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Technological Application and Overview of Experimental Researchon the Gyrotron Traveling -Wave-Tube Amplifier

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Abstract:*The gyrotron traveling-wave tube amplifier (gyro-TWT) is mainly used as high power millimeter wave sources that addresses the well-known concept of the electron cyclotron maser (ECM) instability. This paper present technical overview of the Gyro-TWT amplifiers over a long period of time. Mainly focused on the techniques, beam wave interaction structure, controlling instability, broadband operation, high-power, low magnetic field.*

Keywords:*Amplifier; Electron cyclotron maser; gyrotron traveling-wave tube amplifier (gyro-TWT); beam wave interaction.*

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I. INTRODUCTION

Unlike linear beam tubes, gyro-devices employ an electron beam that consists of electronically accelerating electrons and the free energy remains in motion transverse in the applied magnetic field. In these devices, cyclotron resonances; (a new dimension in the interaction mechanism), permitting wave generation in simple and large-size as well as structures provides the physics underpinning. When the interaction involves the gyrational motion of electrons in a static magnetic field, the synchronism condition can be written as

$$\omega - k_z v_z - s\Omega_c \cong 0 \qquad (1)$$

Where, (s=1,2,...) ω, k_z, v_z are the wave frequency, propagation constant and electron axial velocity respectively, ($k_z v_z =$ doppler term) and s, Ω_c are the cyclotron harmonic number, and relativistic electron cyclotron frequency respectively. From equation (1) permits a simple fast- wave ($\omega/k_z > c$)interaction structure.

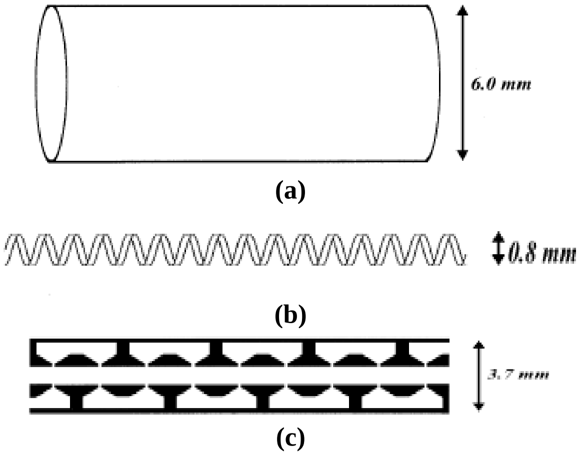
In electron cyclotron masers electromagnetic energy is emitted by relativistic electrons rotating in an outward longitudinal magnetic field. In ECMs, the effective frequency Ω_c corresponds to the relativistic electron cyclotron frequency:

$$\Omega_c = \Omega_{c0}/\gamma \text{ with } \Omega_{c0} = e\mathrm{B}_0/\mathrm{m}_0 \qquad (2)$$

and

$$\gamma = \left[1 - \left(\frac{v}{c}\right)^2\right]^{-1/2} \approx 1 + \frac{eV_0}{m_0 c^2} = 1 + \frac{eV_0}{511} \qquad (3)$$

In the lowest order mode 30 GHz interaction frequency transverse dimensions of three different shape waveguide structure (smooth waveguide, helix & coupled-cavity structure) as shown in figure 1.



(a)

(b)

(c)

Figure 1: Transverse dimensions of three different shape waveguide structure (a) Smooth waveguide structure, (b) Helix waveguide structure (c) Coupled-cavity waveguide structure.

Apart from the physical structural simplicity, from figure 1 (a) smooth waveguide structure transverse dimension is noticeably greater than the other two basic structure figure 1 (a) and 1(b) of slow-wave waveguide structures working in TWT.

The commercially available (the word record parameters) of maximum pulse is 140 GHz, 0.92 Mega-Watt-class gyrotrons using artificial diamond output power windows at 30 minutes pulse duration, 44% efficiency and 97.5% Gaussian mode purity. (CPI and European KIT-CRPP-TED (The Research University in the Helmholtz Association) collaboration). Employing a SDC (single-stage depressed collector) for energy recovery.

