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[54] **COUPLED CAVITY GYROTRON-TRAVELING-WAVE-TUBE AMPLIFIER**

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[51] **Int. Cl.**^{6} **H01J 25/00**

[52] **U.S. Cl.** **330/45**; 315/5; 315/5.39

[58] **Field of Search** 315/3.5, 4, 5, 5.39; 330/43, 45

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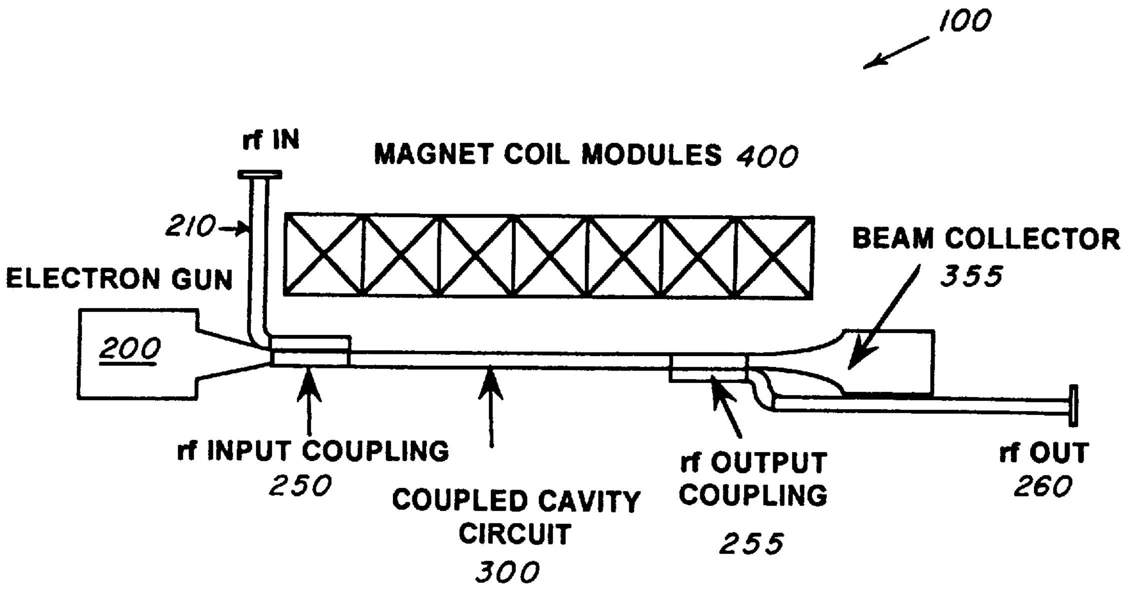
Primary Examiner—Daniel T. Pihulic

[57] **ABSTRACT**

The present invention is a coupled cavity gyrotron-traveling-wave-tube amplifier which produces highly efficient, broad band millimeter wave radiation. The present invention comprises an electron gun, a double ridged coupled cavity interaction circuit and a beam collector. In operation the gun injects a gyrating electron beam through a beam tunnel of a side wall of the coupled cavity. When the electron beam phase is synchronized with the rf phase of the transverse electric mode in the coupled cavity circuit, the electron beam is modulated and amplifies the rf input signal through the negative mass instability called electron cyclontron instability. The coupled cavity design of the interaction circuit effctively slows the rf-wave velocity, allowing amplification of the rf- wave over a broad band. This t ype of broad band microwave energy is highly useful in radar, communications and jamming technology.

