Some broadbanding aspects in slow-wave and fast-wave travelling-wave tubes

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“For whatever may be said about the importance of aiming at depth rather than width in our studies, and however strong the demand of the present age may be for specialists, there will be work, not only for those who build up particular sciences and write monographs on them, but for those who open up such communications between the different groups of builders as will facilitate a healthy interaction between them.”

— James Clerk Maxwell

My presentation of two lectures is dedicated to
Professor Dr. Dr. h. c. Manfred Thumm
known as “Gyrotron Man” in India

I am thankful to Professor Dr. John Jelonnek, the Institute Director, and all the teachers, scientists, and students of the Institute for giving me this prestigious ‘platform of learning’ for interacting with and learning from you

What man 'learns' is really what he discovers by taking the cover off his own soul, which is a mine of infinite knowledge

— **Swami Vivekananda**

Some broadbanding aspects in slow-wave and fast-wave travelling-wave tubes

Some broadbanding aspects in

- **Slow-wave travelling-wave tubes**

  (i) Conventional TWT: Cerenkov radiation, longitudinal space-charge-wave interaction, linear beam device

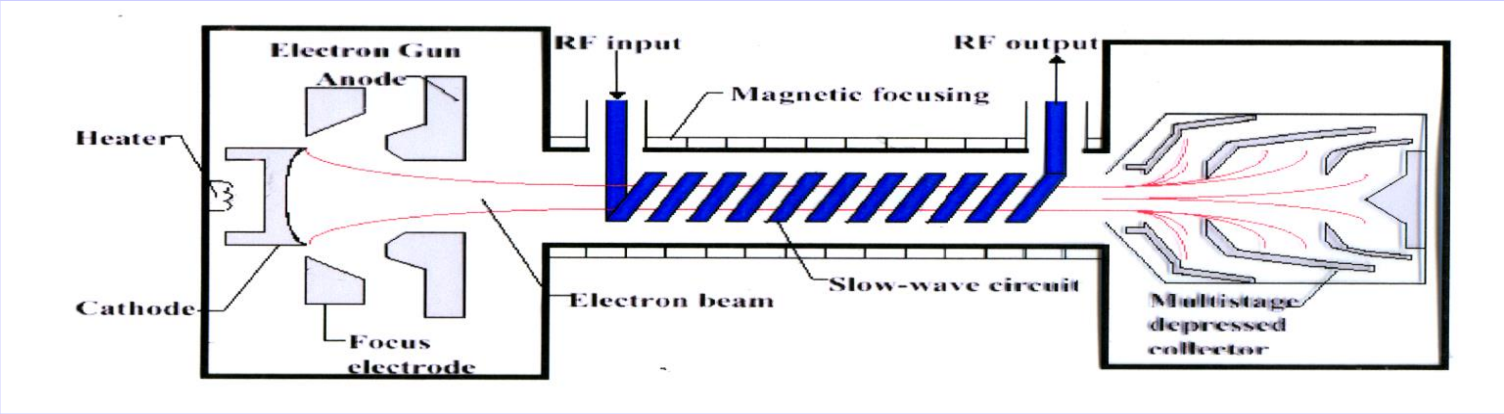
  (ii) Slow-wave cyclotron amplifier (SWCA): Bremsstrahlung radiation, Weibel instability based, cyclotron-mode interaction, gyro-device

- **Fast-wave travelling-wave tubes**

  (i) Gyro-TWT: Bremsstrahlung radiation, CRM instability based, cyclotron-mode interaction, gyro-device

  (ii) Cyclotron auto-resonance maser (CARM): Bremsstrahlung radiation, both CRM instability and Weibel instability based, cyclotron-mode interaction, gyro-device

Travelling-wave tube (TWT) is a slow-wave device



- ❑ TWT is also known as Kompfner tube named after the inventor, though **Lindenblad** invented the device earlier than Kompfner
- ❑ Slow-wave structure is a periodic structure, typically, helical
- ❑ Electron beam is non-periodic and is formed, typically, by Pierce gun
- ❑ TWT is a Cerenkov device

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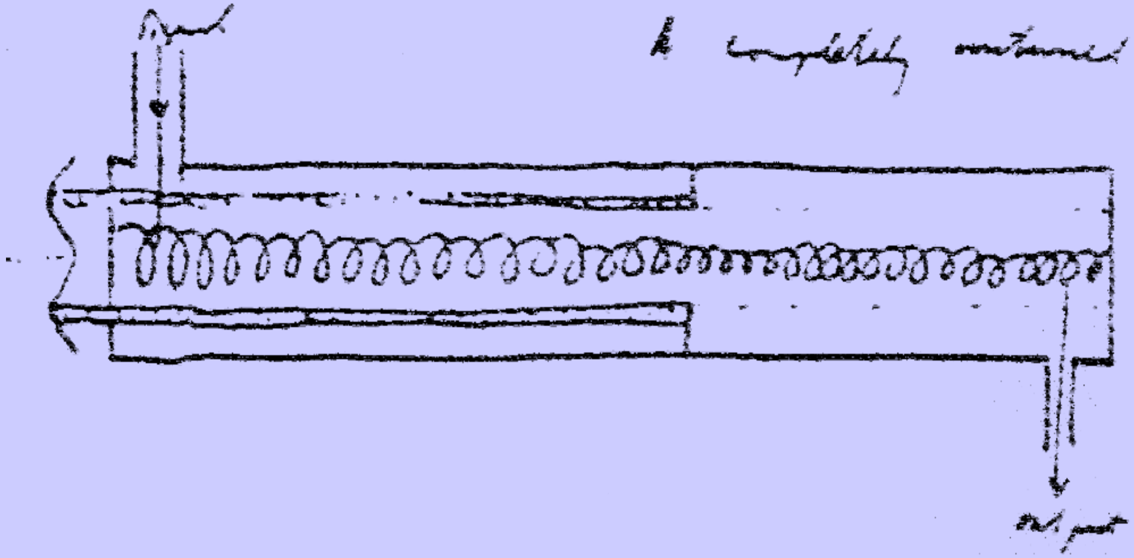
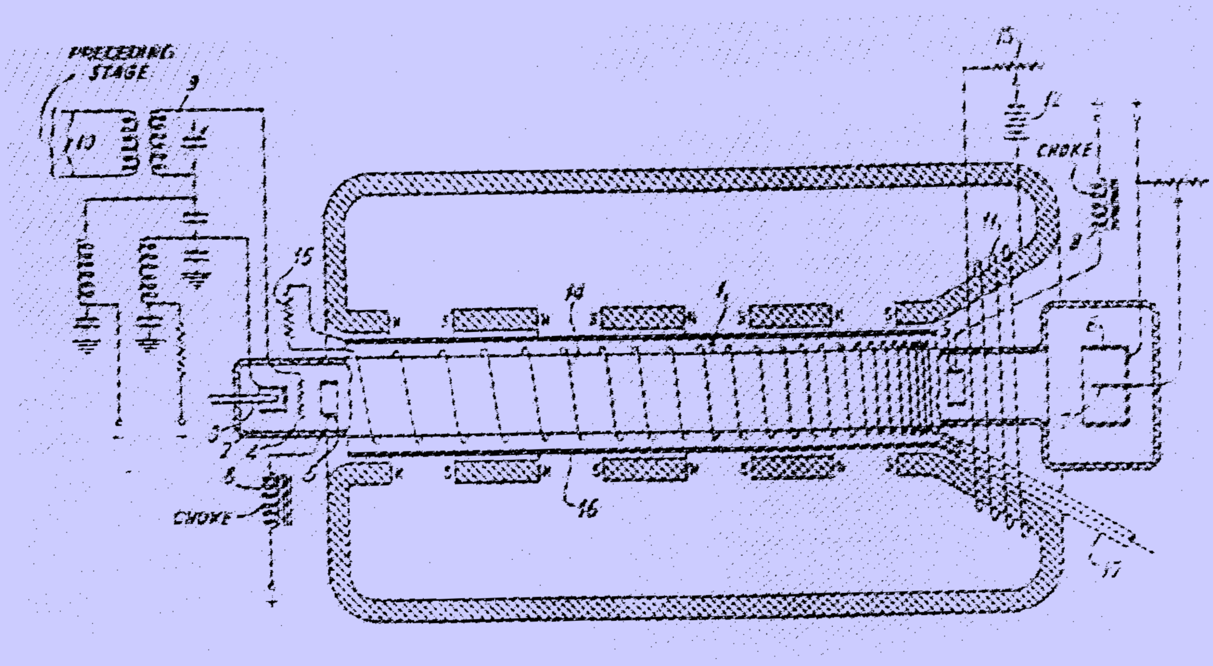
A completely untuned amplifier!



Would it work? Are the electrons in the output region not moving <u>parallel</u> to the equipotential surfaces of the line? If so, then there can be no amplified shot noise

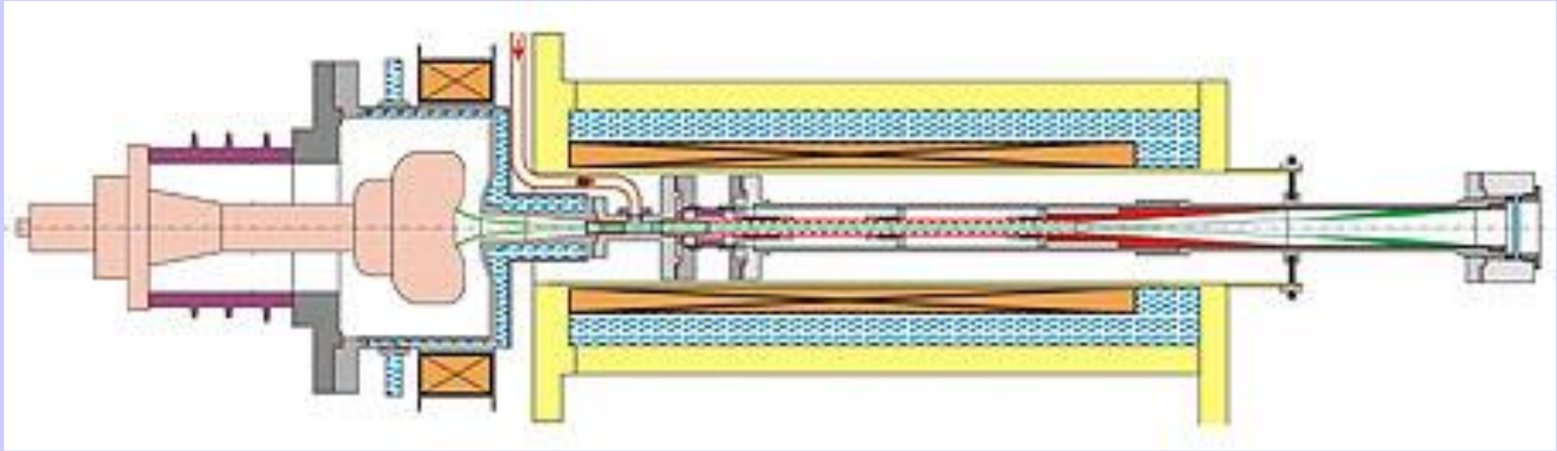
Sketch of the travelling-wave tube from R. Kompfner's note book



N. E. Lindenblad's travelling-wave tube amplification at 390 MHz over a 30 MHz band (U. S. Patent 2,300,052, filed on May 4, 1940 issued on October 27, 1942)

Helix wound around the outside the glass envelope. Signal applied to the grid of the electron gun (also applied to the helix in other experiments). Series of permanent magnets (non-periodic). Pitch tapered for velocity re-synchronization

Gyro-TWT is a fast-wave device



http://www.insight-product.com/Gyro-TWTv1.html

- Interaction structure is usually non-periodic, typically, a hollow-pipe waveguide
- Electron beam is periodic and is formed, typically, by magnetic injection gun
- Gyro-TWT is a bremsstrahlung device

Millimetre-wave consideration in conventional microwave tubes

- Reduction of structure size
- Reduction of beam radius
- Larger magnetic field for beam confinement for
  - ✓ Smaller beam radius
  - Larger beam current
  - Smaller beam voltage
  - Larger beam perveance

  Heavy solenoids or advanced magnetic materials are required
- Larger cathode emission densities entailing the risk of cathode life

Higher beam voltage can increase the beam power and also reduce the required magnetic field but is associated with a reduced beam pervenace making it difficult to contain thermal electrons, and has limitation arising from backward-wave oscillation in wideband helix TWTs.

Lower beam current can reduce magnetic field but it reduces the beam power and is associated with a reduced beam pervenace making it difficult to contain thermal electrons.

Tight tolerances required for tiny interaction structures

Thermal management becomes difficult

- Pressure fitting, instead of more effective than brazed-helix technology that would be difficult to implement
- Special thermally conducting materials, like Type II-A diamond, for dielectric helix-supports
- Plasma spraying of beryllia on the surface of the helix

COMMERCIALLY AVAILABLE MILLIMETER-WAVE TWT'S

Communication

Type	Frequency Range	Power Output	Duty Cycle	Saturated Gain
814H	91.0-96.0 GH	0.10 kW	CW	25 dB

Space

Type	Frequency Range	Power Output	Duty Cycle	Saturated Gain
944H	42.0-42.5 GHz	100 W	CW	44 dB

Pulsed Radar And ECM

Type	Frequency Range	Power Output	Duty Cycle	Saturated Gain
982H	93.0-95.0 GHz	12kW	0.5	50dB

CW Radar and ECM

Type	Frequency Range	Power Output	Duty Cycle	Saturated Gain
920H	59.7-60.3 GHz	0.05 kW	CW	35 dB

Millimetre-wave technology gap

- ❑ Difficulty of operating conventional microwave tubes at higher frequencies arising from interaction structures becoming tiny, etc.

- ❑ Difficulty of operating quantum mechanical devices like the laser in view of

  - ♣ Decrease of quantum energy at lower frequencies according to the relation $E = h\nu$
  - ♣ Difficulty to retain population inversion at lower frequencies

Fast-wave tubes come to rescue!

Size of interaction structures

Slow-wave structure:
Helix (typically)

$$\gamma a = 1.6$$

$$a = \frac{1.6\lambda}{2\pi \times 10} \sim 0.025\ \lambda$$

Axial phase propagation constant β

$$\gamma = (\beta^2 - k^2)^{1/2} \approx \beta = \frac{\omega}{v_p}$$

(under slow-wave assumption)

Fast-wave structure:
Cylindrical waveguide
(typically)

TE_{01} mode

$$k_c\, a = 3.832$$

$$a \sim 0.61\ \lambda$$

TE_{02} mode

$$k_c\, a = 7.016$$

$$a \sim 1.12\ \lambda$$

TE_{01} waveguide radius is (0.61λ/0.025 λ)~25 times helix radius

TE_{02} waveguide radius is (1.12λ/0.025 λ)~45 times helix radius

The mechanism of interaction of a slow-wave device such as the slow-wave TWT is based on the property of an electron beam to support
space-charge waves

The mechanism of interaction of a fast-wave device such as the fast-wave gyro-TWT is based on the property of an electron beam to support
cyclotron waves

Space-charge and cyclotron waves

Space-charge waves

$J = \rho v$ (Current density equation)

$\frac{\partial J_1}{\partial z} + \frac{\partial \rho_1}{\partial t} = 0$ (Continuity equation)

$\frac{dv_1}{dt} = \frac{e}{m} E_s = \eta E_s$ (Force equation)

$\frac{\partial E_s}{\partial z} = \frac{\rho_1}{\varepsilon_0}$ (Poisson's equation)