The JAEA-TOSHIBA 110 GHz gyrotron generated a 1.5 MW output power (maximum) in 4.0 second pulse duration at 45% efficiency. The maximum energy of 2.88 GJ (word record) in 60 minutes at 0.8 Mega-Watt was generated with the Japan 170 GHz ITER gyrotron, also achieved 1 Mega-Watt, 800 second pulse duration at 55% efficiency and the output power of greater than 0.5 Mega-Watt with the 57% efficiency record for tubes.

The Russian 170 GHz ITER gyrotron generated 0.99 Mega-Watt with a 1000 second pulse duration at 53 % efficiency and also achieved 1.2 Mega-Watt with a 100 second pulse duration and 53 % efficiency. European 170 GHz coaxial-cavity gyrotron (prototype tube) achieved of the 2 MW, in short pulses, 96% Gaussian mode purity and 46% efficiency.

Numerous short-pulse applications, pulsed magnet with gyrotron achieved at frequencies up to 670 GHz deliver 210 kilo-Watt in 20 second at 20% efficiency, 1 THz deliver 5.3 kilo-Watt in at 6.1% efficiency and 1.3 THz deliver 0.5 kilo-Watt in 20 second at 0.6 % efficiency.

II. GRYOTRON TRAVELING-WAVE AMPLIFIER

The Gyro-device basically four types namely - gyrotron (gyrotron oscillator), gyroklystron amplifier, gyro-BWO (gyrotron backward-wave oscillator) and gyro-TWT (gyrotron traveling-wave tube amplifier). Gyro-devices principally differ in the interaction structure and each of them advantages for particular application and they offer unique properties. There schematics diagram as shown in figure 2. Through the local cavity interaction all gyro-devices can excite electromagnetic radiation.

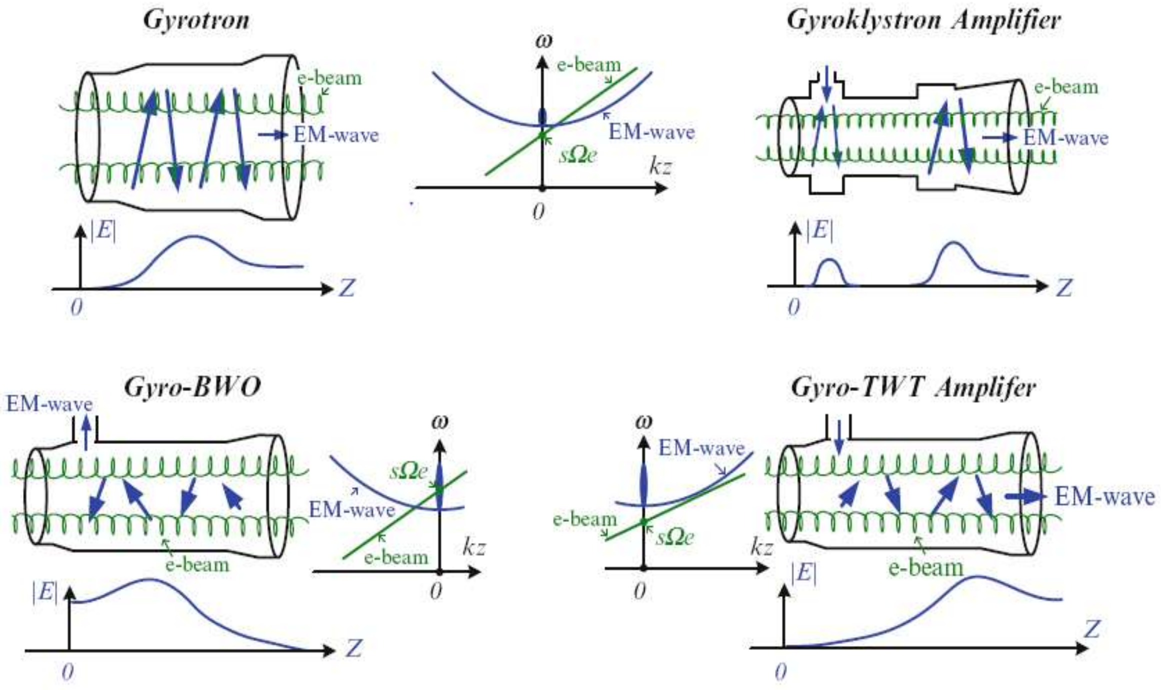


Figure 2: Four types of gyrotron schemes

Gyrotron Traveling-Wave-Tube Amplifier has been extensively investigated for its characteristics of high peak or average power, high efficiency, and broad bandwidth, and has been widely applied in many fields such as high-power wave radar, microwave weapon, electronic warfare, and early warning. Generally, high-frequency characteristics of the related components used in the gyro-TWTs need to be measured before fabricating the gyro-TWT.