1 Claim, 3 Drawing Sheets



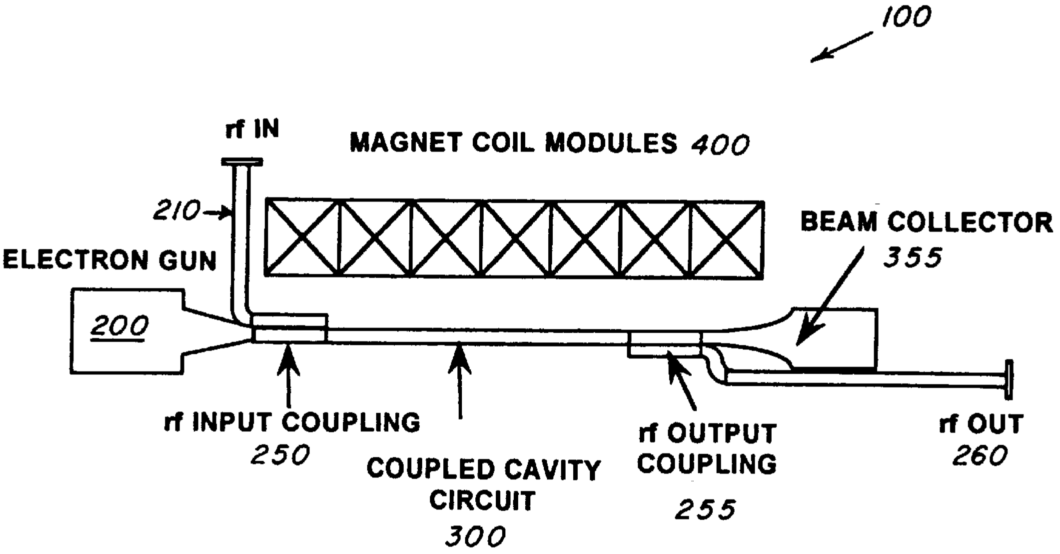

100
rf IN
MAGNET COIL MODULES 400
210
ELECTRON GUN
200
BEAM COLLECTOR
355
rf INPUT COUPLING
250
COUPLED CAVITY
CIRCUIT
300
rf OUTPUT
COUPLING
255
rf OUT
260

FIG. 1

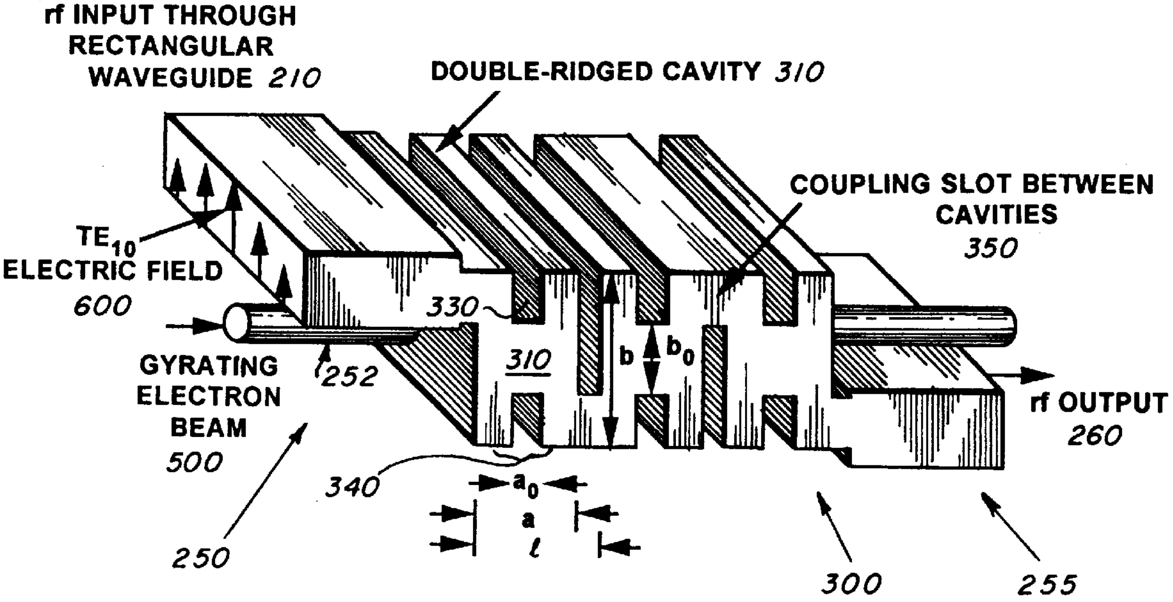

rf INPUT THROUGH
RECTANGULAR
WAVEGUIDE 210
DOUBLE-RIDGED CAVITY 310
COUPLING SLOT BETWEEN
CAVITIES
350
TE_{10}
ELECTRIC FIELD
600
330
310
b
b_0
GYRATING
ELECTRON
BEAM
500
252
rf OUTPUT
260
340
a_0
a
ℓ
250
300
255