RF quantities vary as $\exp j(\omega t - \beta z)$

$\Downarrow$

$$\beta = \beta_e \mp \beta_p$$

$$\boxed{\omega - \beta v_0 \mp \omega_p = 0}$$

$$v_p = \frac{\omega}{\omega \mp \omega_p} v_0$$

$$\beta = \frac{\omega}{v_p}$$

$$\beta_e = \frac{\omega}{v_0}$$

$$\beta_p = \frac{\omega_p}{v_0}$$

$$\omega_p = \left(\frac{|\eta||\rho_0|}{\varepsilon_0}\right)^{1/2}$$

Cyclotron waves

Force equations along x and y for a magnetic field along z

$$m\frac{dv_{1x}}{dt} = e(\vec{v} \times \vec{B})_x$$

$$m\frac{dv_{1y}}{dt} = e(\vec{v} \times \vec{B})_y$$

RF quantities vary as $\exp j(\omega t - \beta z)$

$$\boxed{\omega - \beta v_0 \mp \omega_c = 0}$$

$$\omega_c = -\eta B = |\eta| B$$

Upper sign for the fast wave and lower sign for the slow wave

Space-charge waves

$\boxed{J = \rho v}$ $J = J_0 + J_1$ $\rho = \rho_0 + \rho_1$ $v = v_0 + v_1$

$$J_0 = \rho_0 v_0$$

$$J_1 = \rho_0 v_1 + v_0 \rho_1$$

$$\frac{\partial J_1}{\partial z} = \rho_0 \frac{\partial v_1}{\partial z} + v_0 \frac{\partial \rho_1}{\partial z}$$

$$\boxed{\frac{\partial J_1}{\partial z} + \frac{\partial \rho_1}{\partial t} = 0}$$

$$-\frac{\partial \rho_1}{\partial t} = \rho_0 \frac{\partial v_1}{\partial z} + v_0 \frac{\partial \rho_1}{\partial z}$$

$$\frac{\partial \rho_1}{\partial t} + v_0 \frac{\partial \rho_1}{\partial z} = -\rho_0 \frac{\partial v_1}{\partial z}$$

$$D\rho_1 = -\rho_0 \frac{\partial v_1}{\partial z}$$

$$D = \frac{\partial}{\partial t} + v_0 \frac{\partial}{\partial z}$$

$$\boxed{\frac{dv_1}{dt} = \frac{e}{m} E_s = \eta E_s}$$

$$\frac{dv_1}{dt} = \frac{\partial v_1}{\partial t} + \frac{dz}{dt}\frac{\partial v_1}{\partial z} = \frac{\partial v_1}{\partial t} + v \frac{\partial v_1}{\partial z} = \frac{\partial v_1}{\partial t} + (v_0 + v_1)\frac{\partial v_1}{\partial z} = \frac{\partial v_1}{\partial t} + v_0 \frac{\partial v_1}{\partial z}$$

$$\frac{\partial v_1}{\partial t} + v_0 \frac{\partial v_1}{\partial z} = \eta E_s$$

$$Dv_1 = \eta E_s$$

$$[\frac{d}{dt} = \frac{\partial}{\partial t} + v_0 \frac{\partial}{\partial z} = D]$$

$$D\rho_1 = -\rho_0 \frac{\partial v_1}{\partial z}$$

$$Dv_1 = \eta E_s$$

$$D^2\rho_1 = -\rho_0 D\frac{\partial v_1}{\partial z} = -\rho_0 \frac{\partial}{\partial z} Dv_1 = -\rho_0 \frac{\partial}{\partial z}\eta E_s = -\eta\rho_0 \frac{\partial E_s}{\partial z}$$

$$\left[\frac{d}{dt} = \frac{\partial}{\partial t} + v_0 \frac{\partial}{\partial z} = D\right]$$

$$D^2\rho_1 = -\eta\rho_0 \frac{\partial E_s}{\partial z}$$

$$\frac{\partial E_s}{\partial z} = \frac{\rho_1}{\varepsilon_0}$$

RF quantities vary as $\exp j(\omega t - \beta z)$

$$D = \frac{\partial}{\partial t} + v_0 \frac{\partial}{\partial z} = j\omega - j\beta v_0 = j(\omega - \beta v_0)$$

$$D^2\rho_1 = -\eta\rho_0 \frac{\rho_1}{\varepsilon_0} = \frac{-\eta\rho_0}{\varepsilon_0}\rho_1 = \frac{-|\eta||\rho_0|}{\varepsilon_0}\rho_1 = -\omega_p{}^2\rho_1$$

$$D^2 = -\omega_p{}^2$$

$$\left[\frac{|\eta||\rho_0|}{\varepsilon_0} = \omega_p{}^2\right]$$

$$D = \pm j\omega_p$$

$$\omega - \beta v_0 = \pm\omega_p$$

$$\omega - \beta v_0 \mp \omega_p = 0$$

Dispersion relation for space-charge waves

Cyclotron waves

$$m\frac{dv_{1x}}{dt} = e(\vec{v}\times\vec{B})_x \qquad m\frac{dv_{1y}}{dt} = e(\vec{v}\times\vec{B})_y \qquad \vec{v}\times\vec{B} = \begin{vmatrix} \vec{a}_x & \vec{a}_y & \vec{a}_z \\ v_x & v_y & v_z \\ B_x & B_y & B_z \end{vmatrix}$$

$$B_x = 0,\; B_y = 0,\; B_z = B$$

$$\frac{dv_{1x}}{dt} = \frac{e}{m}(\vec{v}\times\vec{B})_x = \eta(\vec{v}\times\vec{B})_x$$

$$[\frac{d}{dt} = \frac{\partial}{\partial t} + v_0\frac{\partial}{\partial z} = D]$$

RF quantities vary as $\exp j(\omega t - \beta z)$

$$Dv_{1x} == \eta(\vec{v}\times\vec{B})_x \qquad Dv_{1y} == \eta(\vec{v}\times\vec{B})_y$$

$$Dv_{1x} = \eta B v_y = -\omega_c v_y \qquad [\omega_c = -\eta B] \qquad Dv_{1y} = -\eta B v_x = \omega_c v_{1x}$$

$$D^2 v_{1x} = -\omega_c D v_{1y} = -\omega_c(\omega_c v_{1x}) = -\omega_c{}^2 v_{1x}$$

$$D^2 = -\omega_c{}^2 \qquad \omega - \beta v_0 \mp \omega_c = 0$$

Dispersion relation for cyclotron waves

Space-charge and cyclotron waves

Space-charge waves

$$\omega - \beta v_0 \mp \omega_p = 0$$

$$\beta = \beta_e \mp \beta_p$$

$$\beta = \frac{\omega}{v_p} = \frac{\omega}{v_0} \mp \frac{\omega_p}{v_0} = \frac{\omega \mp \omega_p}{v_0}$$

$$v_p = \frac{\omega}{\beta} = \frac{\omega}{\omega \mp \omega_p} v_0$$

Cyclotron waves

$$\omega - \beta v_0 \mp \omega_c = 0$$

$$\beta = \beta_e \mp \beta_c$$

$$\beta = \frac{\omega}{v_p} = \frac{\omega}{v_0} \mp \frac{\omega_c}{v_0} = \frac{\omega \mp \omega_c}{v_0}$$

$$v_p = \frac{\omega}{\omega \mp \omega_c} v_0$$

Upper sign for the fast wave and lower sign for the slow wave

$$\beta_e = \frac{\omega}{v_0}; \beta_p = \frac{\omega_p}{v_0}; \omega_p = \left(\frac{|\eta|\rho_0}{\varepsilon_0}\right)^{1/2}$$

$$\beta_e = \frac{\omega}{v_0}; \beta_c = \frac{\omega_c}{v_0}; \omega_c = |\eta| B$$

Amplification of space-charge waves

- An electron beam of uniform diameter in a resistive-wall cylindrical waveguide

- An electron beam in a rippled-wall (varying diameter) conducting-wall cylindrical waveguide

- An electron beam of varying diameter in a conducting-wall cylindrical waveguide

- An electron beam mixed with another beam of a slightly different DC electron beam velocity (two-stream amplifier)

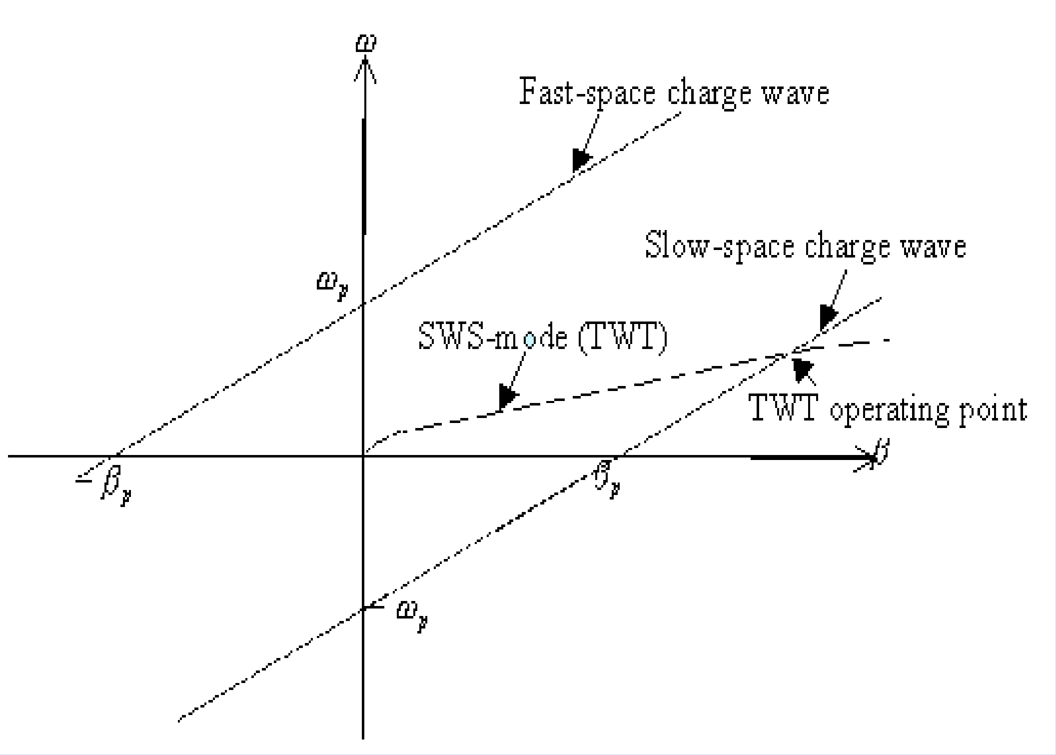
- An electron beam penetrating through a plasma (beam-plasma amplifier)

- An electron beam interacting with RF waves supported by a slow-wave structure (TWT)

Intersection between slow space-charge and circuit waves

$$\omega - \beta v_0 \mp \omega_p = 0$$

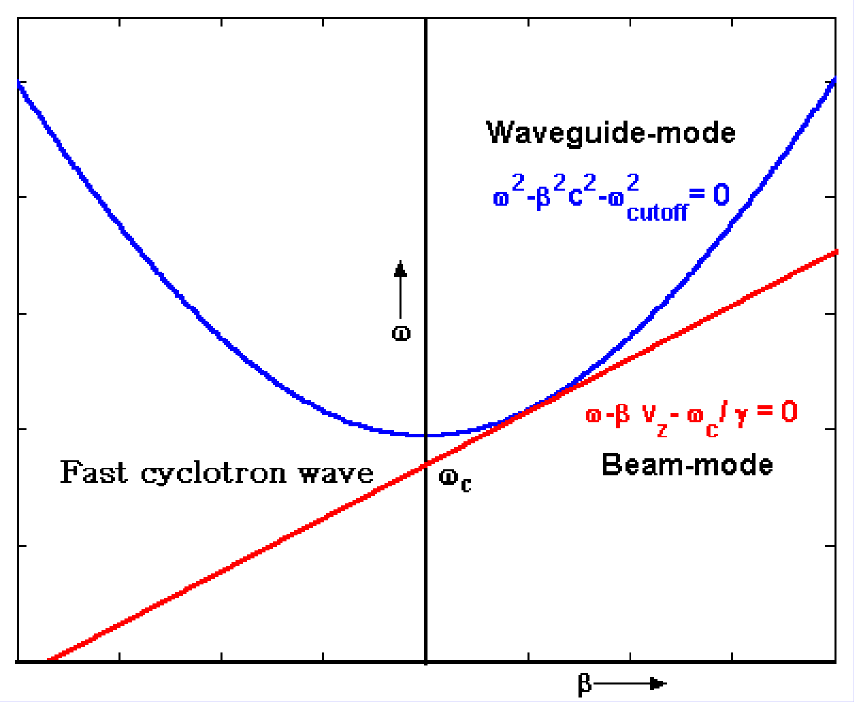
Upper sign for the fast wave and lower sign for the slow wave

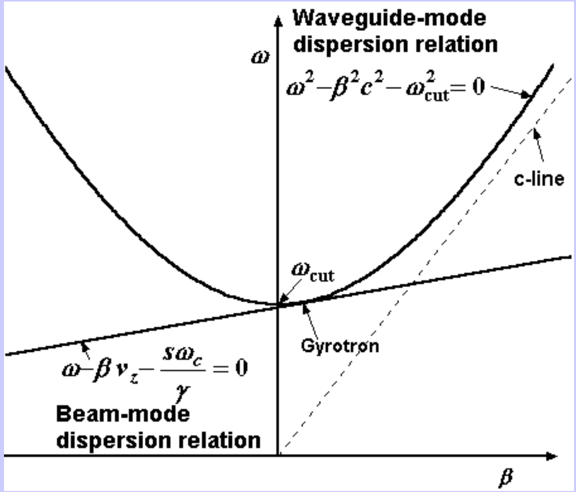


Intersection between fast-cyclotron and circuit waves

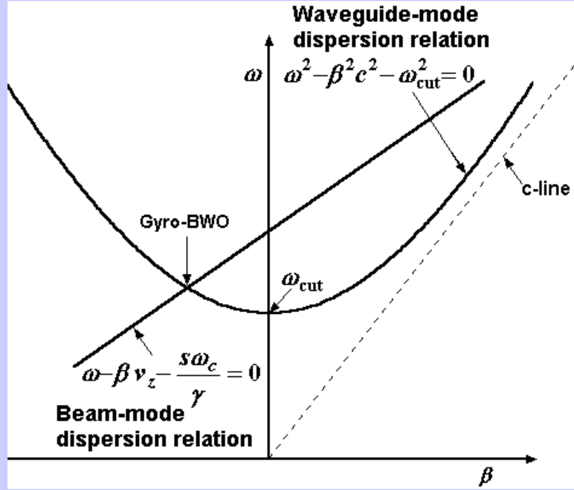
$$\omega - \beta v_0 \mp \omega_c = 0$$

Upper sign for the fast wave and lower sign for the slow wave

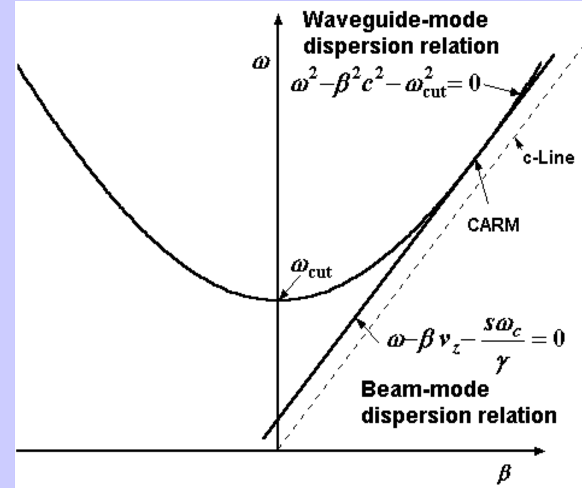




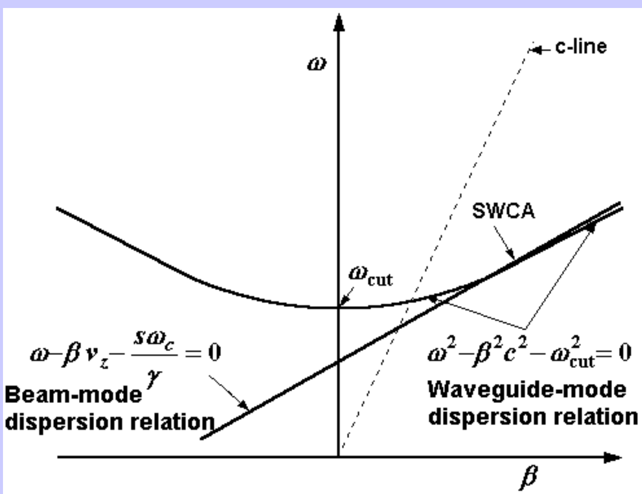
Gyrotron



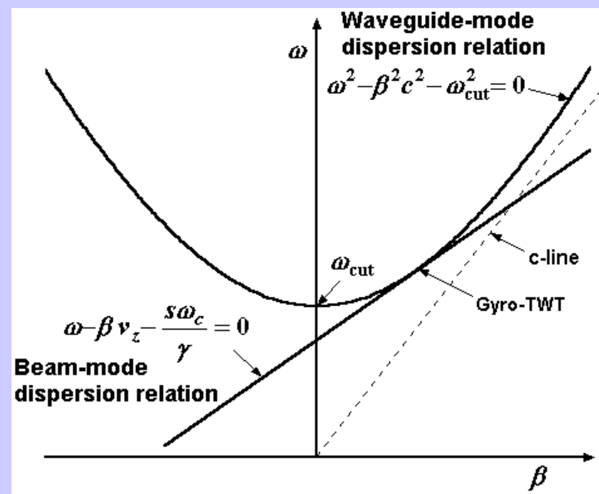
Gyro-BWO



CARM



SWCA



Gyro-TWT

Plots of beam-mode and waveguide-mode dispersion characteristics showing the operating point as the intersection between these plots (*Prepared by Vishal Kesari <vishal_kesari@rediffmail.com>*)

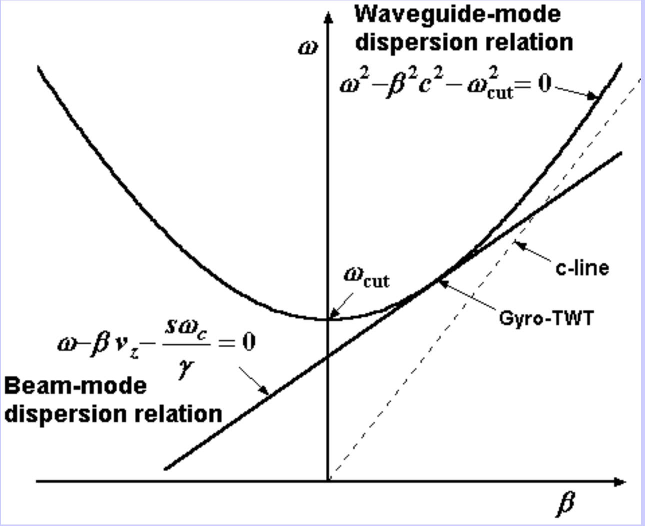
Conditions for grazing intersection or coalescence between the beam-mode and waveguide-mode dispersion characteristics

Dispersion relation for cyclotron wave

$$\omega - \beta v_0 \mp \omega_c = 0$$ (upper sign for the fast cyclotron wave)

Dispersion relation for fast cyclotron wave:

$$\omega - \beta v_0 - \omega_c = 0 \qquad (v_0 = v_z)$$



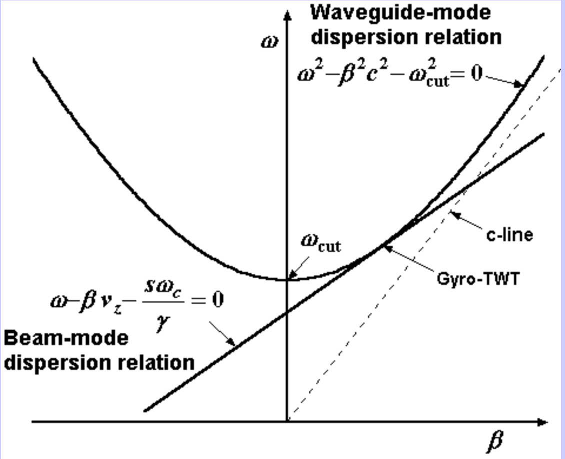
Beam-mode dispersion relation: $\omega - \beta v_z - \dfrac{s\omega_c}{\gamma} = 0$