In millimeter wave band gyrotron traveling-wave-tube amplifier can generate coherent radiation of several hundreds of kilowatts, which make to gyro-TWT is the most suitable device for transmitter source of next generation high data rate remote communication system and high-resolution imaging radar. Hence, gyro-TWT is a mile stone in national security stratagem.

This paper presents an overview of the gyro traveling wave tube amplifier, in which an injected wave of low power level is amplified through the ECM (electron cyclotron maser) instability along the length of waveguide.

EARLY GYRO TWT RESEARCH

Gyro-TWT development process is basically divided into three stages [1]. Between mid-1960s and 1980s, via the ECM instability in a crass field device (trochotron) employing an electron beam in which the electrons move along the waveguide in $E \times B$ drift motion [2]. Later the gyro traveling wave tube enter the stage of fast development in 1990s. and it enters the phase of real-world application from 2000 and then on.

Aimed at high power microwave generation by intense relative electron beam present form of the gyrotron traveling wave tube studies [3] involved from a sequence of trials [4]-[9].

The linear stage of the interaction stage is loaded with a thin layer of lossy Aquadag, functioning as the distributed wall loss to boost the thresholds of self-exciting oscillation [10]-[11]. The lossy interaction structure demonstrated in figure 3.

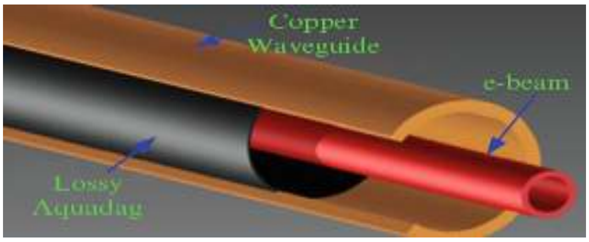
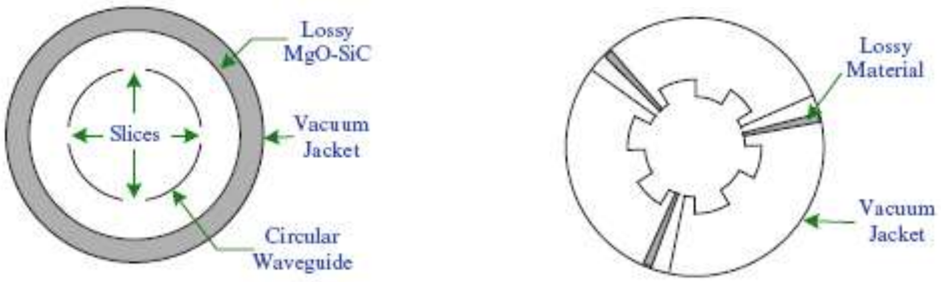


Figure 3: Decomposition diagram of the Loss Aquadag coated interaction waveguide

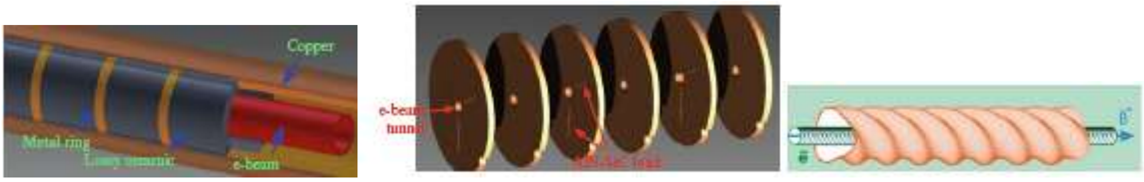
This lossy interaction arrangement can be comprehended via different traditions. Wang QS carried out gyro-TWT experiments functioning at the second harmonic [12] and the third harmonics [13]. The interaction circuit in the experiments is shown in Figure 4 (a) (sliced waveguide) and Figure 4 (b) (slotted waveguide), respectively. They are similar in loss mechanisms of the interaction circuits.