FIG. 2

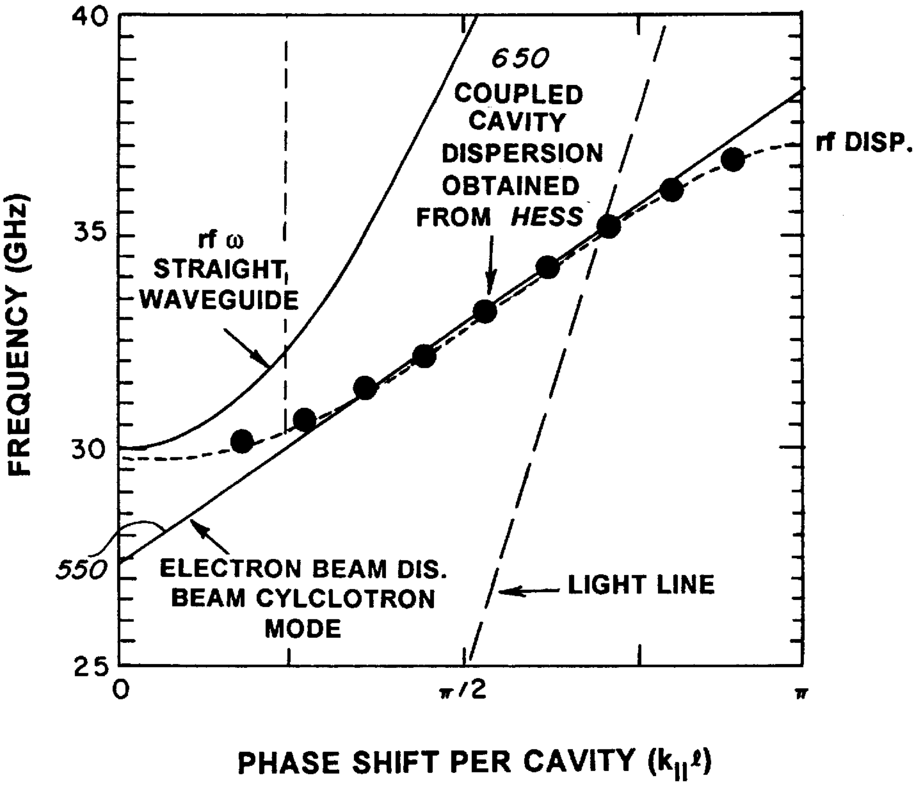

40
35
30
25
FREQUENCY (GHz)
0
π/2
π
PHASE SHIFT PER CAVITY ($k_{||}\ell$)
650
COUPLED CAVITY DISPERSION OBTAINED FROM HESS
rf DISP.
rf ω STRAIGHT WAVEGUIDE
550
ELECTRON BEAM DIS. BEAM CYLCLOTRON MODE
LIGHT LINE