(for beam harmonic *s* operation) $(v_0 = v_z)$

$$\gamma = \left(1 - \frac{v_z^{\,2} + v_t^{\,2}}{c^2}\right)^{-1/2} \qquad \gamma = 1 + \frac{|e|V_0}{mc^2}$$

ω_c absorbs the relativistic factor γ if it does not appear in the expression

Beam-mode dispersion relation: $\omega - \beta v_z - \dfrac{s\omega_c}{\gamma} = 0$ $\qquad [\omega_c = \dfrac{|e|B}{m}]$



Waveguide-mode dispersion relation: $\omega^2 - \beta^2 c^2 - \omega_{cut}^2 = 0$

$$2\omega \frac{\partial \omega}{\partial \beta} - 2\beta c^2 = 0 \;\Rightarrow\; \frac{\partial \omega}{\partial \beta} = \frac{\beta c^2}{\omega} \quad \Rightarrow \quad v_g = \frac{\partial \omega}{\partial \beta} = \frac{\beta c^2}{\omega}$$

Grazing intersection: $v_z = v_g \;\Rightarrow\; v_z = \dfrac{\beta c^2}{\omega}$

From $\omega - \beta v_z - \dfrac{s\omega_c}{\gamma} = 0$ and $v_z = \dfrac{\beta c^2}{\omega} \;\Rightarrow\; \omega = \dfrac{s\omega_c}{\gamma}\gamma_z^{\,2}$ $\quad [\gamma_z = (1 - \dfrac{v_z^{\,2}}{c^2})^{-1/2}]$

From $\omega^2 - \beta^2 c^2 - \omega_{cut}^2 = 0$ and $v_z = \dfrac{\beta c^2}{\omega} \;\Rightarrow\; \omega = \omega_{cut}\gamma_z$

$$\left.\begin{aligned} &\omega = \frac{s\omega_c}{\gamma}\gamma_z^{\,2} = \omega_{cut}\gamma_z \\ &\omega_c = \frac{|e|B}{m} \end{aligned}\right] \Rightarrow$$

Grazing magnetic flux density $\boxed{B = \dfrac{\gamma}{\gamma_z}\dfrac{m}{|e|}\dfrac{1}{s}\omega_{cut}}$

Features of conventional TWT and gyro-TWT

Conventional TWT

- Cerenkov radiation type
- Magnetic field for beam confinement
- Larger magnetic field at higher frequencies for beam confinement
- Conversion of axial beam kinetic energy
- Axial non-relativistic electron bunching
- Near-synchronism between DC beam velocity and circuit phase velocity

Gyro-TWT

- Bremsstrahlung radiation type
- Magnetic field for interaction
- Larger magnetic field at higher frequencies for cyclotron resonance
- Conversion of azimuthal beam kinetic energy
- Azimuthal relativistic electron bunching
- Near-synchronism between wave frequency and cyclotron frequency

(*Continued*)

Conventional TWT	**Gyro-TWT**
Electron beam velocity to be slightly greater than RF phase velocity	Wave frequency to be slightly greater than cyclotron frequency
Slow space-charge wave on electron beam to couple to forward circuit wave	Fast cyclotron wave on electron beam to couple to forward waveguide mode
Space-charge-limited operation	Temperature-limited operation
Pierce gun	MIG
Smaller structure sizes at higher frequencies	Relatively larger structure sizes at higher frequencies
BWO absolute instability above the pi-point frequency	BWO absolute instability above a threshold current that depends sensitively on the applied magnetic field

Dispersion relation of a conventional TWT

$$(\beta_0^{\,2} - \beta^2)(\beta_p^{\,2} - (\beta_e - \beta)^2) = -2\beta_e^{\,4} C^3$$

$$C^3 = \frac{KI_0}{4V_0}$$

For weak coupling, the right hand side of the dispersion relation is zero.

$\beta = \pm\beta_0$ **(Cold circuit forward and backward propagation constants)**

$\beta = \beta_e \mp \beta_p$ **(Propagation constants of space-charge waves)**

Dispersion relation of a gyro-TWT

$$(k_0{}^2-\beta^2-k_t{}^2)(\omega-\beta v_z-\frac{s\omega_c}{\gamma})^2 == \frac{-\mu_0|e|^2 N_0\eta_t{}^2 H_{m,-s}(\omega^2-\beta^2c^2)}{\gamma m\pi K_{mn}a^2}$$

$$K_{mn}=(1-\frac{m^2}{k_t{}^2a^2})J_m^2\{k_ta\} \qquad H_{m,-s}=J_{s-m}^2\{k_tr_c\}J_s'^2\{k_tr_L\}$$

r_c, r_L : hollow beam radius, Larmor radius

N_0 : no. of electrons per unit length

$I_0 = N_0|e|\, v_z$

$\eta_t = \frac{v_t}{c}$

m: waveguide angular harmonic number
s: beam harmonic mode number

For weak coupling, the right hand side of the dispersion relation is zero, giving

$k_0{}^2-\beta^2-k_t{}^2=0$ **(Cold waveguide-mode dispersion relation)**

$\omega-\beta v_z-\frac{s\omega_c}{\gamma}=0$ **(Dispersion relation for fast Cyclotron wave)**

$\omega-\beta v_0 \mp \omega_c = 0$ taking the upper sign, and interpreting $v_z = v_0$ and $s=1$

Pierce-type gain expression $G = A + BCN$

For the beam-wave coupled system, RF quantities vary as $\exp\ j(\omega t - \Gamma z)$

<u>Conventional TWT</u>

$$-\Gamma = -j\beta_e + \beta_e C\delta$$

$$\beta_e = \frac{\omega}{v_0}$$

$$\delta^2(\delta + jb) = -j$$

β_{mn} : TE_{mn} waveguide-mode propagation constant

Cubic dispersion relation

$$\delta = x + jy$$

$$\delta_1 = x_1 + jy_1$$

Solution with the positive real part

<u>Gyro-TWT</u>

$$-\Gamma = -j\beta_{mn} + \beta_e C\delta$$

$$\beta_e = \frac{\omega - s\omega_c/\gamma}{v_z}$$

$$\delta(\delta + jb)^2 = j$$

Conventional TWT

$$b = \frac{\beta_0 - \beta_e}{\beta_e C}$$

$$N = \frac{\beta_e l}{2\pi}$$

$$B = 40\pi(\log_{10} e)(x_1) = 54.6 x_1$$

$$K = \frac{|E|^2}{2\beta^2 P}$$

$$G = A + BCN$$

$$A = 20\log_{10}\left|\frac{1}{(1-\frac{\delta_2}{\delta_1})(1-\frac{\delta_3}{\delta_1})}\right|$$

$$C^3 = \frac{KI_0}{4V_0}$$

Gyro-TWT

$$b = \frac{\beta_e - \beta_{mn}}{\beta_{mn} C}$$

$$N = \frac{\beta_{mn} l}{2\pi}$$

$$B = \frac{54.6 x_1}{1 - C y_1}$$

$$K = \frac{(\mu_0/\varepsilon_0)^{1/2}(v_t/c)^2 k_t^2 (1+\alpha_0) H_{m,-s}}{\pi(1-\frac{m^2}{k_t^2 a^2}) J_m^2\{k_t a\}(v_z/c)\beta_{mn}^4}$$

$\alpha_0 = \dfrac{v_t}{v_z}$: Beam pitch factor

Some concepts in widening slow-wave TWTs

Zero-to-slightly-negative-dispersion structure for wideband performance

Anisotropically loaded helix

Metal vane/ segment loaded envelope

Inhomogeneously loaded helix:

Helix with tapered geometry dielectric supports such as half-moon-shaped and T-shaped supports

Negative dispersion ensures constancy of Pierce's velocity synchronization parameter *b* with frequency

Multi-dispersion structures for wideband performance

Constancy of b with frequency with negative dispersion

$$b = \frac{v_0 - v_p}{v_p C} = \frac{v_0 - v_p}{v_p (K I_0 / 4V_0)^{1/3}} = \frac{\dfrac{v_0 - v_p}{v_p}}{K^{1/3}} \frac{1}{(I_0 / 4V_0)^{1/3}}$$

Negative dispersion: v_p increases with frequency

$v_0 - v_p$ decreases with frequency

$\dfrac{v_0 - v_p}{v_p}$ decreases with frequency

$\rightarrow$ Numerator of the expression for b decreases with frequency

K decreases with frequency and hence the

$\rightarrow$ Denominator of the expression for b decreases with frequency

b remains constant with frequency

Conventional TWTs with multi-dispersion, multi-section structures

Small-signal gain equation $G \sim BCN$

$$N\lambda_e = l$$

$$N\frac{v_0}{f} = l$$

$$C = (KI_0 / 4V_0)^{1/3}$$

$$N = \frac{f\,l}{v_0}$$

$$G \sim B(KI_0 / 4V_0)^{1/3}\frac{f\,l}{v_0}$$

G is proportional to $K^{1/3} f\, l$

G is proportional to $K^{1/3} f\, l$

Gain-frequency response:

Lower gain at lower frequencies as G is proportional to f

Lower gain at higher frequencies as G is proportional to $K^{1/3}$, the latter decreasing with frequency

Conventional structure: If you had increased the length l, then the gain G would be compensated at lower frequencies f. However, then the gain G would become very high at higher frequencies f.

Therefore, let us arrive at the design of a helical slow-wave structure the **effective length** of which is **large at lower frequencies,** which at the same time becomes relatively **smaller at higher frequencies**. (The design should ensure that the gain is not enhanced at any frequency to a high value causing oscillation in the device).

The answer lies in a multi-dispersion, multi-section helix TWTs!

.

One positive-dispersion helix section of length l_1 synchronous with the beam only at lower frequencies and the other nearly dispersion-free helix section of effective length length l_2 synchronous with the beam both at lower and higher frequencies.

Effective length increased to $l_1 + l_2$ at lower frequencies
Effective length reduced to l_2 at higher frequencies (since the section of length l_1 goes out of synchronism at higher frequencies

Gain is proportional to $K^{1/3} f\, l$

We have to control (i) the nature and the amounts of dispersion of of the sections by suitably loading the sections and (ii) the lengths of the two sections

Select structure sections such as segment loaded helices of controllable dispersion

Analysis should be capable of finding the dispersion and interaction impedance characteristics of the structure sections, say, with metal segment loaded envelopes and their control by structure section parameters like segment dimensions and relative section lengths.

Two-section configuration with one of the sections providing a double-hump in the gain-frequency response

One of the seconds provides a double-hump peaks while the second section provides a single peak between the humps in the gain frequency response

Twystron

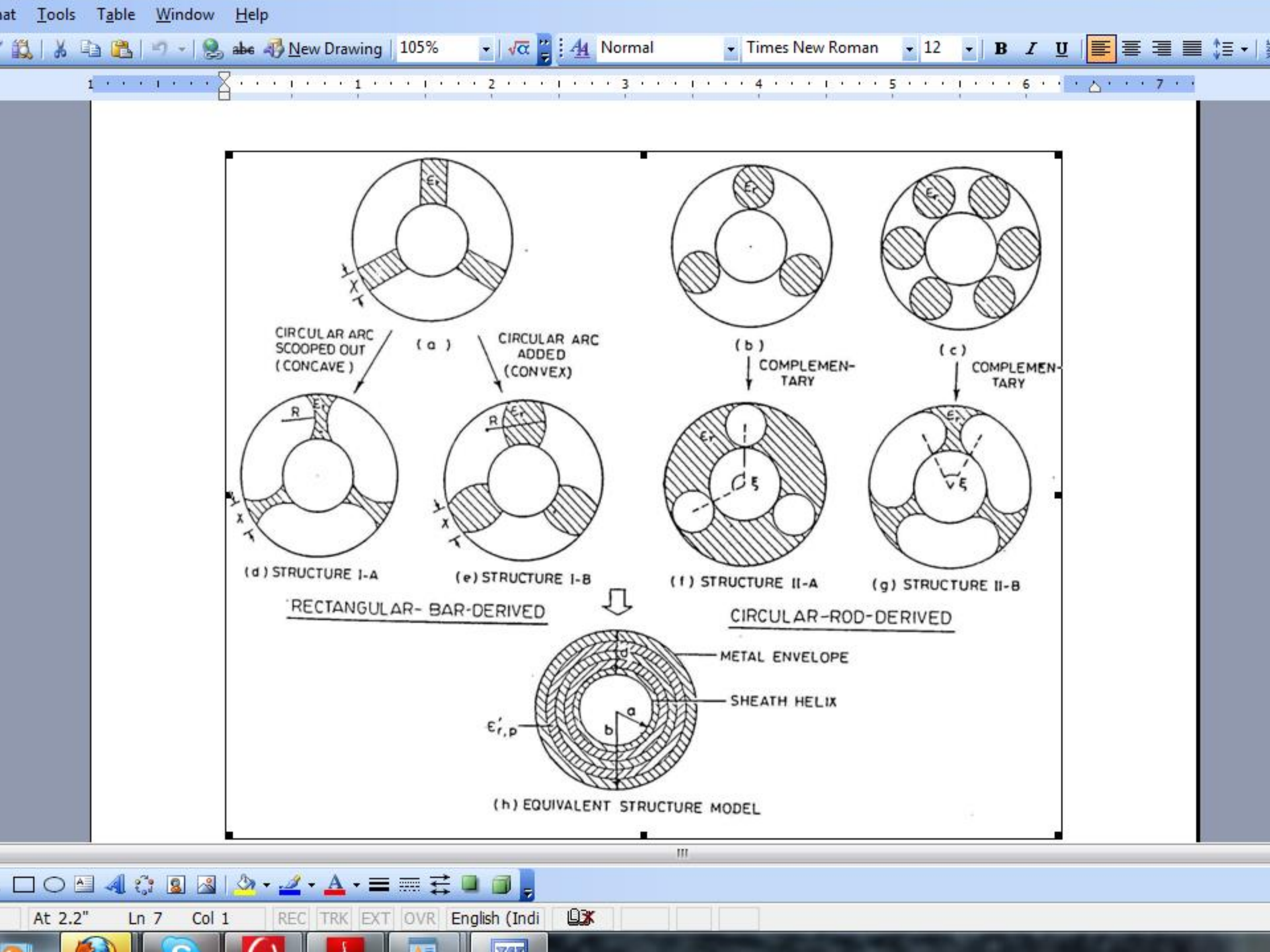
The first section is a klystron providing a double-hump gain-frequency response. The second section is a TWT providing a peak between the two humps of the first section in the gain-frequency response.

Gyro-twystron

Two-section Gyro-TWT

Two-hump peaks result from the beam-mode dispersion line intersecting with the waveguide dispersion hyperbola at two points.

One may use two dielectric loaded sections, one of which should provide a single peak between the two peaks provided by the other section, in the gain-frequency response.


at Tools Table Window Help
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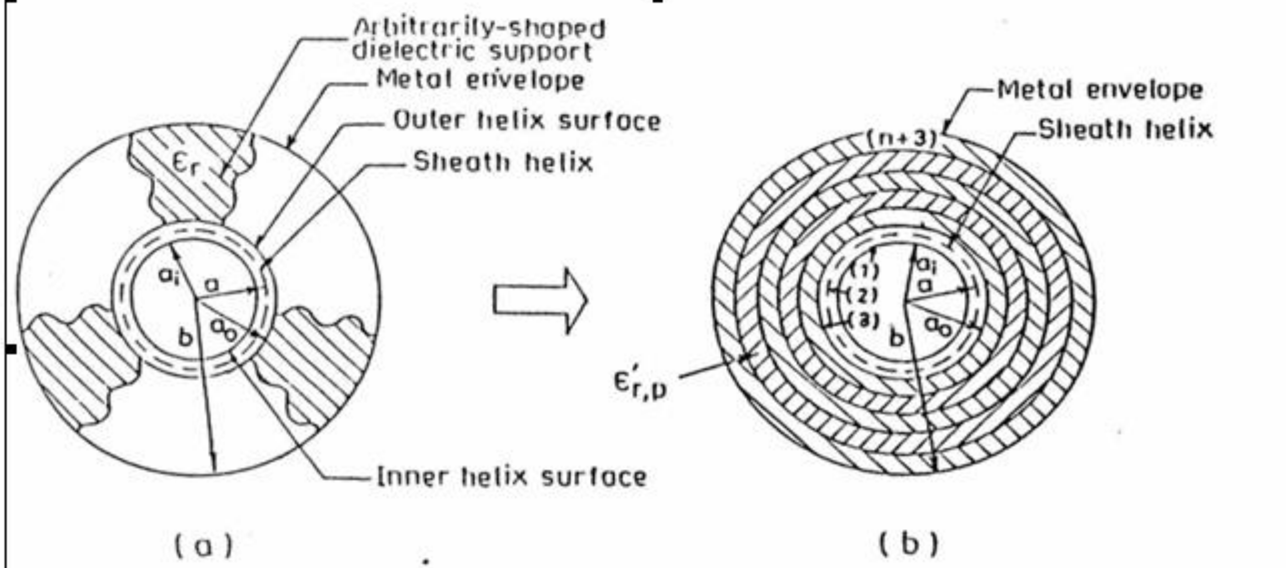
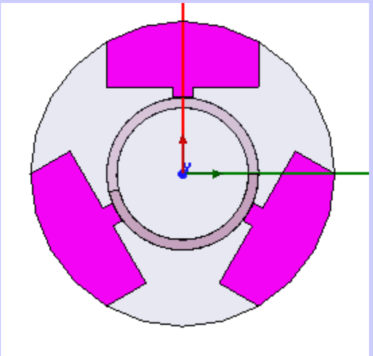
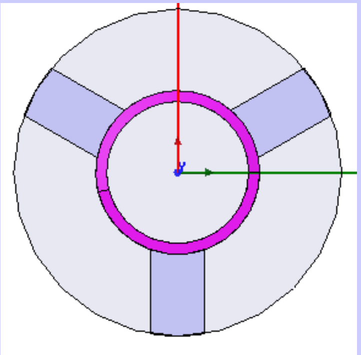
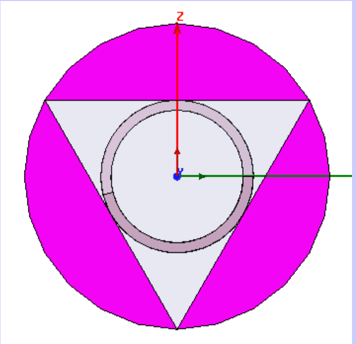
ε_r
(a)
CIRCULAR ARC SCOOPED OUT (CONCAVE)
CIRCULAR ARC ADDED (CONVEX)
(b)
(c)
COMPLEMENTARY
COMPLEMENTARY
R
X
ξ
(d) STRUCTURE I-A
(e) STRUCTURE I-B
(f) STRUCTURE II-A
(g) STRUCTURE II-B
RECTANGULAR-BAR-DERIVED
CIRCULAR-ROD-DERIVED
METAL ENVELOPE
SHEATH HELIX
ε'_{r,p}
a
b
d
(h) EQUIVALENT STRUCTURE MODEL
At 2.2" Ln 7 Col 1 REC TRK EXT OVR English (Indi

