon Carbide
BWOs	Backward Wave Oscillations
CARM	Cyclotron Auto-Resonance Maser
CPI	Communication and Power Industries
CRM	Cyclotron Resonance Maser
CST	Computer Simulation Technologies
DC	Direct Current
ECRM	Electron Cyclotron Resonance Maser
EM	Electromagnetic
FDTD	Finite-Difference Time-Domain
FEM	Finite-Element Method
FIT	Finite Integration Technique
GHz	Gigahertz
MW	Megawatt
Gyro-amplifier	Gyrotron Amplifier
Gyro-BWO	Gyrotron Backward Wave Oscillator
Gyro-TWAs	Gyrotron Travelling Wave Amplifiers
Gyro-TWT	Gyrotron Travelling Wave Tube
IAP	Institute of Applied Physics
LHC	Large Hadron Collider
MHz	Megahertz
MIG	Magnetron Injection Gun

MoM	Method of Moments
MW	Megawatt
NRL	Naval Research Laboratory
OFHC	Oxygen free High conductivity
PBA	Perfect Boundary Approximation
PBG	Photonic Band Gap
PDL	Periodic Dielectric Loading
PIC	Particle-in-Cell
PML	Perfect Matched Layer
RF	Radio Frequency
SOC	Start Oscillation Current
SSDs	Solid State Devices
SWSs	Slow wave Structures
TE	Transverse Electric
TM	Transverse Magnetic
TeV	Tera Electron Volt
THz	Terahertz
TWAs	Travelling Wave Amplifiers
TWTs	Travelling Wave Tubes
UDL	Uniform Dielectric Loading
VEDs	Vacuum Electronic Devices

LIST OF SYMBOLS

Symbol	Details
γ	Relativistic mass factor
α	Pitch factor
V_b	Beam voltage
I_b	Beam current
r_w	Radius of waveguide
r_g	Electron guiding centre radius
r_{cav}	Radius of cavity
r_L	Larmor radius
r_d	Radius of drift tube
L_c	Length of cavity
L_d	Length of drift tube
L_{wg}	Length of waveguide
v_t	Transverse electron velocity
v_z	Axial electron velocity
ω	Angular frequency of RF wave
Ω	Electron cyclotron frequency
c	Velocity of light in free space
λ	Operating wavelength
e	Electron charge
m_e	Mass of electron
B_0	DC magnetic field
s	Electron beam harmonic number

m_q, n_q	Azimuthal, and radial indices of q^{th} mode
N_q	Total number of modes
q	Particular number of mode
p	Normalized momentum of electrons
p_t	Transverse momentum of electrons
p_z	Axial momentum of electrons
θ	Phase of electron
I_o	Normalized beam current
μ	Normalized interaction length
J_t	Transverse AC current density
H_{mn}	Azimuthal coupling coefficient
x_{mn}	The nth zero of J_m (Bessel function)
ε	Complex permittivity
ε_0	Free-space permittivity
μ_0	Free-space permeability
I_{soc}	Start oscillation current
F	Normalized field amplitude
X	Bunching parameter of the electron beam
$\eta_\perp$	Transverse efficiency
η_{ele}	Electronic efficiency
P_{in}	Driver power at the input cavity
E	RF electric field
B	RF magnetic field
E_0	Electric field amplitude at the input cavity
Q	Quality factor
Q_{cpl}	Coupling quality factor

k_t	Transverse propagation constant
k_z	Axial propagation constant
β_t	Normalized transverse electron velocity
β_z	Normalized axial electron velocity
V_d	Voltage depression
I_l	Limiting current
G	Gain
s_d	Skin depth
σ	Conductivity
t_w	Window thickness
r_{win}	Radius of window
ε_{rw}	Relative permittivity of RF window

PREFACE

The work of the present thesis focus on the beam-wave interaction study of the gyro-twystron amplifier. The thesis aims to develop studies on the most unexplored gyrotron variant of vacuum electron device (VED), i.e. gyro-twystron, to create a solid theoretical background for future experimental studies. In addition to VEDs, the historical developments of gyro-twystron is scrutinised to bring out the research gap and problems. The Identification of oscillations and its suppression have been done, in a series of works on the gyro-twystron amplifier, and the part of these works has been published in *IEEE Transaction on Electron Devices*. Further, the aim, introduction and scope of the thesis are briefly discussed below.

As compared to solid state devices, VEDs generates high RF power to serve the various applications from space exploration to nuclear researches. At higher frequencies, the fabrication difficulties and operational limitation of conventional microwave tubes push the research and development activities towards Gyrotron devices. With high power generation/ amplification and handling capabilities, gyrotron devices find applications in plasma heating, ceramic sintering, RADAR and particle accelerator application. Gyrotron oscillator finds application in plasma heating in popularly known thermonuclear fusion reactors while its amplifier counterparts are found suitable for RADAR and particle accelerator applications.

Gyro-twystron amplifier derived from the gyrokl***ystron*** and gyro-***TW***T amplifier (***TWystron***) and combines the advantages of both amplifiers thereby possess high power-bandwidth product and gain-bandwidth product. A slow-wave counterpart of Gyro-twystron have a successful services history in the US AN/TPS RADAR system and renders as a veteran tube. Despite these aspects, the gyro-twystron is the most unexplored device in gyrotron family. These advantages and applications attract authors to extend the study of gyro-twystron to answer the challenges of vacuum electronics.

For the megawatt-class operation, the stability of gyro-twystron is an issue as the output waveguide section is vulnerable to parasitic instabilities and backward wave oscillations. A nonlinear multimode code has been developed to investigate the growth of operating as well as competing modes in RF interaction structure of X-band gyro-twystron and predicted the second harmonic TE_{02} is most troublesome mode. To suppress the second TE_{02}, the periodic dielectric rings are introduced in the output waveguide section of gyro-twystron, and the design and stability study of PDL waveguide has been made. A multimode study of PDL gyro-twystron has been made to investigate the suppression of parasitic modes in addition to the growth of operating mode. A study has also been made for the performance improvement of the gyro-twystron amplifier by introducing an intermediate cavity. The particle emitter and collector is designed/optimized to improve the electron beam quality for beam-wave interaction and improve the energy extraction at collector electrode, respectively. The work of author is supported by UGC, Government of India, New Delhi through the UGC-NET JRF Fellowship under Grant 3956/NET-JUNE 2013.