FIG. 3

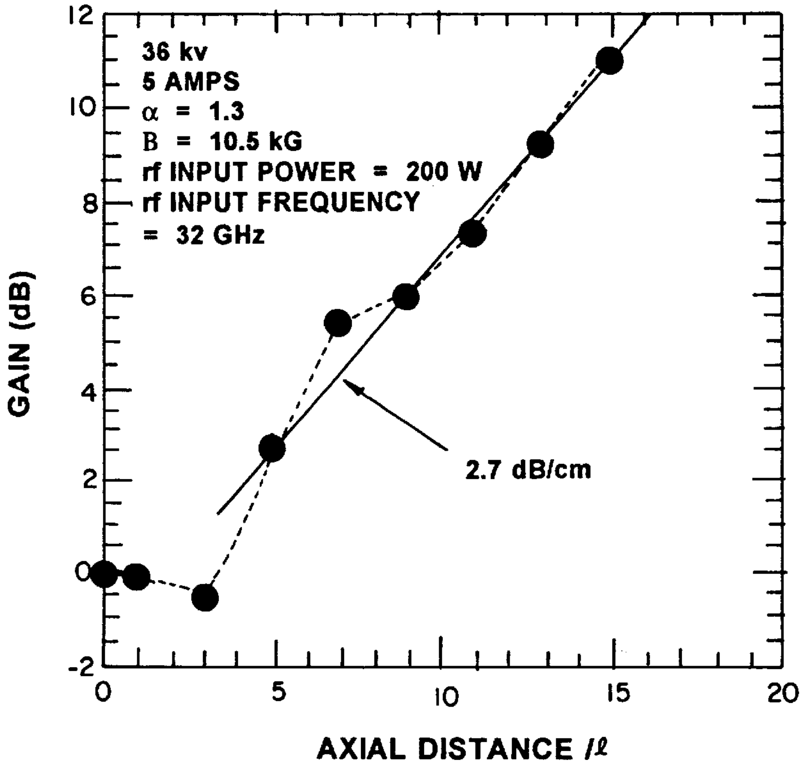

12
10
8
6
4
2
0
-2
GAIN (dB)
0
5
10
15
20
AXIAL DISTANCE /ℓ
36 kv
5 AMPS
α = 1.3
B = 10.5 kG
rf INPUT POWER = 200 W
rf INPUT FREQUENCY = 32 GHz
2.7 dB/cm