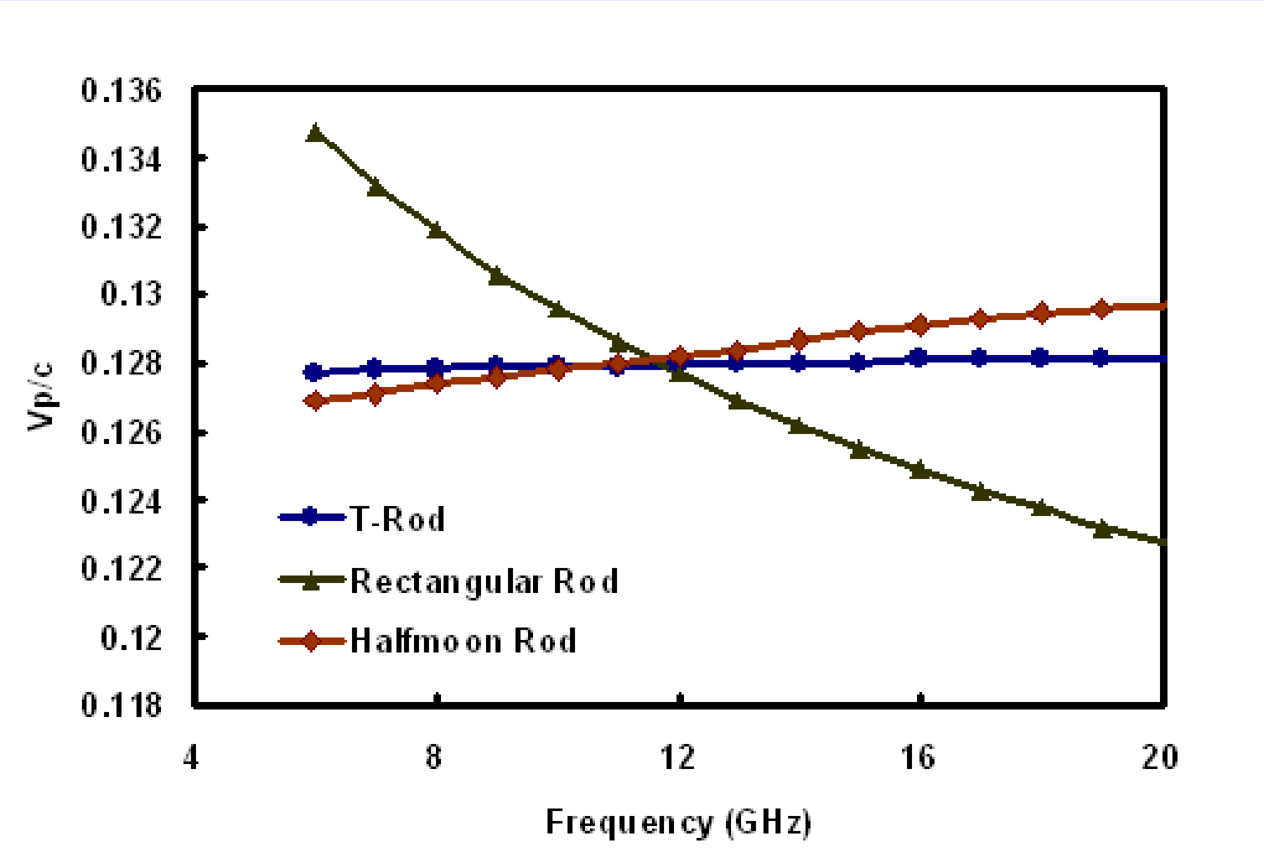


Cross section of a helical slow-wave structure supported by arbitrarily shaped identical dielectric bars **(a)** and its equivalent analytical model **(b)**.

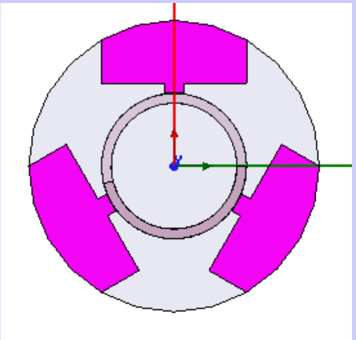


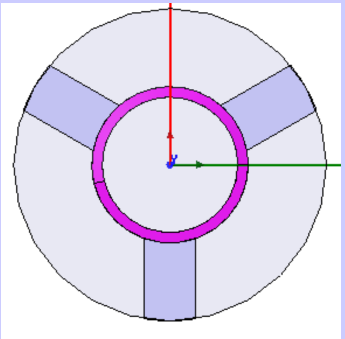


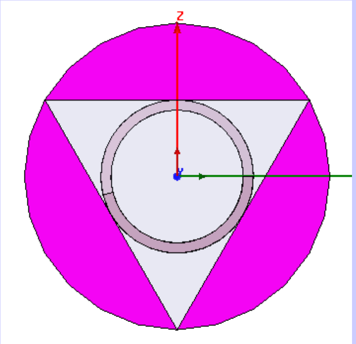


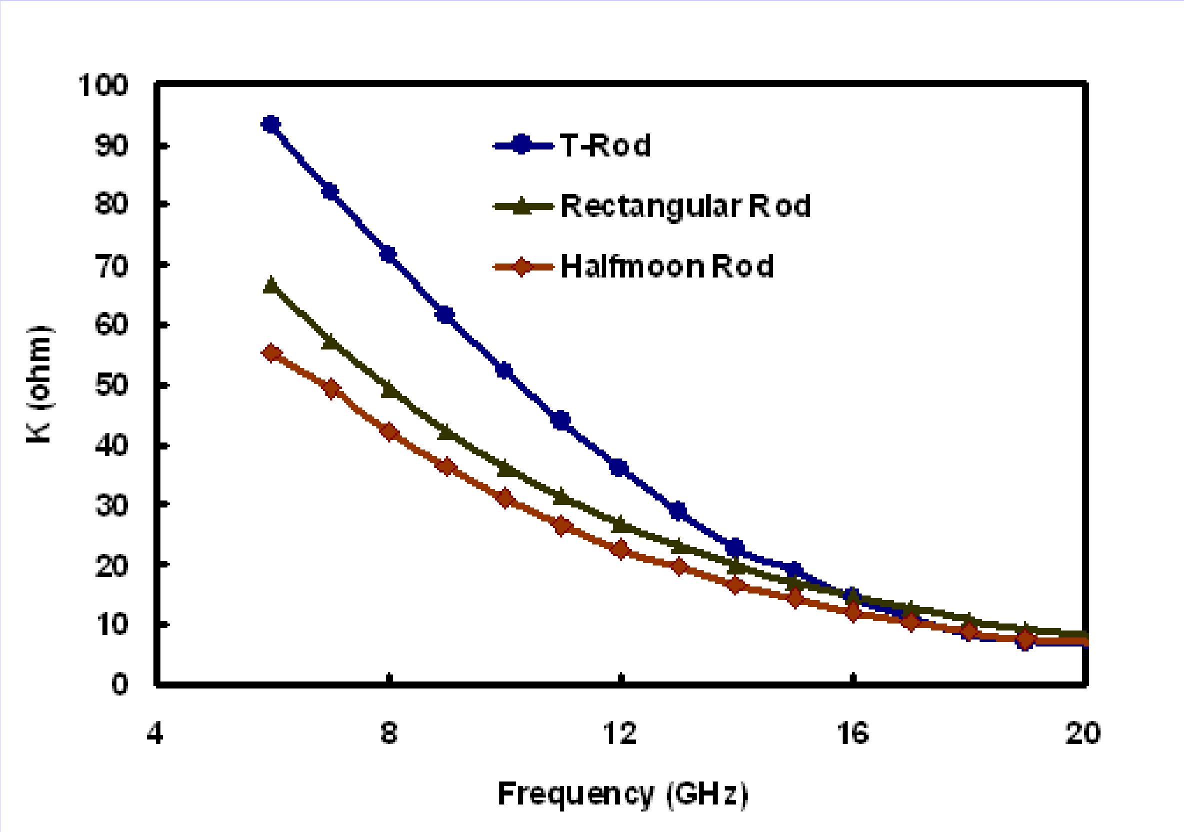


Source: MTRDC (DRDO)

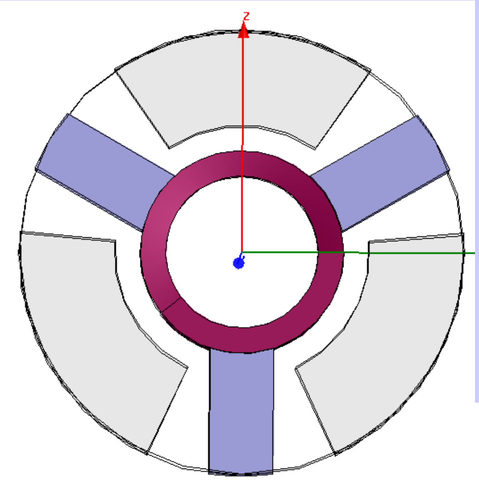








Source: MTRDC (DRDO)



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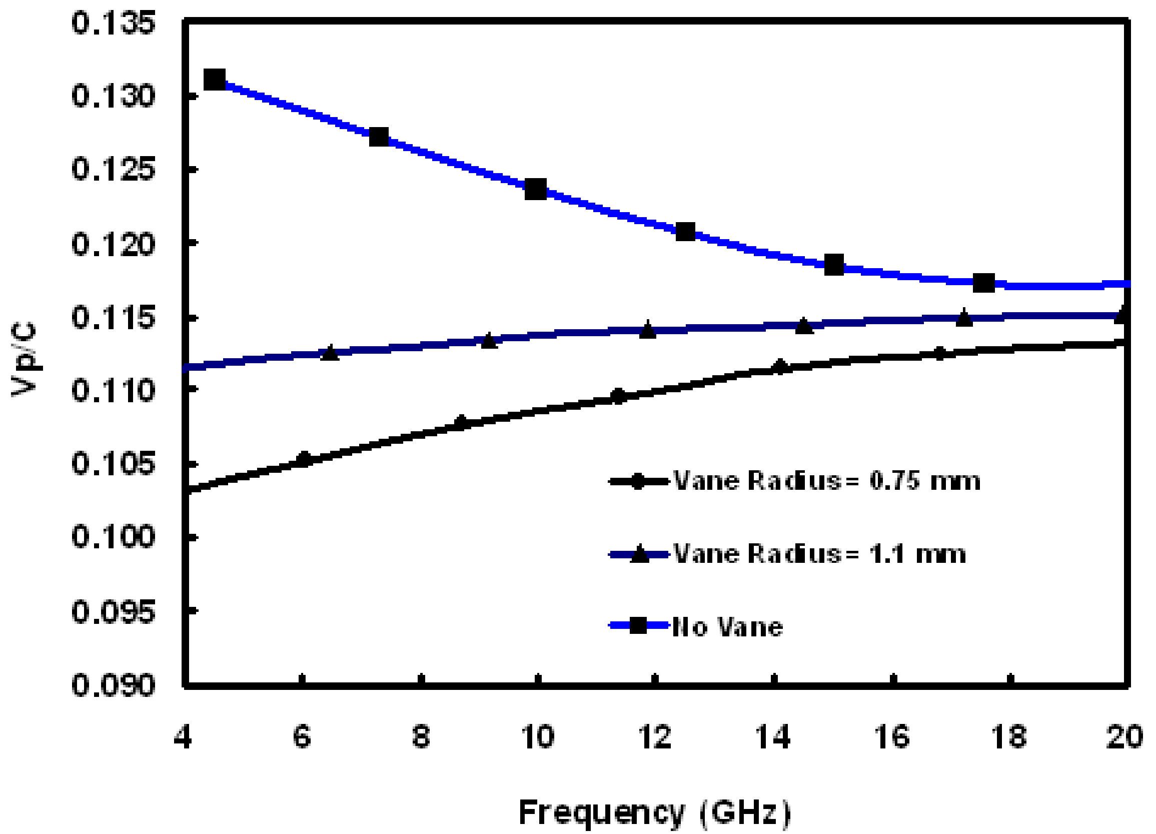

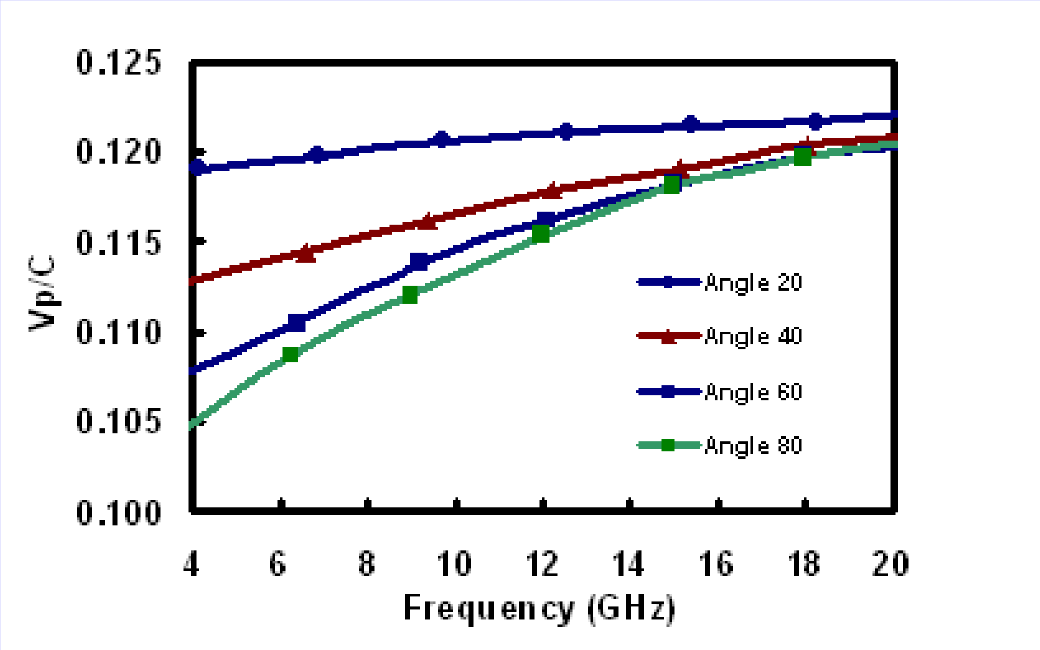

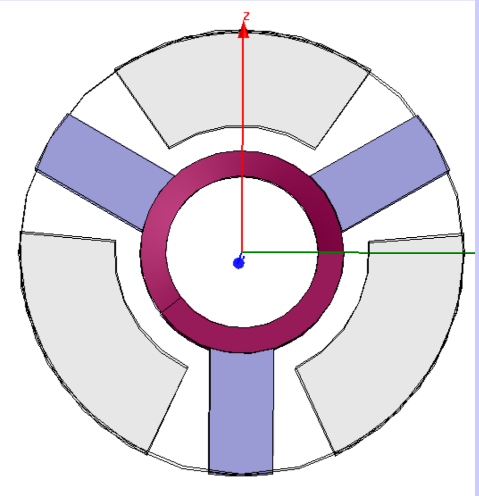

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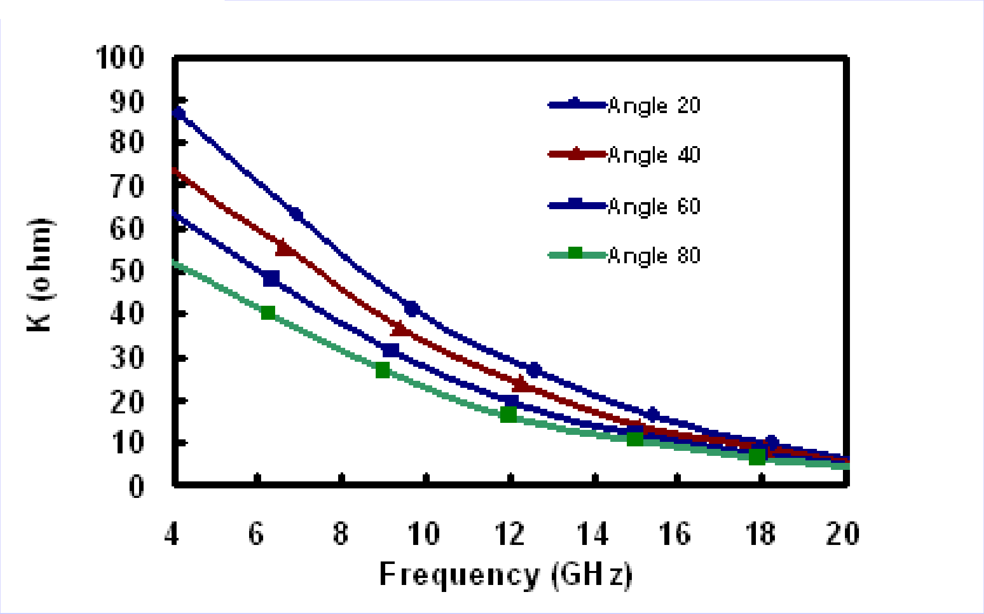
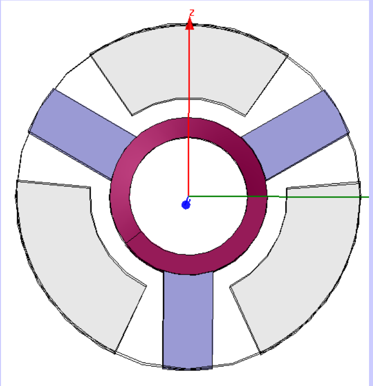
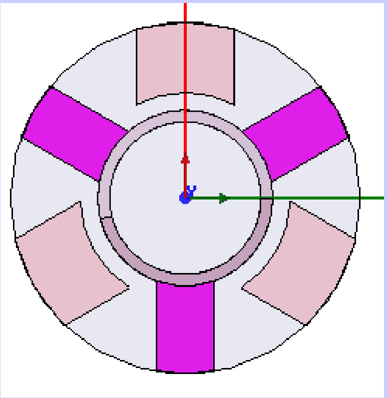
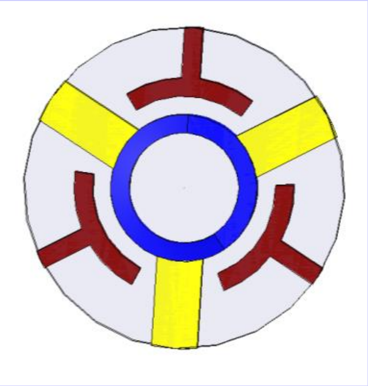