(a) **(b)**

Figure 4 (a): Sectional view of the sliced interaction waveguide (b) Sectional view of the slotted waveguide

Naval Research Laboratory (NRL) carry through a series of gyro-TWT setup based on various interaction circuits as shown in figure 5 (a) and figure 5 (b) [16]-[17]. In addition, harmonic interaction system based on a corrugated waveguide is another candidate of the broadband gyro-TWT interaction circuit, as shown in figure 5 (c) [18].



(a) **(b)** **(c)**

Figure 5: (a)The TE_{01} mode periodic lossy ceramic-loaded interaction circuit (b) The TE_{11} mode sliced interaction circuit (c) Corrugated waveguide

Demonstrates a loss circuit iteratively loaded with dielectric rings and metal rings along the axis [14], [15]. Using the compound and inventive design, the attenuation of the action mode is small, although the challenging modes are strongly attenuated by the lossy setup.

In theory and in practical setup ECM interaction and strong relativistic electron beam at comparatively low efficiencies was found to saturated. A survey of experimental setup of gyro-TWT and subsequence experiments are summarized in Table 1.

Table 1: Summery of exiting Experimental Gyro-TWTs Amplifiers

Persons, [references]	**Cyclotron Mode / harmonic no.**	**Center Frequency (GHz)**	**Output voltaage (kV)**	**Saturated Gain (dB)**	**Bandwidth 3dB (%)**	**Peak power (kW)**	**Efficiency** (%)	**Remarks**
NRL [20], [21]	TE01 / 1	35	70	20	1.5	16.6	7.8	First demonstration of gyro-TWT
Varian [22]-[25]	TE11 / 1	5	60	18	6	120	26	Distributed wall losses, AM/PM sensitivity, noise characterization
NRL [26]	TE01 / 1	35	70	42	2	3.2	1.5	Gain enhancement with distributed wall losses
NRL [27]	TE01 / 1	35	70	18 (linear)	13 (linear)	--	--	Bandwidth broadening with tapered waveguide and magnetic field
NTHU, Taiwan [28], [29]	TE11 / 1	35	80	18	10	18.4	18.6	Systematic characterization of mode competition
NTHU, Taiwan [30]	TE11 / 1	35	90	35	7.5	27	16	Improved stability with a sever
Varian [31]	TE11 / 1	94	50	30	2	20	8	First attempt at the W-band (unpublished)
NTHU, Taiwan [32]	TE11 / 1	35	100	33	12	62	21	Study of oscillation suppression with distributed wall losses
NTHU, Taiwan [33]	TE11 / 1	35	100	70	8.6	93	26.5	Demonstration of an ultra high gain scheme employing distributed wall losses
UCLA [34],	TE81 / 8	16.2	350	10 (linear)	4.3 (linear)	0.5	1.35	First proof-of-principle experiment on harmonic gyro-TWT
UCLA and UC Davis [35], [36]	TE21 / 2	15.7	80	16	2.1	207	13	Demonstration of stability and high power with harmonic interaction
NRL [37]-[38]	TE10 / 1 (rectangular	34	33	20 (linear)	33 (linear)	--	--	Record bandwidth achieved with a single-stage tapered circuit
NRL [39]	TE10 / 1	35	33	25	20	8	16	Broadband two-stage tapered circuit
NRL [40]	TE11 / 1	35	900	30	--	20000	11	IREB-driven gyro-TWT
IAP, Russia and U Strathclyde, UK [41]-[42]	TE11 + TE21 / 2	9.4	185	37	21	1100	29	Demonstration of broadband and highly efficient corrugated circuit
Varian/CPI	--	35	50	40	6	50		State-of-the-art ka-band TWT

III. COMMENTS ON TECHNOLOGY AND TECHNICAL APPLICATIONS

In the prior gyro-TWT setups several types of interaction mechanism were applied [19]. Each one setup discovered explanation to the problem to the of positive aspect. During these experiments time explore the key technology to developed and evaluate of the amplifier. For better appreciate these technologies, make known to the problems introduce four aspects, including technology of high-order harmonic interaction, high-order mode interaction, bandwidth extending or broadband operation, and waveguide wall loss. The summery of gyreotons for technical application as listed in table 2.