FIG. 4

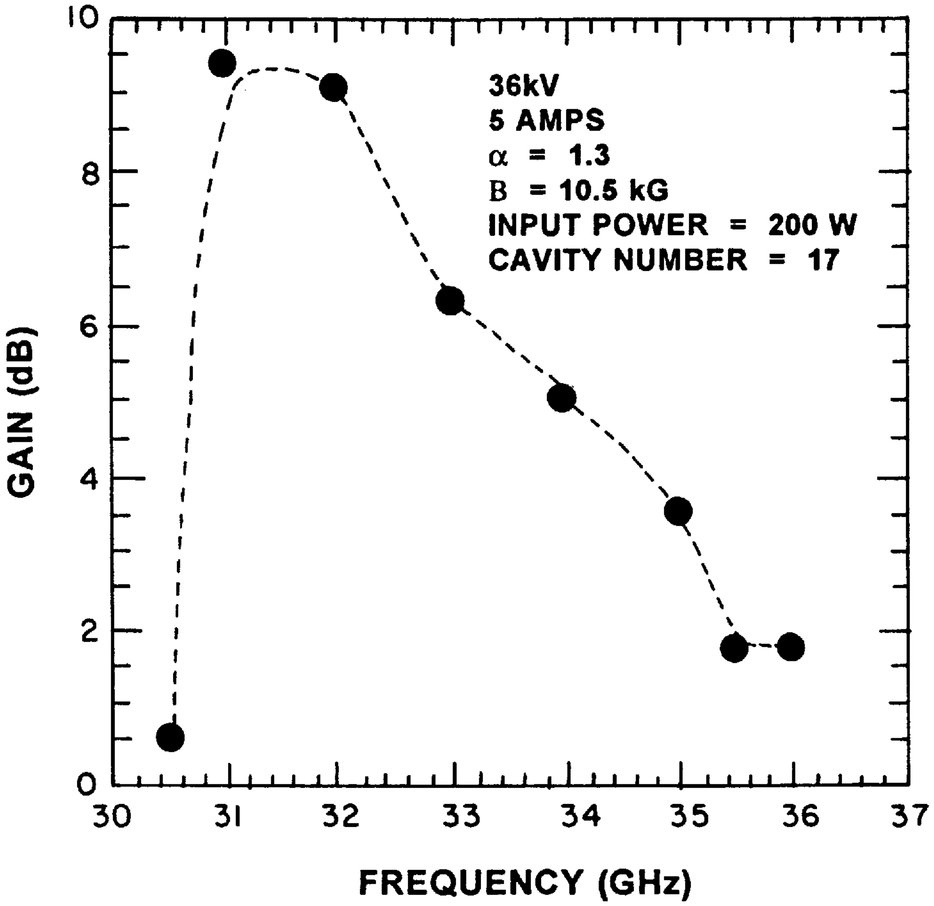

36kV
5 AMPS
α = 1.3
B = 10.5 kG
INPUT POWER = 200 W
CAVITY NUMBER = 17
GAIN (dB)
10
8
6
4
2
0
30
31
32
33
34
35
36
37
FREQUENCY (GHz)

FIG. 5

COUPLED CAVITY GYROTRON-TRAVELING-WAVE-TUBE AMPLIFIER

BACKGROUND OF THE INVENTION

The present invention relates to traveling wave tube amplifiers (TWT Amplifiers) in general and in specific to a coupled cavity gyrotron-traveling-wave-tube amplifier for producing highly efficient, broad band millimeter wave radiation.

Many of today's high-tech military and commercial applications require a high power, broadband radiation source in the millimeter wave frequency range. Military applications for such TWT amplifiers include, but are not limited to, high resolution radar, communications and electronic jamming equipments. Commercial applications include, but are not limited to, equipment for high resolution airborne and shipboard navigation and communication systems, high efficiency satellite communications systems, millimeter-wave material processing, millimeter wave imaging systems and radiation source for laboratory test and measurement to name a few. Light weight, compact design and low cost are also critical factors for practical use and commercial production.

The use of free electron beams, linear and rotating, in vacuum tubes has been successful in producing multi-kilowatt high power, broadband radiation. Tens of kilowatts power in the millimeter wave frequency range with a large bandwidth, operating at a low beam voltage (<60 kV) is more attractive in today's TWT community.

Conventional approaches for achieving broadband rf amplification in the linear beam TWT-amplifiers are the use of a helix circuit supported by dielectric rods, an E-plane bend folded waveguide or the use of a staggered ladder circuits.

Millimeter wave helix circuits are generally too small to handle high peak and average power radiation. In both the ladder circuit and the folded waveguide, since the beam tunnel size is directly related to beam wave interaction impedance, the amount of beam power which can be injected into the circuit is limited by the small beam tunnel size. The radiation electronic efficiency of the linear beam devices in general is not more the 10%.

Until now approaches for attaining broadband rf amplification in the conventional gyro-TWT amplifiers have involved either loading disks, or dielectric material, into the waveguide to slow down the rf phase velocity of the wave, or tapering both the waveguide and the external magnetic field along the axial distance. In general, the gyro-devices are not suitable for high power, broadband millimeter wave radiation sources, due to the complexity of the circuit, the high magnetic field required, and the lengthy circuit.

SUMMARY OF THE INVENTION

Accordingly it is an object of the present invention to provide a coupled cavity gyrotron TWT amplifier which produces efficient, broadband, millimeter wave radiation.

It is also an object of the present invention to provide a coupled cavity gyro-TWT device which allows the natural separation of beam and rf applicable for depressed collector operation.

It is also an object of the present invention to provide a coupled cavity gryo-TWT device which has high power handling capability.

It is also an object of the present invention to provide a coupled cavity gyro-TWT amplifier which features a large beam tunnel for high power beam injection with little distortion of the waveguide field structure.

It is also an object of the present invention to provide a coupled cavity gyro-TWT amplifier which is robust and easy to fabricate.

It is also an object of the present invention to provide a coupled cavity gyro-TWT which offers simplicity of coupling and severing.

It is a further object of the present invention to provide a coupled cavity gyro-TWT device with a compact design.