Angular segment

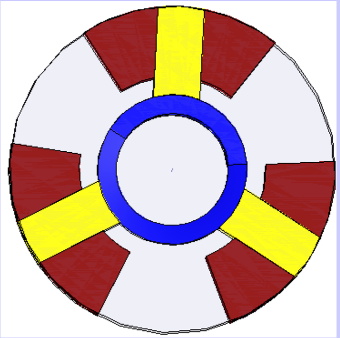


Straight segment

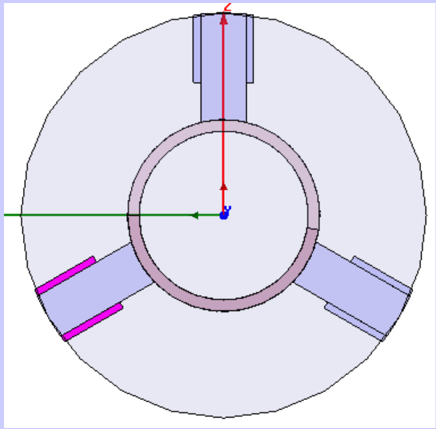


T- segment

Source: MTRDC (DRDO)

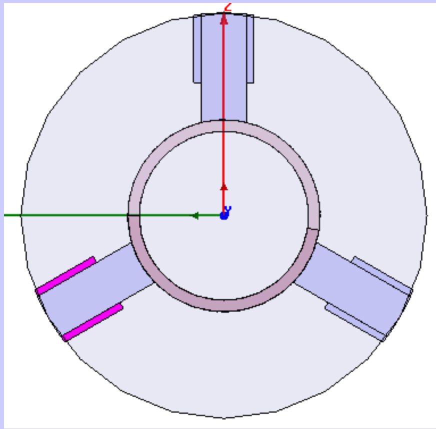


Embedded rod



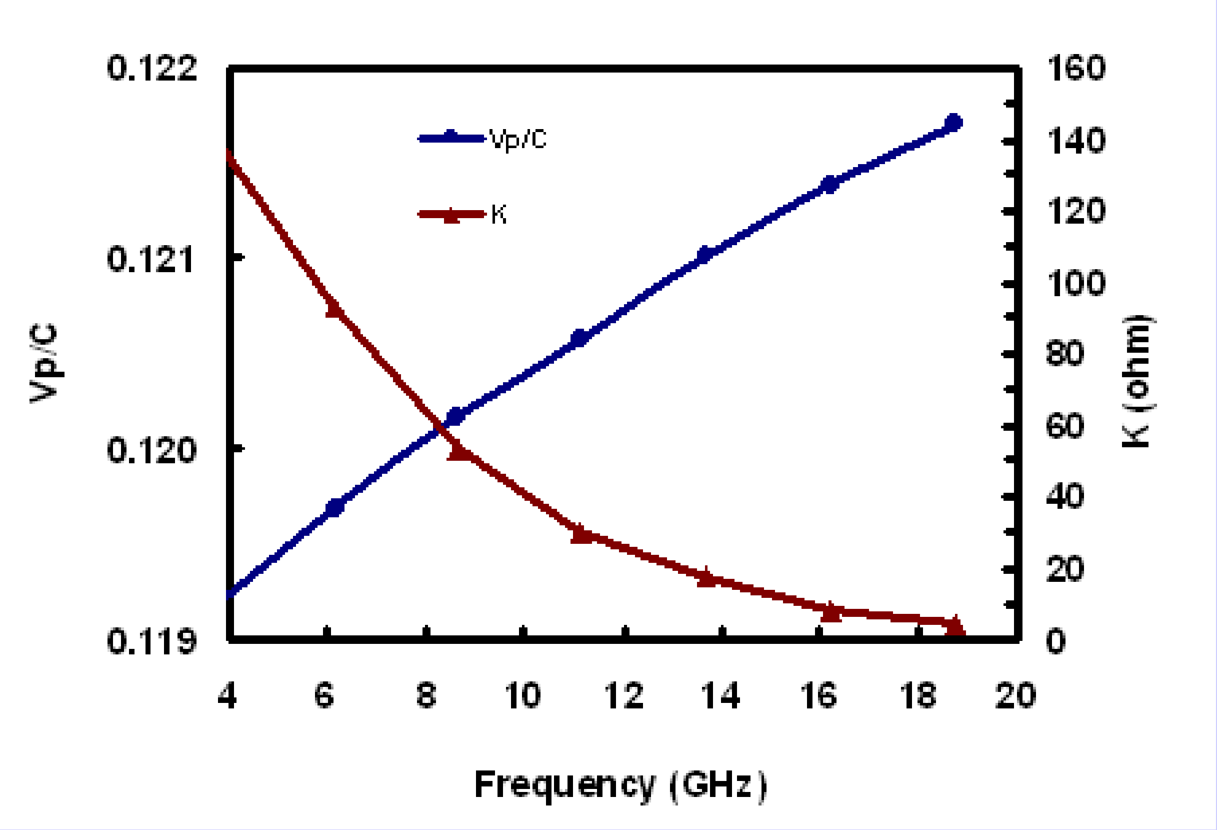
Source: **MTRDC (DRDO)**

Metal-coated support rods

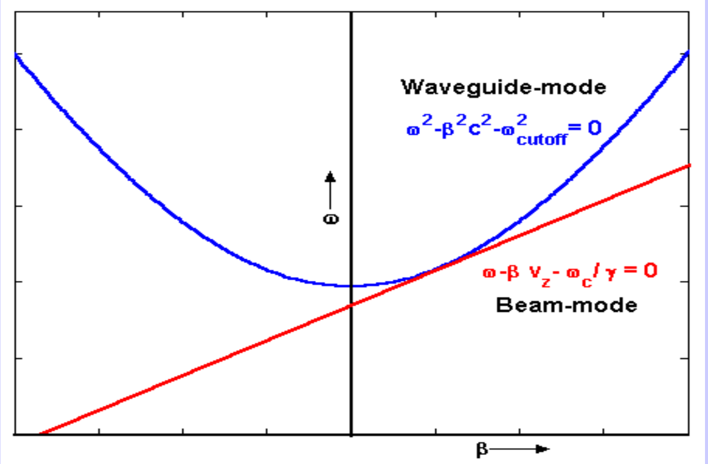


Provides negative dispersion with quite high interaction impedance compared to other segment variants

Source: MTRDC (DRDO)



Methods of broadbanding a single-stage gyro-TWT



- Controlled dispersion characteristics of the waveguide for wideband coalescence with beam-mode dispersion characteristics

  i) by dielectric lining the metal wall of a circular waveguide

  → Method entails the risk of dielectric charging that results into heating if the dielectric is lossy

  ii) by metal disc loading a circular waveguide

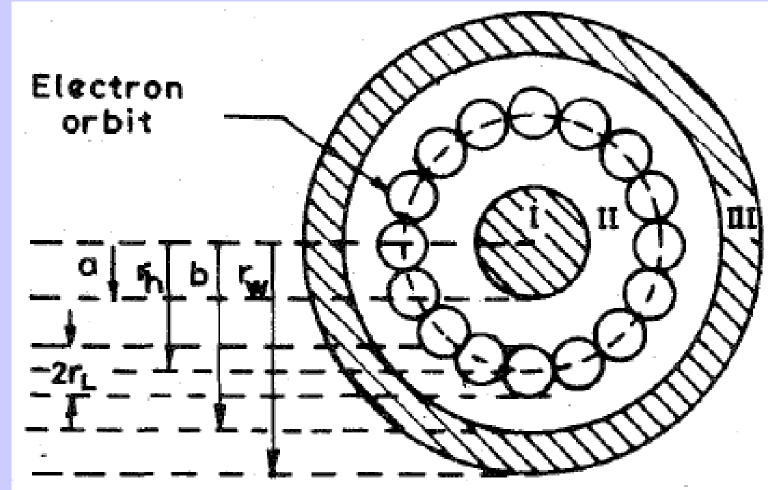
  → Optimisation of the disc parameters brings about the desired shape of the structure dispersion for wide coalescence bandwidth for wideband device performance

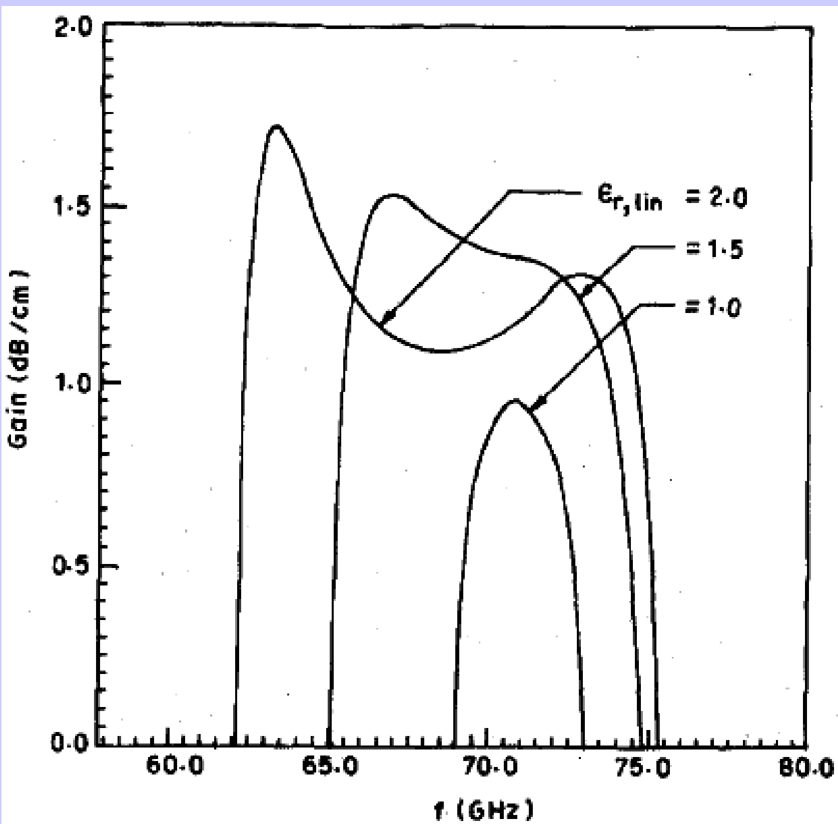
- Tapered waveguide cross section and profiled magnetic field

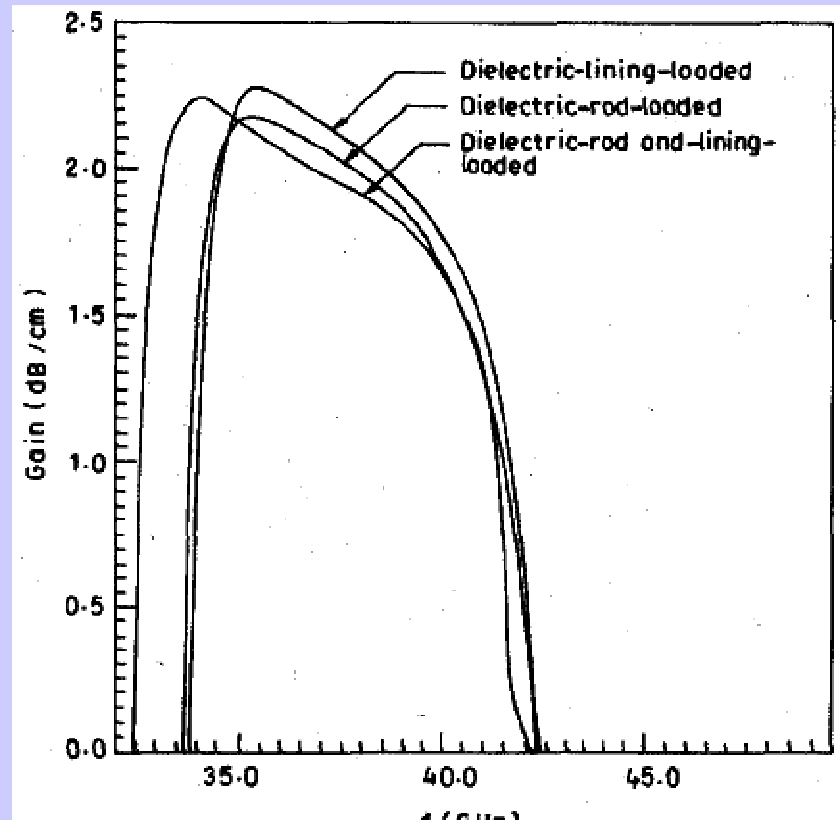
  → Device bandwidth is increased

  → Device gain is decreased due to reduction of the effective interaction length at each of frequency zones of the bandwidth

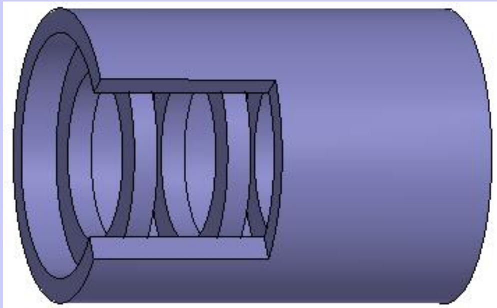
Broadbanding a Gyro-TWT by Dielectric-loading

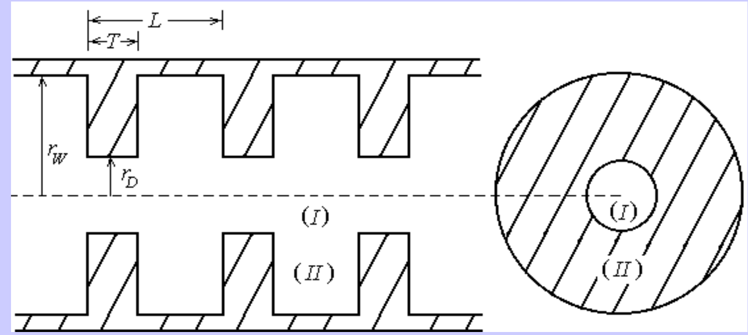






Disc-loaded Circular Waveguide





Beam-absent (cold) analysis

- Clarricoats and Olver	Surface impedance model
- Amari *et al.*	Coupled-integral-equation technique
- Esteban and Rebollar	Modal expansion technique
- Choe and Uhm	Field matching technique
- Kesari *et al.*	Field matching technique

considering
higher order propagating wave space harmonics in disc-free region
higher order standing wave modal harmonics in disc-occupied region
finite disc thickness

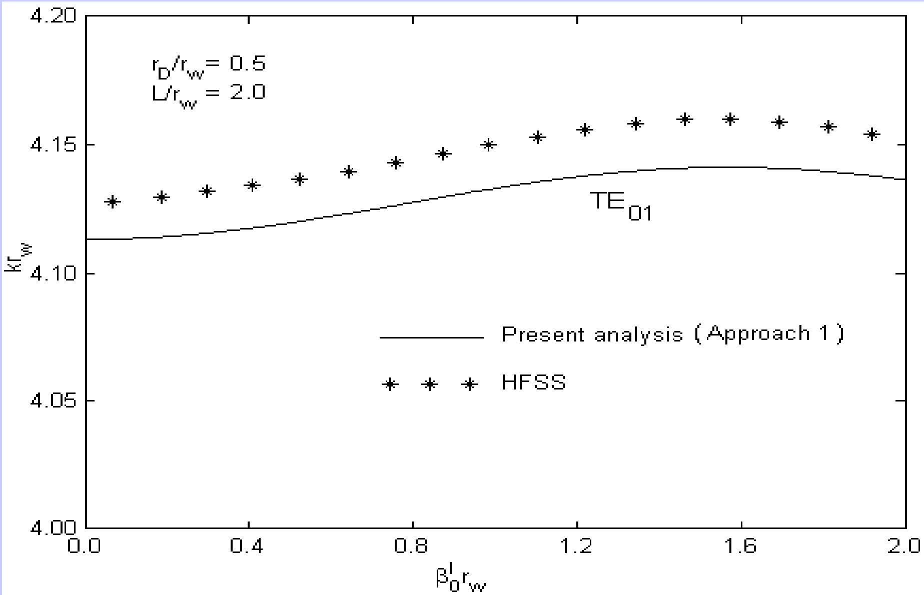
Field Matching Technique for Dispersion Relation