Table 2 : Performance of present CW gyrotron oscillators for technical applications :

Institutions	Frequency (GHz)	Mode		Power (kW)	Efficiency (%)	Voltage (kV)	Magnet
		Cavity	Output				
CPI, Palo Alto [42-44]	28	TE_{02}	TE_{02}	15	38	40	Room temp.
	28 ($2\Omega_C$)	TE_{02}	TE_{02}	10.8	33.6	30	Room temp.
	60	TE_{02}	TE_{02}	30	38	40	Cryo. mag.
KIT, Karlsruhe [45]	28 ($2\Omega_C$)	TE_{12}	TE_{12}	22.5	43	23.4	Room temp.
MICRAMICS, San Jose[46]	24.1($2\Omega_C$)	TE_{22}	TEM_{mixed}	5	25	23	Room temp.
	24.1($2\Omega_C$)	TE_{22}	TE_{22}	10	25	23	Room temp.
CPI, NIFS [47-53] Palo Alto Toki	84	$TE_{15,3}$	TEM_{00}	50	14	80	Cryo. mag.
MITSUBISHI, Amagasaki[54-57]	28($2\Omega_C$)	TE_{02}	TE_{02}	10	38.7	21	PM,600 kg tapered B
UESTC, Chengdu [58]	37.5	TE_{13}	TE_{13}	57(0.4 average)	9	50.5	Room temp.
GYCOM/IAP Nizhny Novgorod [59-105]	13(15)	TE_{01}	TE_{01}	0.3(4)	20(50)	25(15)	Room temp.
	24.1($2\Omega_C$)	TE_{11}	TE_{11}	3.5	23	12	Room temp.
	24.1($2\Omega_C$)	TE_{21}	TE_{11}	3.4	23	15	PM, 116kg
	24.1	TE_{32}	TE_{32}	36	50	33	Room temp.
	24.1($2\Omega_C$)	TE_{12}	TE_{12}	13	50	25	Room temp.
				28	32	25	Room temp.
				6.5	60(SDC)	17.5	Room temp.
	28/30 ($2\Omega_C$)	TE_{02}	TE_{02}	10	42	26	Room temp.
				30	35	26	Room temp.
	28.1/28.7 ($2\Omega_C$)	TE_{02}/ TE_{23}	TE_{02}/ TE_{23}	10	20	23-24	2-kHz freq. switching
	28.25($2\Omega_C$)	TE_{12}	TE_{12}	12	20	25	PM, 68 kg
	31.8-34.8	TE_{11}	TE_{11}	1.2	40	12	mech. tun.
	35.5-37.5	TE_{01}	TE_{01}	0.5	15.3	16	mech. tun.
	35.15	TE_{02}	TE_{02}	9.7	43	25	Cryo. mag.
	35	TE_{02}	TEM_{00}	10-50	30-40	25-30	Cryo. mag.
	37.5	TE_{62}	TEM_{00}	20	35	30	Cryo. mag.
	45	TE_{63}	TEM_{00}	26	49	25	LF Cryo.mag.
	68-72	TE_{13}	TE_{13}	1.4	22	17.5	Cryo. mag.
	83	TE_{93}	TEM_{00}	10-50	30-40	25-30	Cryo. mag.
	150	TE_{03}	TE_{03}	22	30	40	Cryo. mag.
	157($2\Omega_C$)	TE_{03}	TE_{03}	2.4	9.5	18	Cryo. mag.
	191.5($2\Omega_C$)			0.55	6.2	22	Cryo. mag.
	250 ($2\Omega_C$)	TE_{02}	TE_{02}	4.3	18	20	Cryo. mag.
	250 ($2\Omega_C$)	TE_{65}	TE_{65}	1	5	20	Cryo. mag.
	326($2\Omega_C$)	TE_{23}	TE_{23}	1.5	6	20	Cryo. mag.
University Fukui, IAP Nizhny Novgorod/ GYCOM[106-114]	300	$TE_{22,8}$	TEM_{00}	2.3	16.4	14	Cryo. mag.

IV. CONCLUSION

In this paper we have described technology issues and experimental setup or physics of the gyro-devices along with worldwide research highlights of these issues. An overview survey shows Gyro-TWT as a practical millimeter wave band and beyond one of the most promising devices of high-power generator, broadband operation, and high gain. It is revealed that gyro-TWT amplifiers are have mostly problems in developing of high power correlated to the uncertainty competition.

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