The present invention comprises an electron gun, a double ridged coupled cavity interaction circuit and a beam collector. In operation the gun injects a gyrating electron beam through a beam tunnel of a side wall of the coupled cavity. When the electron beam phase is synchronized with the rf phase of the transverse electric mode in the coupled cavity circuit, the electron beam is modulated and amplifies the rf input signal through the negative mass instability called electron cyclotron instability. The coupled cavity design of the interaction circuit effctively slows the rf-wave velocity, allowing amplification of the rf- wave over a broad band. This type of broad band microwave energy is highly useful in radar, communications and jamming technology.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a diagram of the basic architecture of the coupled cavity gyrotron traveling wave tube amplifier.

FIG. **2** is a diagram of one section of the coupled cavity circuit.

FIG. **3** is a graph of the dispersion relations (frequency vs. phase shift per cavity) of the coupled cavity circuit.

FIG. **4** is a graph of the gain as a function of axial distance.

FIG. **5** is a graph of the gain as a function of frequency.

DETAILED DESCRIPTION OF THE INVENTION

Referring now to the figures wherein like reference characters indicate like elements throughout the several views, FIG. **1** illustrates a block diagram of the basic architecture of the coupled cavity traveling wave tube amplifier **100**. Electron gun **200** injects a gyrating electron stream into coupled cavity interaction circuit **300** through rf input coupling **250**. An rf-source (not shown), provides rf-energy (rf-wave) which is injected into rf-input guide **210**. The rf-energy propagates through guide **210** an into rf-input coupling **250** from where the rf-energy is also injected into interaction circuit **300**. The rf-energy and the gyrating electronic stream then copropagate through interaction circuit **300**, the gyrating electron stream and the rf-wave interacting as both travel the length of interaction circuit **300**. Interaction circuit is oriented so that the electric field of the rf-wave is perpendicular to the propagation direction of the gyrating electron stream. A magnetic field across the gun **200**, interaction circuit **300**, and couplings **250**, **255**, is produced by magnetic coil module **400** which encircles the system **100**. The magnetic field is used to position the gyrating electron stream to ensure coupling of the gyrating electric stream and the rf-wave over a broad band. When the gyrating electron stream and the rf wave couple, the electron stream's transverse momentum transfers energy to the rf-wave resulting in a net gain in the rf-energy through the phenomena known as electron cyclotron instability. The coupled cavity design of interaction circuit **300** which slows the phase velocity of the rf-wave and the magnetic field which positions the gyrating electron stream provide the necessary coupling between the electron beam velocity and rf-wave's transverse electric field, in order to allow the transverse electric field and the gyrating electric stream to interact over a wide band. The electron stream then passes through rf-output coupling **255** and is collected by depressed beam collector **355**, while the amplified rf-wave passes through rf-output coupling **255** and propagates through rf-output waveguide **260**.

FIG. **2** shows a detailed illustration of interaction circuit **300**. Interaction circuit **300**, features a coupled cavity structure, comprising rectangular cavities **310** which feature ridges **330** which protrude into the cavity **310**. The ridged cavities **340** are connected through coupling slots **350** which may be arranged in a staggered or other configuration but must couple the inner volume of ridged cavities **310** to allow propagation of the rf-wave **600** and gyrating electron stream **500** through interaction circuit **300**. The rectangular cavities **310** which form interaction circuit **300** support a TE_{10} like mode of rf wave **600**, and unlike conventional linear beam coupled cavity devices, is oriented so that the electric field of the TE_{10} like mode **600** is perpendicular to the propagation direction of electron beam **500**. TE wave **600** propagates through alternating rectangular coupling slots **350**, placed in the side wall of cavities **310**. A finite element code HFSS, is used to increase the accuracy of predicting of the wave dispersion characteristics in periodic coupled cavity circuits and allows the structural design to be tailored to maximize bandwidth (*Hewlett Packard High Frequency Structure Simulator Reference,* Santa Rosa, Calif. (1992)). The cavity resonant frequencies are found in a closed cavity structure to predict the dispersion characteristics of each coupled cavity structure. Each peak represents a phase shift per cavity which may be expressed as:

$$k_{\parallel} l = \frac{p\pi}{(N_c + 1)} \tag{1}$$

where $k_{\parallel}$ is the axial propagation constant, p=1, 2, 3, . . . , N_c, and N_c is the number of cavity **310** forming interaction circuit **300** and l is the distance defined by the combined length of the structure defined by cavity **310** and coupling slot **350**.

