Metamaterial Slow-wave Structures for High-Power Microwave Devices

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Traditional Slow-wave Structure for Travelling Wave Tubes

Cerenkov Maser: Dielectric Lined Cylindrical Waveguide

Slow-wave Structure

- Electron gun
- RF signal, $v_p$
- Dielectric liner
- Collector

Bunched electron beam, $v_e$

Cherenkov Radiation Condition

1) Microwave signal $v_p \approx$ electron velocity $v_e$

$$v_p = \frac{C}{\sqrt{\varepsilon_{eq}}} \quad \Rightarrow \quad v_e = \frac{\sqrt{2eV_0}}{m}$$

*$e$ and $m$ are electron charge and mass.
$V_0$ = voltage applied to electron gun.

2) Strong longitudinal E-field at waveguide center (TM$_z$ modes) for mode coupling

Corresponding $K$-$\omega$ diagram

- Wide BW (constant $v_p$)
- Free Space
- Dielectric liner ($\varepsilon_r$)
- Equivalent dielectric medium ($\varepsilon_{eq}$)
Experimental Validation of Wave Slow-Down

In Volumetric Form
Finite 15-unit-cell Volumetric MPC

In Printed Form
Finite 9-unit-cell Printed MPC

Measured Group Delay (ns)

@ SIP: 7.2ns 0.18ns

Wave velocity reduction by a factor of 286
Nonreciprocal Leaky Wave Antenna Using Coupled Microstrip Lines

Ferrite substrate: \( \varepsilon_r=14 \), \( 4\pi M_s=1000 \) G, \( \delta H=100 \) Oe, \( \tan \delta_e=0.0002 \)

Unit-cell

Permanent magnet

Dispersion Diagram

Nonreciprocal Transmitting and Receiving Properties

- leaky/fast wave: \( |\beta_{-1}/k_0|<1 \) \( \rightarrow \) radiates
- guided/slow wave: \( |\beta_{+1}/k_0|>1 \) \( \rightarrow \) does not radiate

Beam-steering capability without frequency modulation due to tunable dispersion properties with bias field strength, \( H_i \)

\( l_1=110, l_2=120, w_1=60, w_2=20, w_3=30, s_1=105, s_2=10, h=100, d=440 \) (mils)
Possible Slow-wave Structures for Travelling Wave Tubes

Travelling Wave Tube with Periodic Slow-wave Liner

- **Dielectric/Ferrite Corrugations**
- **Metal Corrugations**
- **Concentric Metallic Rings**
- **Coupled Transmission Lines on Dielectric**

**Cherenkov Radiation in Periodic Media**

- Limited wave slow-down
  - good for relativistic e-beams, \( v_e \approx c \)
  - Less control over phase velocity

- Enormous wave slow-down
  - (good for slower e-beams, \( 0.1c < v_e < 0.3c \))
  - More control over phase velocity

\[ v_p = \frac{c}{n} \]

\( n = \text{effective refractive index of the medium} \)

Electron particle
Issues to be Addressed in Designing High-Power Microwave Devices

Cerenkov Maser

Advantages:
• Simple geometry
• Wider bandwidth
• Tunable operation
• Several MWs of output microwave power
• Validated performance

Shortcomings:
• Limited wave slow-down, depends on the filling ratio \(a/b\) and \(\varepsilon_r\)
• Dielectric charging
• Surface breakdown
• Bulky design

Dielectric filling ratio = a/b

• Fully metallic structures can overcome the shortcomings
• Goal is to explore all metal slow wave structures
**Traditional Vacuum Electronic Amplifiers**

**Linear Beam Amplifier**

**Advantage:**
- Highly linear gain, high efficiency
- Ultra-wide bandwidth
- Ultra-small size and low weight

**Disadvantage:**
- Not suitable for very high power (above 100KW)
- High manufacturing cost

**Working Principle:**
- Electron gun supplies the linear electron beam
- Input coupler supply the weak RF signal
- Focusing magnets confines the electron beam to center
- Slow-wave structure (i.e. helix, ring-bar structure, cerenkov maser) reduce phase velocity of electrons
- Collector absorbs electrons
- Output coupler receives the amplified RF signal

**MASER/Cross-Field Amplifier**

**Advantage:**
- Very high power and high efficient device
- Compact in size, reliable
- Inexpensive manufacturing cost
- Relatively stable operation

**Disadvantage:**
- Very poor linearity
- Limited bandwidth
- Bulky and heavy

**Working Principle:**
- Thermionic cathode supplies the electron beam
- Electrons are swept away by strong axial magnetic field and DC electric field
- Input RF field modulates electrons around the cathode
- Output port receives the amplified RF signal
**Parameters of TWT**

**Design Parameters**
- Electron velocity ($v_e$)
  - Related to beam voltage
- Wave Phase velocity ($v_p$)
  - Controls slow wave behavior within the TWT
- Interaction impedance, $K_0(\omega) = \frac{E_{axial}^2}{2\beta^2 W \nu_s}$
  - $K_0$ depends on the axial E-field strength and group velocity ($u_g$)
- Coupling parameter, $C = \sqrt[3]{K_0(\omega) \frac{I_0}{4V_0}}$
  - Parameter related to beam coupling into modes

**Performance Parameters**
- Gain ($G$) depends on
  - Coupling between electron beam and RF wave
  - Beam/Wave mode synchronization
  - Space-charge forces
  - Typical maximum gain can be 50-60dB
- Saturated Output Power ($P_{out}$) depends on
  - Gain and coupling parameter
  - Available electron kinetic energy
- Bandwidth (BW)
  - Saturated output power within a defined band
- Efficiency (%)
  - Efficiency of electron energy conversion into modes and electron gun efficiency