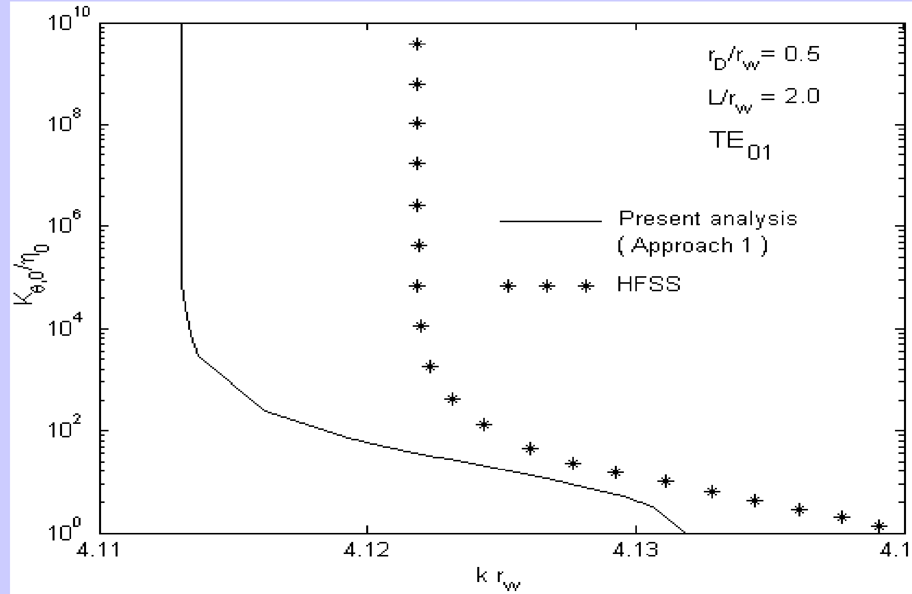
Field expressions → Boundary conditions → Integration within limits of validity → Elimination of field constants → Dispersion relation

Place of work: CRMT, BHU

Vishal Kesari, vishal_kesari@rediffmail.com

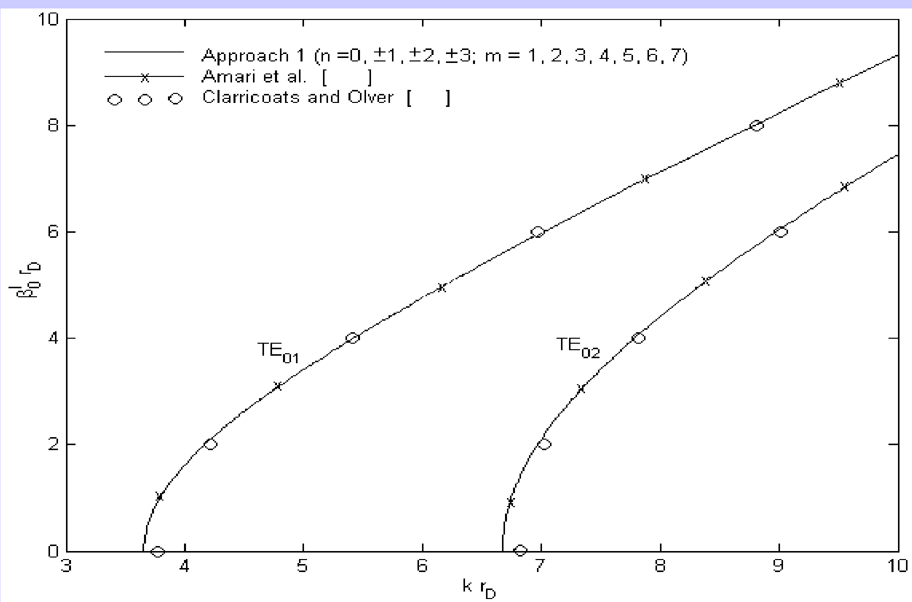
Infinitesimally Thin Disc-loaded Circular Waveguide

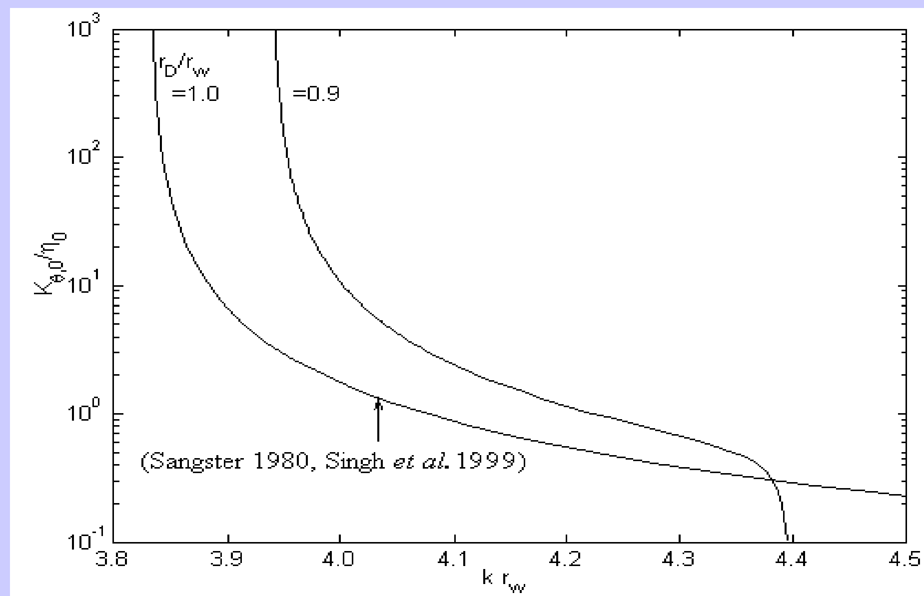




Dispersion Characteristics

Interaction Impedance Characteristics





Place of work: CRMT, BHU

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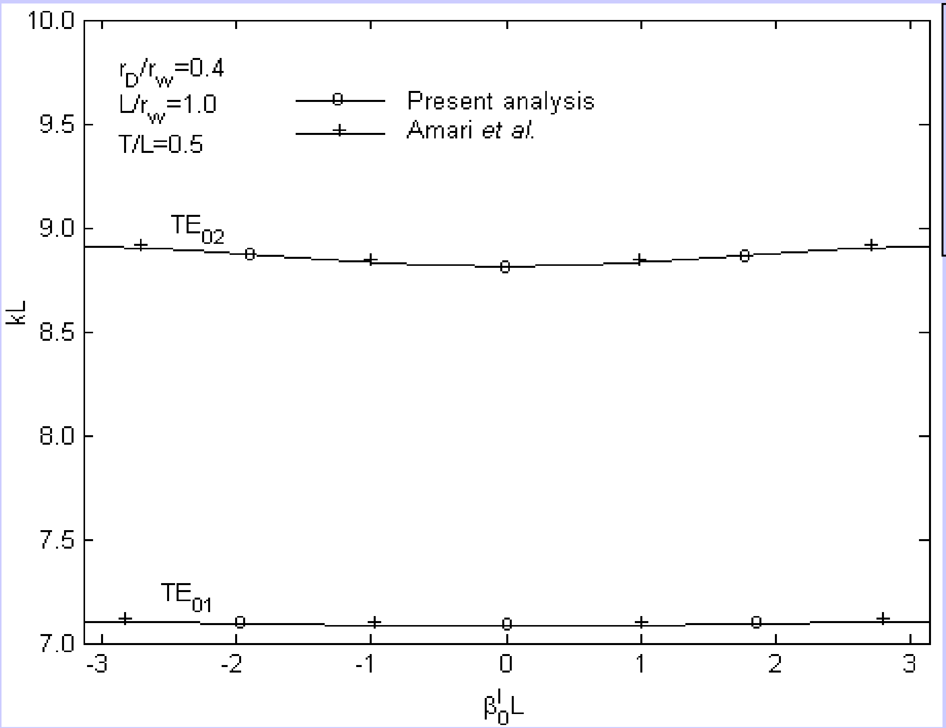
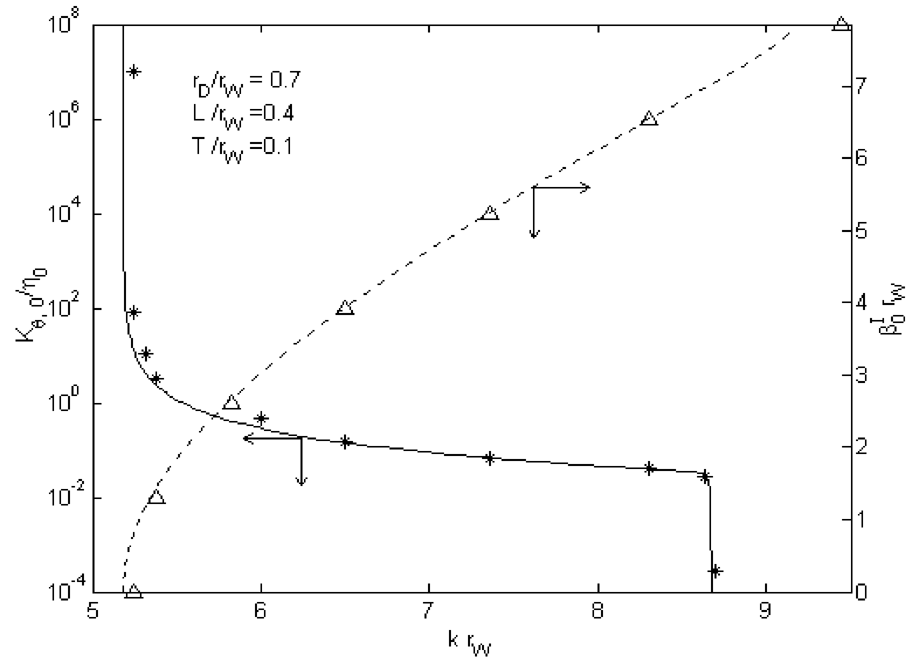
Disc-loaded Circular Waveguide having Finite Disc Thickness



Comparison of dispersion characteristics of a disc-loaded circular waveguide obtained by field matching technique with those due to Amari *et al.*

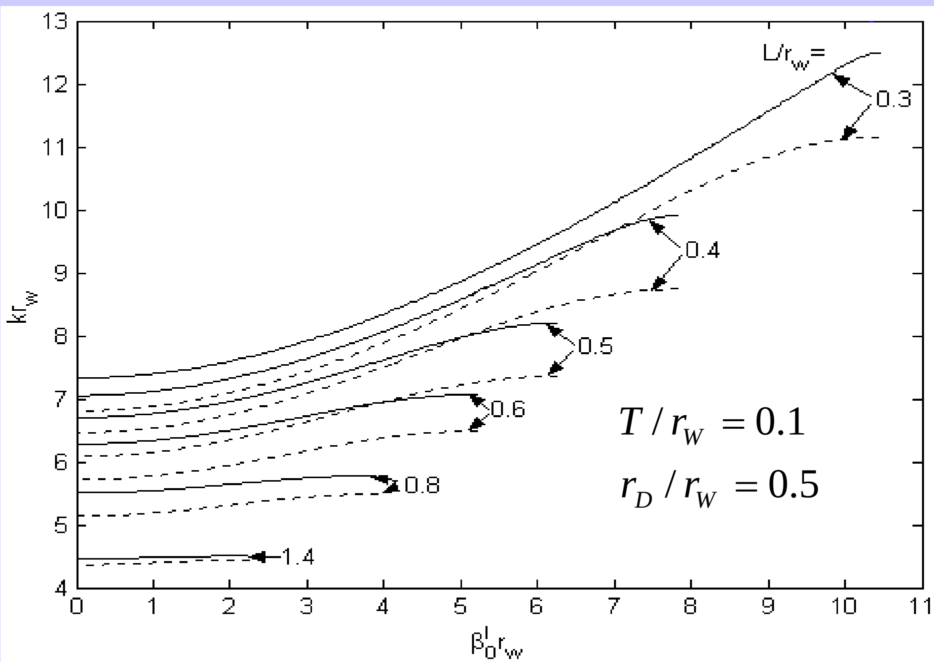


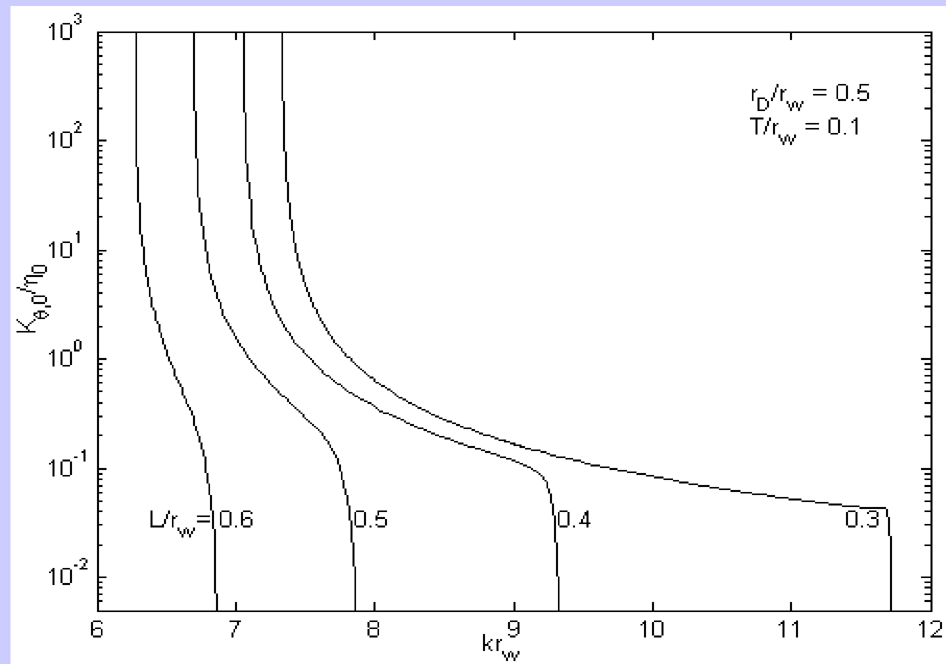
Comparison of dispersion and azimuthal interaction impedance characteristics of a disc-loaded circular waveguide, excited in the TE_{01} mode obtained by field matching technique with those obtained by HFSS

Place of work: CRMT, BHU Vishal Kesari, vishal_kesari@rediffmail.com

Disc-loaded Circular Waveguide

Dispersion and azimuthal interaction impedance characteristics of the disc-loaded circular waveguide typically for the TE_{01} mode, taking disc periodicity as the parameter
(Broken curves refer to circular waveguide loaded with infinitesimally thin discs)

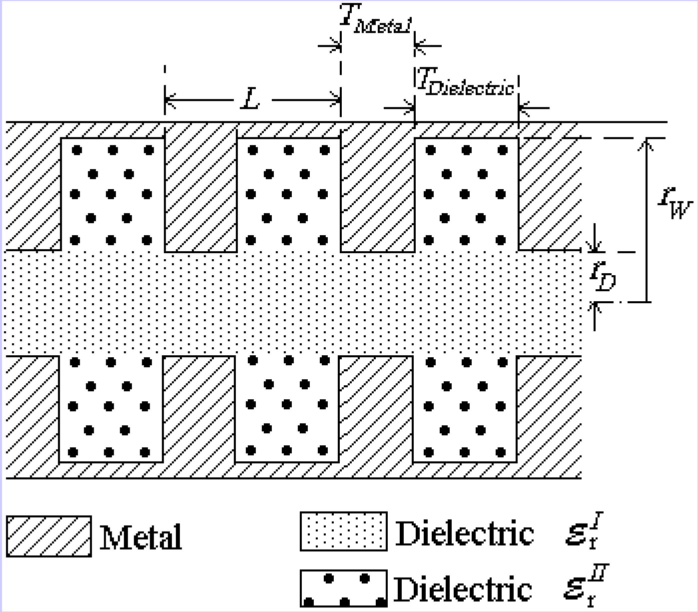


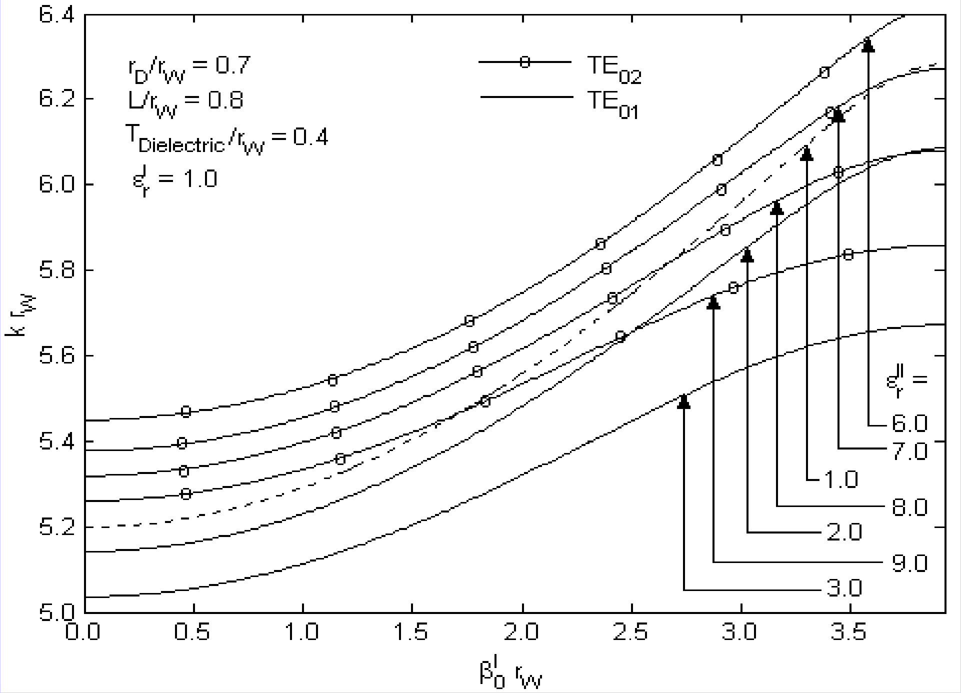


Place of work: CRMT, BHU Vishal Kesari, vishal_kesari@rediffmail.com

Circular Waveguide loaded with Alternate Dielectric and Metal Annular Discs

Dispersion characteristics of a circular waveguide loaded with alternate dielectric and metal annular discs showing wider coalescence bandwidth of TE_{02} mode than that of TE_{01} mode excited conventional metal disc-loaded circular waveguide (broken curve)