When a beam cyclotron mode, is tuned to be synchronized with the rf-wave dispersion, the electron cyclotron instability will take place. This relationship may be expressed as follows:

$$\omega = \frac{\Omega_c}{\gamma} + k_{\parallel} v_{\parallel} \tag{2}$$

for the gyrating electron stream where Ω_c is the magnetic field frequency, γ is the relativistic factor, $k_{\parallel}$ is the axial propagation constant, and $v_{\parallel}$ is the beam axial velocity. The rf-wave dispersion may be expressed as:

$$\omega^2 = \omega_{co}^2 \leftrightarrows (k_{\parallel} c)^2 \tag{3}$$

where ω_{co} is the lower rf-cutoff frequency and c is the speed of light in a vacuum.

Referring to FIG. **3** which shows a graph of the dispersion relation of an example coupled cavity circuit constructed in accordance with FIG. **2**. The code predicted wave dispersions as plotted are $a_o/a=0.3$, $b_o/a=0.5$, b/a=1.6, l/a=1.2, where a=0.254 cm. The first stop-band in the periodic structure illustrated in FIG. **3** is found at ~37 GHz, where the rf-phase shift per cavity becomes Y. When gyrating electron beam **500**, is tuned to be synchronized with the rf-wave dispersion in accordance with the parameters set fourth in expression **2**, the electron cyclotron instability occurs resulting in a gain realized by rf-wave **600**. The reader should note that in FIG. **3**, the cyclotron beam mode **550** is nearly tangential to the rf-wave dispersion **650** over the bandwidth of 20% indicating electron cyclotron instability will occur over that bandwidth thus allowing wideband rf amplification.

Again referring to FIG. **2** a detailed view of rf input coupling **250** is illustrated. Input coupling **250** comprises wave guide **210** and electron beam tunnel **252**. Wave guide **210** injects the rf wave into coupled cavity **310** which defines the front end of interaction circuit **300**. Electron beam tunnel **252** is coupled to said coupled cavity **310** with the beam tunnel hole located on the wall of coupled cavity **310**. In a preferred embodiment, electron beam tunnel **252** is located at the point on the wall with the minimum electric field. By locating the electron beam tunnel **252** at the point on cavity **310** with the least electric field the beam tunnel sized does not perturb or distort the rf wave. This structural feature allows the size of the beam tunnel to be increased enabling one to use a higher power gyrating beam without negatively affecting the rf wave, thus allowing the coupled cavity structure to have a higher power handling capabilities than traditional TWT structures.

The coupled cavity structure of interaction circuit **300** also allows for the natural separation of the rf wave **600** and gyrating electron stream **500** at rf output coupling **255** since the rf wave **600**, unlike the gyrating electron stream **500**, will be deflected by coupling slots **350** propagating along the path defined by the coupled cavity circuit **300**. The gyrating electron stream **500** will, in general, propagate straight through the coupled cavity circuit **300** predominately along direction defined by the beam tunnel **252**, thus allowing rf-wave **600** to be separated from the electron stream **500** by rf-output waveguide **260**.

As rf wave **600** and gyrating beam **500** at times copropagate through interaction circuit **300**, the interaction of rf-wave **600** and electron beam **500** cause rf-wave **600** to experience gain through electron cyclotron instability.