Place of work: CRMT, BHU

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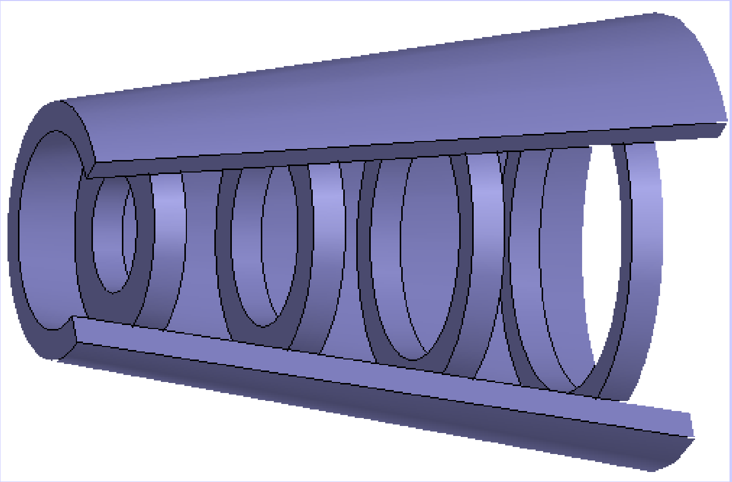
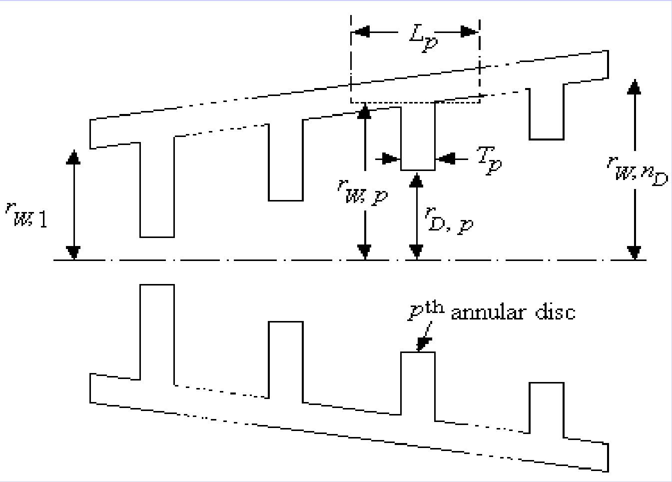
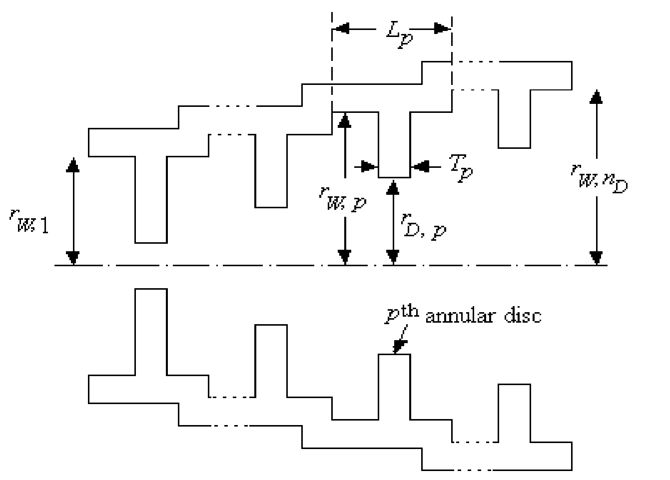
Tapering the Structure Cross-section

bandwidth is increased
device gain is decreased due to reduction of effective interaction length







$r_{W,p} \rightarrow$ waveguide-wall radius of p^{th} step

$L_p \rightarrow$ axial length of p^{th} step

$r_{D,p} \rightarrow$ disc-hole radius of p^{th} disc

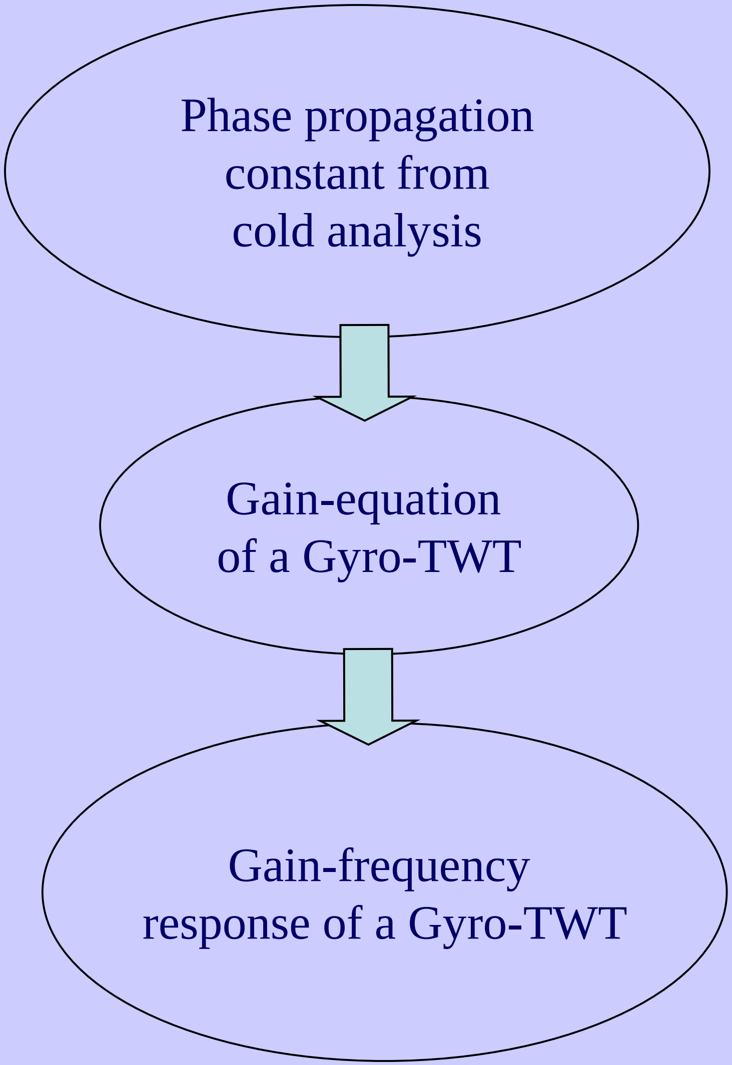
$T_p \rightarrow$ disc thickness of p^{th} disc

$n_D \rightarrow$ total number of discs in tube length

Tapered Disc-loaded circular waveguide and its analytical model

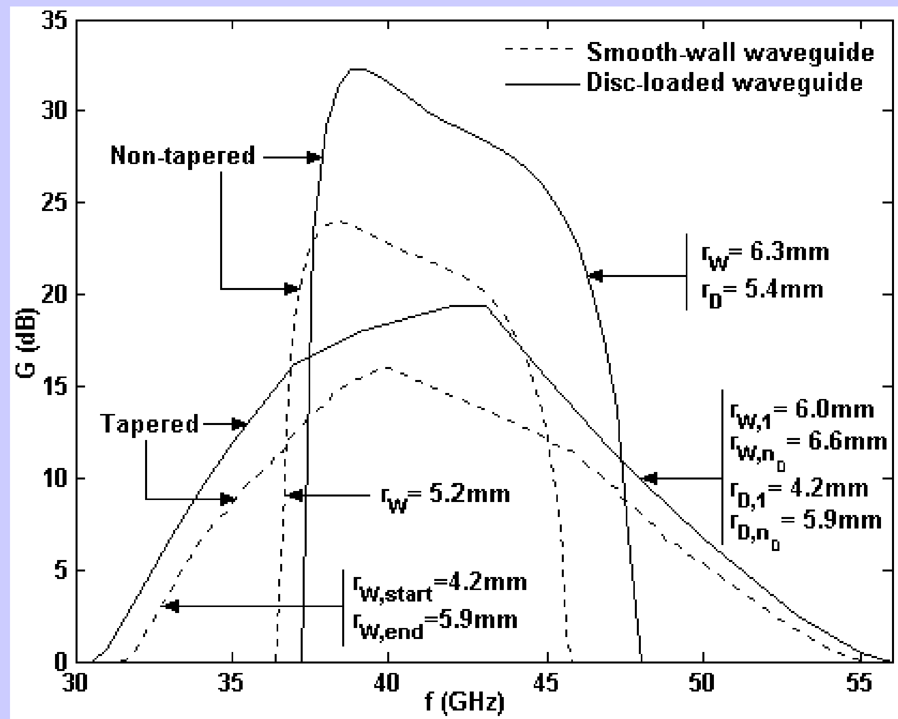
Place of work: CRMT, BHU Vishal Kesari, vishal_kesari@rediffmail.com

Gain-frequency Response



i) disc-hole radius, to spread the device gain over a wide range of frequencies without regard to the gain value

ii) waveguide-wall radius, to compensate for the gain values that would be reduced at the band edges due to tapering of the disc-hole radius



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Interaction Structure	Bandwidth (3-dB)	Gain
Smooth-wall circular waveguide without tapered cross section	4.8 GHz	24.0 dB
Smooth-wall circular waveguide with tapered cross section	6.5 GHz	16.2 dB
Disc-loaded circular waveguide without tapered cross section	5.0 GHz	31.5 dB
Disc-loaded circular waveguide with tapered cross section	7.3 GHz	19.4 dB

	Smooth-wall (Disc-free)	Disc-loaded
Non-tapered cross section	—	Increase in device bandwidth and gain by 4% and 7.5 dB (31%)
Tapered cross section	Increase in device bandwidth by 35% at the cost of 7.2 dB (33%) device gain	Increase in device bandwidth by 52% at a little cost of 4.6 dB (19%) device gain

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Broadbanding techniques

Conventional TWT

- Homogeneous dielectric loading cannot shape structure dispersion for wide device bandwidths
- Inhomogeneous dielectric loading by tapered-cross-section helix supports can shape structure dispersion for wide device bandwidths
- Anisotropic loading by azimuthally periodic metal vanes provided with the envelope can shape structure dispersion for wide device bandwidths

Gyro-TWT

- Homogeneous dielectric loading can shape dispersion, and can provide wideband coalescence between the beam-mode and waveguide-mode dispersion characteristics and consequently wide device bandwidths
- Two-stage homogeneous dielectric loading can widen gain-frequency response
- Anisotropic loading by azimuthally periodic metal vanes provided with the waveguide wall cannot shape structure dispersion for wide device bandwidths

Broadbanding techniques (***Continued***)

Conventional TWT

- Axially periodic disc loading cannot shape structure dispersion and cannot widen device bandwidth but can enhance device gain

Gyro-TWT

- Axially periodic disc loading can shape structure dispersion and can widen device bandwidth

- Waveguide cross section tapering can broadband the device at small gains

- Axially periodic discs plus tapering the waveguide cross section can broadband the device at large gains

CARM, SWCA, and Gyro-TWT

Beam-mode dispersion relation

$\omega - \beta v_z - s\omega_c / \gamma = 0$ s is the beam harmonic number

$\omega = \beta v_z + s\omega_c / \gamma = \omega_D$ Doppler-shifted cyclotron angular frequency

$$\Delta\omega_D = \beta \Delta v_z - \frac{s\,\omega_c}{\gamma^2} \Delta\gamma$$

Δv_z is caused by Weibel instability due to Lorentz force on electrons in transverse motion in transverse RF magnetic field

$\Delta\gamma$ is caused by energy exchange between electrons with transverse motion in transverse RF electric field

$$\Delta\omega_D = \beta\,\Delta v_z - \frac{s\,\omega_c}{\gamma^2}\Delta\gamma$$

$$\gamma m\frac{dv_z}{dt}\vec{a}_z = e\vec{v}_\perp \times \vec{B}_\perp$$

$$\gamma m\Delta v_z = e\vec{v}_\perp \times \vec{B}_\perp \Delta t = e\vec{v}_\perp \times (B_r\vec{a}_r + B_\theta\vec{a}_\theta)\Delta t$$

$$\Delta v_z = \frac{e\vec{v}_\perp \times (B_r\vec{a}_r + B_\theta\vec{a}_\theta)}{\gamma m}\Delta t$$

Let us express magnetic field quantities in terms of electric field quantities with the help of Maxwell's equations

$$\nabla\times\vec{E} = -\frac{\partial\vec{B}}{\partial t} \qquad \rightarrow \qquad \frac{1}{r}\begin{vmatrix} \vec{a}_r & r\vec{a}_\theta & \vec{a}_z \\ \partial/\partial r & \partial/\partial\theta & \partial/\partial z \\ E_r & rE_\theta & 0 \end{vmatrix} = -\frac{\partial}{\partial t}(B_r\vec{a}_r + B_\theta\vec{a}_\theta + B_z\vec{a}_z)$$

$$\frac{1}{r}\begin{vmatrix} \vec{a}_r & r\vec{a}_\theta & \vec{a}_z \\ \partial/\partial r & \partial/\partial\theta & \partial/\partial z \\ E_r & rE_\theta & 0 \end{vmatrix} = -\frac{\partial}{\partial t}(B_r\vec{a}_r + B_\theta\vec{a}_\theta + B_z\vec{a}_z)$$

$$\Delta v_z = \frac{e\vec{v}_\perp \times (B_r\vec{a}_r + B_\theta\vec{a}_\theta)}{\gamma m}\Delta t$$

r- component of magnetic field: $-\frac{\partial E_\theta}{\partial z} = -\frac{\partial B_r}{\partial t} \Rightarrow -j\beta E_\theta = j\omega B_r \Rightarrow B_r = -\frac{\beta E_\theta}{\omega}$

θ-component: $\frac{1}{r}\frac{\partial E_r}{\partial z} = -\frac{\partial B_\theta}{\partial t} \Rightarrow -j\beta E_r = -j\omega B_\theta \Rightarrow B_\theta = \frac{\beta E_r}{\omega}$

$$\Delta v_z = \frac{e\vec{v}_\perp \times (B_r\vec{a}_r + B_\theta\vec{a}_\theta)}{\gamma m}\Delta t = \frac{e\beta\vec{v}_\perp \times (-E_\theta\vec{a}_r + E_r\vec{a}_\theta)}{\gamma m\omega}\Delta t = \frac{e\beta\vec{v}_\perp \times \vec{a}_z \times \vec{E}_\perp}{\gamma m\omega}\Delta t$$

$$\vec{a}_z \times \vec{E}_\perp = \vec{a}_z \times (E_r\vec{a}_r + E_\theta\vec{a}_\theta) = E_r\vec{a}_\theta - E_\theta\vec{a}_r = -E_\theta\vec{a}_r + E_r\vec{a}_\theta$$

$$\Delta v_z = \frac{e\beta \vec{v}_\perp \times \vec{a}_z \times \vec{E}_\perp}{\gamma m \omega} \Delta t$$

$$\Delta v_z = \frac{e\beta \vec{v}_\perp \times \vec{a}_z \times \vec{E}_\perp}{\gamma m \omega} \Delta t = \frac{e\beta [(\vec{v}_\perp \cdot \vec{E}_\perp)\vec{a}_z - (\vec{v}_\perp \cdot \vec{a}_z)\vec{E}_\perp]}{\gamma m \omega} \Delta t = \frac{e\beta [(\vec{v}_\perp \cdot \vec{E}_\perp)\vec{a}_z]}{\gamma m \omega} \Delta t$$

$$\vec{v}_\perp \cdot \vec{a}_z = 0$$

$$\Delta v_z = \frac{e\beta [(\vec{v}_\perp \cdot \vec{E}_\perp)\vec{a}_z]}{\gamma m \omega} \Delta t$$

$$\Delta \omega_D = \beta \, \Delta v_z - \frac{s\,\omega_c}{\gamma^2} \Delta \gamma$$

$$\Delta \gamma = ?$$

$$\Delta\gamma = ?$$

Rate of change of kinetic energy with time

$$\frac{d}{dt}(\gamma mc^2) = e(\vec{v}_\perp \cdot \vec{E}_\perp)$$

$$\Delta v_z = \frac{e\beta[(\vec{v}_\perp \cdot \vec{E}_\perp)\vec{a}_z]}{\gamma m\omega}\Delta t$$

(Weibel instability)

$$mc^2(\Delta\gamma) = e(\vec{v}_\perp \cdot \vec{E}_\perp)\Delta t$$

$$\boxed{\Delta\gamma = \frac{e}{mc^2}(\vec{v}_\perp \cdot \vec{E}_\perp)\Delta t}$$

(CRM instability)

$$\Delta\omega_D = \beta\,\Delta v_z - \frac{s\,\omega_c}{\gamma^2}\Delta\gamma$$

$$\Delta\omega_D = \beta\frac{e\beta}{\gamma m\omega}(\vec{v}_\perp \cdot \vec{E}_\perp)\Delta t - \frac{s\omega_c}{\gamma^2}\frac{e}{mc^2}(\vec{v}_\perp \cdot \vec{E}_\perp)\Delta t = [\frac{e\beta^2}{\gamma m\omega} - \frac{s\omega_c}{\gamma^2}\frac{e}{mc^2}]\Delta t(\vec{v}_\perp \cdot \vec{E}_\perp)$$

(Weibel instability)

(CRM instability)

$$\Delta\omega_D = \beta \frac{e\beta}{\gamma m \omega}(\vec{v}_\perp \cdot \vec{E}_\perp)\Delta t - \frac{s\omega_c}{\gamma^2}\frac{e}{mc^2}(\vec{v}_\perp \cdot \vec{E}_\perp)\Delta t = [\frac{e\beta^2}{\gamma m \omega} - \frac{s\omega_c}{\gamma^2}\frac{e}{mc^2}]\Delta t(\vec{v}_\perp \cdot \vec{E}_\perp)$$