The SOS code, a fully relativistic three dimensional particle-in-cell (PIC) code, is used to examine beam-wave interaction of the coupled cavity gyro-TWT. Referring now to FIG. **4**, which shows a graph of amplifier gain as a function of axial distance, the radiation power is measured in the coupling slot between cavities **350**. In practice rf input and output couplings **250, 255** are optimized, by inserting a capacitive iris window between rectangular waveguide **210** and the first cavity, in order to match wave impedance. In the graph labeled as FIG. **4**, the rf input frequency is 32 GHz, with a rf-drive power of 200 W. A transverse to parallel velocity ratio, α, of 1.3, a grazing magnetic field of 10.5 kG, and a cold gyrating beam of 36 kV at **5**A are assumed. An rf launching loss is clearly seen near the third cavity and the rf power linearly increases along the axial distance. The axial growth rate of ~2.7 dB/cm is calculated, which is comparable to or higher than that of a conventional gyro-TWT device. The maximum gain at the fifteenth cavity is 11 dB, corresponding to the radiation power of 2.5 kW and an efficiency of 1.4%. Note that, as shown in FIG. **4**, there is no indication of amplifier saturation. Higher gain and efficiency are realized when the number of cavity **310** increases. Single mode amplification is confirmed from frequency measurements and transverse field profiles.

The device is simulated for different input frequencies in order to obtain the instantaneous bandwidth of the device, where all the input parameters are kept same a before except the drive frequency. Referring now to FIG. **5**, which is a graph of the amplifier gain as a function of rf freqency, the rf gain is high near the cutoff frequency and it falls of very rapidly as the drive frequency is far from the cutoff frequency. Slow time scale non-linear simulations on the folded waveguide gyro-TWT's reveal similar roll off. In general, the amplifier gain at the circuit length below the saturation length significantly varies in frequency. Therefore, the hot bandwidth at the saturated circuit length of the coupled cavity gyro-TWT is broader than that illustrated in FIG. **5**.

The use of dual coupling slots between cavities allows the coupled cavity gyroTWT to operate over an even wider bandwidth. This wider bandwidth is attained by placing two coupling slots between cavities rather than a single slot. The dual slotted design allows rf- wave to propagate through the interaction circuit at a slightly higher group velocity. The higher rf-group velocity allows coupling of the rf-wave and the electron beam over a greater frequency range thus allowing amplification over a broader band. The reader should note that in a dual slotted configuration a higher beam voltage is necessary for the grazing condition to exist over the wide frequency range, because the rf-wave phase velocity of the wave propagating through the dual slotted circuit increases compared with that of the circuit. with single coupling slots.

The interaction circuit and couplings are preferably constructed of oxygen free high conductivity copper, however other metals and/or alloys are suitable.

This new type of transverse coupled cavity circuits, employed with the gyrating electron beam produces higher power broadband millimeter wave radiation. The non-linear PIC code simulation predicts an axial growth rate of 2.7 dB/cm and an unsaturated gain of 9–11 dB. By increasing

the number of cavity, it is expected to saturate the device with higher gain and efficiency.

The foregoing descriptions of the embodiments are intended to be illustrative and not limiting. The present invention is applicable to any system which requires efficient amplification of electromagnetic waves. Obviously, numerous modifications and variations of the present invention are possible in light of the above teachings without departing from the spirit of scope of the present invention.

We claim:

1. A Gyrotron Traveling Wave Tube Amplifier comprising:

a coupled cavity circuit having a front and a back;

means for coupling an rf signal and an electron beam to said coupled cavity circuit, said coupling means attached to said front of said coupled cavity circuit, said coupling means recieving said rf signal and said electron beam said rf signal and said electron beam being coupled as said electron beam and rf signal copropagate therethrough;

means to decouple said rf signal and said electron beam, said decoupling means attached to said back of said coupled cavity circuit, said decoupling means recieving said coupled electron beam and said rf signal from said coupled cavity circuit and decoupling said rf signal from said electron beam causing said rf signal to propagate therethrough;

wherein said rf signal and electron beam interact as they propagate through said coupled cavity circuit resulting in the amplification of said rf signal.

* * * * *