(Weibel instability) (CRM instability)

$$\Delta\omega_D = [\frac{e\beta^2}{\gamma m \omega} - \frac{s\omega_c}{\gamma^2}\frac{e}{mc^2}]\Delta t(\vec{v}_\perp \cdot \vec{E}_\perp)$$

$$\frac{s\omega_c}{\gamma} \lesssim \omega \qquad \frac{s\omega_c}{\gamma} = F\omega \qquad F \lesssim 1$$

$$\Delta\omega_D = [\frac{e\beta^2}{\gamma m \omega} - F\omega \frac{e}{\gamma mc^2}]\Delta t(\vec{v}_\perp \cdot \vec{E}_\perp)$$

$$\Delta\omega_D = [\frac{e\beta^2}{\gamma m\omega} - F\omega\frac{e}{\gamma mc^2}]\Delta t(\vec{v}_\perp \cdot \vec{E}_\perp)$$

$$\frac{s\omega_c}{\gamma} = F\omega$$

(Weibel instability)

(CRM instability)

If Weibel instability dominates over CRM instability

$$\frac{e\beta^2}{\gamma m\omega} > F\omega\frac{e}{\gamma mc^2} \qquad (F \approx 1)$$

$$\frac{\beta^2}{\omega^2} > \frac{1}{c^2} \longrightarrow \frac{\omega^2}{\beta^2} < c^2$$

$$\frac{\omega}{\beta} < c$$

$$v_p < c$$

Destabilization of slow waves: Slow-wave cyclotron amplifier (SWCA)

If CRM instability dominates over Weibel instability

$$F\omega\frac{e}{\gamma mc^2} > \frac{e\beta^2}{\gamma m\omega} \qquad (F \approx 1)$$

$$\frac{\omega^2}{c^2} > \beta^2 \longrightarrow \frac{\omega^2}{\beta^2} > c^2$$

$$\frac{\omega}{\beta} > c$$

$$v_p > c$$

Destabilization of fast waves: Gyro-TWT

If both Weibel instability and CRM instability are present in equal proportions (auto-resonance)

$$\frac{e\beta^2}{\gamma m\omega} = F\omega\frac{e}{\gamma mc^2} \qquad (\Delta\omega_D = 0)$$

$$\frac{s\omega_c}{\gamma} \lesssim \omega \qquad \frac{s\omega_c}{\gamma} = F\omega \qquad F \lesssim 1$$

$$\frac{\beta^2}{\omega^2} = F\frac{1}{c^2} \qquad F \lesssim 1$$

$$\frac{\omega}{\beta} = c\frac{1}{\sqrt{F}}$$

$$v_p = c\frac{1}{\sqrt{F}} \qquad F \lesssim 1$$

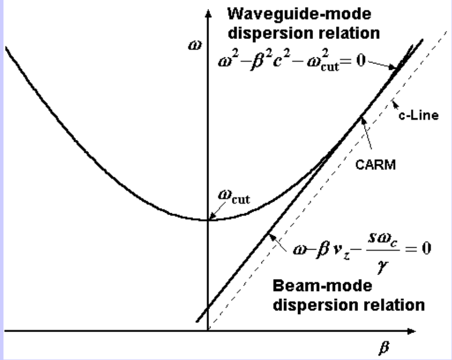
$$v_p \gtrsim c$$

Destabilization of slightly fast waves: Cyclotron auto-resonance maser

Some CARM features

Weibel and CRM instabilities are simultaneously present in equal proportions balancing the effects due to each other leading to auto-resonance.

Once the electron beam is phase-bunched, a large amount of energy could be extracted without loosing synchronism (auto-resonance).



Mildly fast waveguide mode is destabilized $v_p \gtrsim c$

Requires lesser magnetic field due to large βv_z Doppler shift

$$s\omega_c / \gamma = \omega - \beta v_z$$

(beam-mode dispersion relation)

Operated far from cutoff at a large value of the axial phase propagation constant β and hence sensitive to beam velocity spread causing inhomogeneous broadening of the cyclotron resonance band

- ✓ Wideband coalescence between the dispersion plots giving wide bandwidths

Operates at a lower beam pitch factor, higher beam voltage, with higher power capability, and at higher frequencies

Higher efficiency, since the axial kinetic energy is tapped

Increased stability due to higher axial electron velocities

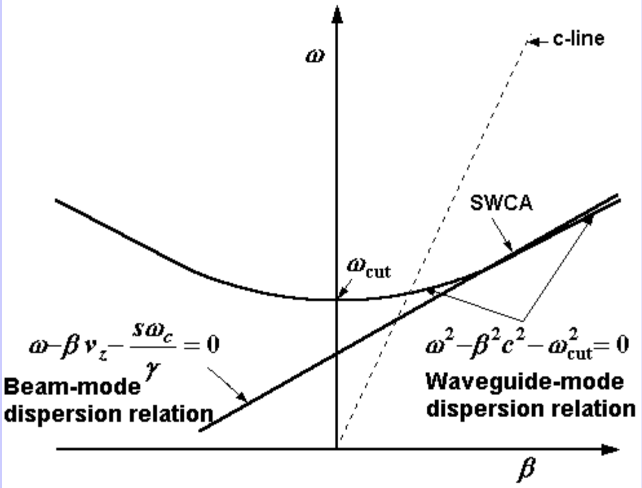
Reduced gain caused by axial bunching offsetting azimuthal bunching

- ✔ Wider device bandwidth due to wideband coalescence between the the beam-mode and waveguide-mode dispersion characteristics

Typical CARM Performance

10 MW, 35 GHz, 45 dB gain and 3% efficiency (1.5 MV, 0.25 kA)
10 MW at 125 GHz, 2% efficiency (0.5 MV, 1.0 kA)

Some SWCA features



Weibel instability dominates over CRM instability

Slow waveguide mode is destabilized $v_p < c$

Requires lesser magnetic field due to large βv_z Doppler shift

$$s\omega_c / \gamma = \omega - \beta v_z$$

(beam-mode dispersion relation)

- Wideband coalescence between the dispersion plots giving wide device bandwidths

Operates at a lower beam voltage,
with relatively lower power capability, and at lower frequencies

- Wider device bandwidth due to wideband coalescence between the the beam-mode and waveguide-mode dispersion characteristics

Typical SWCA performance

Ka band, 50 kW, 60 kV, 5 A, 7kG, 24-28 dB saturated gain, 2 dB/cm power gain, 15% efficiency at 2% axial beam velocity spread (JJ Choi *et al.*, IEEE-PS, Aug 1994, 465-475)

Stabilized by a sever against gyro-BWO instability

35 GHz, 1 dB/cm over 25-65 GHz, 71.5 kV, 9.2 A, 5.9 kG, 10% efficiency, bandwidth: 89.6% (10 dB), 67.1% (20 dB), 53.7% (30 dB), 1.6 mm average beam radius, 3.2 mm dielectric inner radius, 4.6 mm W/G radius, low-loss alumina lining, a metal mesh or coating on the dielectric to prevent static charge buildup

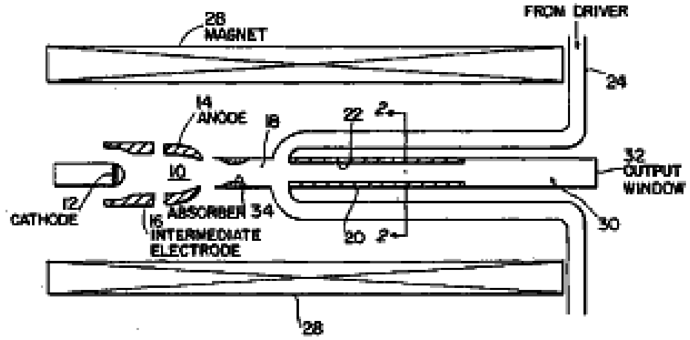


FIG. 1(a)

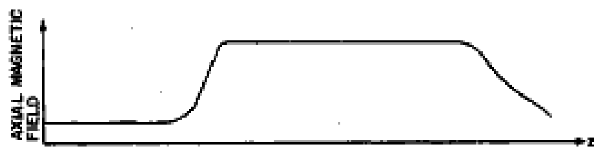


FIG. 1(b)

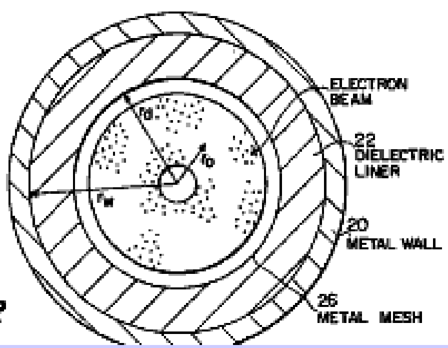


FIG. 2

The bandwidth of a 'slow-wave' TWT can be widened by

- providing azimuthally periodic metal vanes/segments with the metal envelope of the helical slow-wave structure and optimizing the structure parameters, thereby obtaining the desired dispersion characteristics of the structure for wide device bandwidths
- appropriately shaping the cross-sectional geometry of dielectric helix supports, thereby obtaining the desired dispersion characteristics of the structure for wide device bandwidths
- using multi-dispersion, multi-section helical structures
- using a relatively simple conventional fast-wave guiding structure though heavily dielectric loading it to operate it in the slow-wave regime to realize an SWCA for wideband coalescence between the beam-mode and the waveguide-mode dispersion plots for wide device bandwidths operating at a lower beam voltage, with relatively lower power capability and at lower frequencies

The bandwidth of a ‘fast-wave’ TWT can be widened by

- dielectric loading the cylindrical waveguide of a gyro-TWT, by either dielectric lining the waveguide or by providing a coaxial rod insert and optimizing the dielectric parameters for wideband coalescence between the beam-mode and the waveguide-mode dispersion plots resulting in wide device bandwidths
- tapering the waveguide cross section thereby causing the different length elements of the waveguide operate at different elements of frequency ranges, over a wide band of frequencies, thereby providing wide device bandwidths, however, at the cost of the device gain
- using axially periodic disc loading and optimizing the disc parameters for the desired wideband coalescence between the beam-mode and the waveguide-mode dispersion plots resulting in wide device bandwidths
- using multi-dispersion, multi-section waveguides for wide device bandwidths
- using tapered-cross-section axially periodic disc loading and optimizing the disc parameters for the desired wideband coalescence between the beam-mode and the waveguide-mode dispersion plots resulting in wide device bandwidths at relatively large gains
- realizing CARM operation in mildly fast-wave waveguide regime providing the desired wideband coalescence between the beam-mode and the waveguide-mode dispersion plots for wide device bandwidths at relatively higher beam voltages and at higher frequencies obtaining higher power levels and higher efficiencies though at reduced gains

State-of-the-art gyro-TWTs

Frequency	Power (MW)	Efficiency (%)	Bandwidth	Organisation
18.8	13	27	3%	Strathclyd University
35	0.34	51	26%	NRL
51.3	4	6.6	51	MIT
96	0.062	21	12	California University
140	0.03	12	2300 MHz	MIT

(Source: State-of-the-art of high power gyro-devices and free electron masers updates 2007, FZKA 7392)

Specifications of gyro-TWTs developed in some typical laboratories

(*Compiled by Vishal Kesari* <vishal_kesari@rediffmail.com>)

Operating frequency (GHz) / band	Power (kW)	Efficiency (%)	Gain (dB)	Bandwidth (%)/ 3-dB Bandwidth (GHz)	Mode/ Loading/ Tapering	Reference Year
35	340	51	2 (per cm)	2.6	Circular TE_{01}	Chu *et al.* 1979
35	100	>10	17	~ 10	—	Seftor *et al.* 1979
35	—	—	24	1.4	—	Barnett *et al.* 1979
35.1	—	—	32	—		
35	26	—	13	—		
35	10	—	30	—		
35		7.8	20	—		
35.12	3.2	—	42	—	Circular TE_{01} Resistive wall loading	Barnett *et al.* 1980
35.5	—	—	26 (Peak)	3.4		
~ 35	—	—	34	2		
5.2	50	16.6	—	6	Circular TE_{11} Non-tapered magnetic field	Ferguson *et al.* 1981
5.2	128	24	20	7.25	Circular TE_{11} Tapered magnetic field	
	18.8	9.8		9.3		
94	28	8	30	8	Circular TE_{11}	Eckstein *et al.* 1981

[*Continued*]

[*In continuation*]

Specifications of gyro-TWTs developed in some typical laboratories

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Operating frequency (GHz) / band	Power (kW)	Efficiency (%)	Gain (dB)	Bandwidth (%)/ 3-dB Bandwidth (GHz)	Mode/ Loading/ Tapering	Reference Year
35	—	—	18	13	Circular TE_{01} Tapered cross section and magnetic field	Barnett *et al.* 1981
94	20	8	30	2	—	Granastein and Park 1983
—	—	25	45	45	Two-stage tapered cross section	Ganguly and Ahn 1984
35	20×10^3	11	30	—	—	Gold *et al.* 1989
Ku-band	18.4	18.6	18	10	—	Chu *et al.* 1990
Ka band	27 (Peak)	16	35	7.5	Circular TE_{11}	Chu *et al.* 1990
35	5	10 (Saturated)	20	33	Rectangular TE_{10} Tapered cross section and magnetic field	Park *et al.* 1991
9-11	80	30 (Saturated)	15	20	Rectangular Dielectric loaded	Leou *et al.* 1992

[*Continued*]

[*In continuation*]

Specifications of gyro-TWTs developed in some typical laboratories

(*Compiled by Vishal Kesari* <vishal_kesari@rediffmail.com>)

Operating frequency (GHz) / band	Power (kW)	Efficiency (%)	Gain (dB)	Bandwidth (%)/ 3-dB Bandwidth (GHz)	Mode/ Loading/ Tapering	Reference Year
35	533	21.3	20	7.4	Circular TE_{21} Three-stage	Wang *et al.* 1992
35	7.4	15	30	8	—	Park *et al.* 1993
Ka-band (27-38 GHz)	—	10 (Saturated)	25	33	Two-stage	Park *et al.* 1994
35	8 (Saturated)	16	25	20	Two-stage Tapered	Park *et al.* 1995
34.2	62	21	33	12	—	Chu *et al.* 1995
Ku-band	207	12.9	16	2.1	—	Wang *et al.* 1995
16.7	207	—	—	—	Circular TE_{21} Axially sliced	Wang *et al.* 1996
15.9	20	—	—	—	Dielectric loaded	Wang *et al.* 1996
X-band	55	11	27 (Saturated)	11 (Constant) > 14 (Saturated)	Rectangular TE_{10} Dielectric loaded	Leou *et al.* 1996

[*Continued*]

[*In continuation*]

Specifications of gyro-TWTs developed in some typical laboratories

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Operating frequency (GHz) / band	Power (kW)	Efficiency (%)	Gain (dB)	Bandwidth (%)/ 3-dB Bandwidth (GHz)	Mode/ Loading/ Tapering	Reference Year
Ka-band	—	—	50 (Saturated)	—	—	Chu *et al.* 1997
X-band	55- 75	—	30	20	Rectangular Metal disc-loaded	Leou *et al.* 1998
95	6	5	11	3	Slotted structure	Chong *et al.* 1998
Ka band	93 (Saturated peak)	26.5	70	3 GHz (3-dB)	Lossy section	Chu *et al.* 1998
X-band	1×10^3	20	23	—	Helical waveguide	Denisov *et al.* 1998
—	—	28	38	19	Helical waveguide	Denisov *et al.* 1998
—	—	—	29 (Peak)	10	Helical waveguide	Cooke *et al.* 1998
35	2×10^3	20	30 (Saturated)	3.5	Circular TE_{41} Sliced waveguide	McDermott *et al.* 1998
Ka-band	100	26.5	70	8.6	Circular TE_{11} Lossy graphite covered wall	Chu *et al.* 1999

[*Continued*]

[*In continuation*]

Specifications of gyro-TWTs developed in some typical laboratories

(*Compiled by Vishal Kesari* <vishal_kesari@rediffmail.com>)

Operating frequency (GHz) / band	Power (kW)	Efficiency (%)	Gain (dB)	Bandwidth (%)/ 3-dB Bandwidth (GHz)	Mode/ Loading/ Tapering	Reference Year
35	93 (Saturated)	26.5	70	8.6	Circular TE_{11}	Chu *et al.* 1999
9.2	1.1×10^3	29	37 (Saturated) 47 (Linear)	21	Helically waveguide	Bratman *et al.* 2000
91.4	600	24	30	2.7	Circular TE_{02}	Wang *et al.* 2000
92	140	28	50 (Saturated)	5	Circular TE_{01} Distributed-loss circuit	McDermott *et al.* 2001
35	137 (Saturated)	17	47	3.3	Circular TE_{01} Ceramic rings (distributed attenuation)	Garven *et al.* 2002
32.9	155	15	45	2.2 GHz (3-dB)	Multistage	Yeh *et al.* 2003
140	30 (Peak)	12	29	2.3 GHz (3-dB)	Confocal waveguide HE_{06}	Sirigiri *et al.* 2003
34.2	—	10	23.8	4.1	Rectangular Two-stage tapered	Baik *et al.* 2003

[*Continued*]

[*In continuation*]

Specifications of gyro-TWTs developed in some typical laboratories

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Operating frequency (GHz) / band	Power (kW)	Efficiency (%)	Gain (dB)	Bandwidth (%)/ 3-dB Bandwidth (GHz)	Mode/ Loading/ Tapering	Reference Year
34.2	—	12	23.8	4.1	Rectangular Two-stage tapered	Baik *et al.* 2003
—	—	53	—	27	Coaxial irregular waveguide TE_{01}	Kolosov *et al.* 2003
Ka-band	20	—	—	—	Two-stage tapered (Frequency multiplication)	Baik *et al.* 2004
Ka-band	>3 kW	—	< 20 dB/m	4	Two-stage tapered (Frequency multiplication)	Baik *et al.* 2004
Ka-band	435	31	45	~ 5.8	Coaxial waveguide	Hung and Yeh 2005
W-band	≥ 0.5	—	≥ 45	≥ 8 GHz (3-dB)	Circular TE_{01}	Blank *et al.* 2005
95	15	6.2	30	1.6	—	Granastein and Alexeff
95	28	8	31 (Saturated)	—	—	CPI (Varian)
Ka-band	52		60	12	Circular TE_{11} Diffractive loading	Pershing *et al.*
	70		60	17		

Thank You