**Small Signal Gain, $G \approx -9.54 + 47.3 \times C \times N$ (dB)**

where, $N = \frac{L_f}{v_p}$, $L_1$ = Length of the tube

**Geometrical Parameters**
- Pitch or Periodicity ($p$)
  - Dominant parameter for any Slow Wave Structure (SWS)
  - Controls phase velocity ($v_p$) & interaction impedance ($K_0$)
- Radius of waveguide cylinder
  - Mode cut-off determinant parameter
  - Impedance determinant parameter
- Width and thickness
  - Fine tuning parameter for $v_p$
**TWT Gain**

### Cherenkov Radiation Condition

1) RF signal $v_p \leq$ electron velocity $v_e$.

$$\beta = \frac{2\pi}{\lambda_g} \approx \frac{\omega}{v_e}$$

$$v_p = \frac{\omega}{\beta} \approx v_e = \sqrt{\frac{2eV_0}{m}}$$

2) Strong axial E-field at waveguide center (TM$_z$ modes) for mode coupling.

- **Electron gun**

  - $v_e = (2eV_0/m)^{1/2}$
  - $e$ and $m$ are electron charge and mass.
  - $V_0 =$ voltage applied to electron gun.

### Small signal gain

- $\approx -9.54 + 47.3 \times C \times N$ (dB)

- $N =$ number of wavelengths
- $C =$ Pierce gain parameter


**Goal:** Higher gain ($G_0$) • Wider bandwidth

- Needs to be as large as possible to obtain high gain.

- Smaller design ($L$)

### Diagrams

- **Gain vs. Frequency**
- **Gain vs. Device Length**

- **Gain** $G_0$ 
  - Bandwidth $G_0/2$
  - Frequency

- **Gain** $G_0$ 
  - Device Length $L$
  - 9
To achieve good beam-wave coupling, \( v_p \approx v_e \) i.e. \( v_p \downarrow \Rightarrow P_{out} \downarrow \)

**Low Power SWS**
- Low \( v_p (<0.3c) \) → Small \( \lambda_g \) → High N
- High N → High Gain(G)

**Small Signal Gain, \( G \approx -9.54 + 47.3 \times C \times N \) (dB)**

\[
N = \frac{L f}{v_p}, \quad C = \text{coupling parameter}
\]

where, \( L = \text{Tube length} \), \( f = \text{Frequency} \)

**Moderately high Power SWS**
- High \( v_p (>0.3c) \) → Long \( \lambda_g \) → Low N
- Low N → Low Gain(G)
Helix Review: Cold Circuit Performance
(without the electron beam)

1) Phase velocity of EM wave = electron velocity
\[ v_p = c \sin \psi = v_e = \left(2eV_0/m\right)^{1/2} \]
\[ \psi = \cot^{-1}(2\pi a/p) = \text{pitch angle} \]
\( e \) and \( m \) are electron charge and mass, \( V_0 \) is the voltage applied to electron gun.

\[ \text{Helix} \]
\[ a = 4.2 \text{ mm} \]
\[ p = 5, 8, 10 \text{ mm} \]
\[ \delta = 0.7 \text{ mm} \]
\[ b = 11 \text{ mm} \]
\[ w = 1 \text{ mm} \]

Normalized Phase velocity

constant \( v_p \) over wide BW

\[ v_p/c \]

Frequency (GHz)

2) Pierce Impedance:
\[ K_0 = E_z^2/(2\beta^2 P) \]

\[ E_z: \] Longitudinal field strength along z axis
\[ \beta: \] phase constant within WG
\[ P: \] net power flow along helix

\[ \delta \text{ is the dominant parameter for controlling } v_p \]

Advantages:
- Simple geometry, wide bandwidth
- Tunable operation

Shortcomings:
- Limited gain at high frequencies (\( K_0 \) drops)
- Space harmonics inhibiting amplification for \( v_e > 0.2c \) (smaller \( K_0 \) for \( v_e > 0.2c \))
**Miniaturized Low Power TWT by OSU**

**Maximum Gain**

- \( a=4\text{mm} \)
- \( p=4\text{mm} \)
- \( w=0.74\text{mm} \)

**Half-Ring-Helix**

**Maximum Saturated Power**

- \( a=4\text{mm} \)
- \( p=8\text{mm} \)
- \( w=0.74\text{mm} \)

<table>
<thead>
<tr>
<th>Non-relativistic beam</th>
<th>0.4c ( \geq V_p ) ( &gt;0.1c )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Gain</td>
<td>46 dB</td>
</tr>
<tr>
<td>Maximum Power</td>
<td>1KW</td>
</tr>
<tr>
<td>Maximum BW</td>
<td>0.75 GHz</td>
</tr>
</tbody>
</table>

- 10dB improvement in gain compared to regular helix TWT
- 28% miniaturization achieved

Challenges from Low Power to High Power TWT

Challenges

- High Power sources generate extreme heat
- Regular dielectrics cannot be used for high power applications
- High permittivity material cannot be used for support layout
- Metallic structures are desirable to sustain heat stress
- Difficulty in controlling high phase velocity and high interaction impedance
- Powerful magnetic focusing needed
- Smaller electrical length, miniaturization is more difficult
- Low achievable bandwidth

Design goals:

- Design Slow Wave Structure (SWS) that support wave phase velocity $v_p > 0.8c$
- Good interaction impedance ($K_0$) profile
- SWS must be fully metallic to be compatible with heated environment
- Least possible dispersion to maintain good bandwidth
- Smallest possible TWT
Choosing a Workable Structure

- Single-Helix (SH)
- Half-Ring-Helix (HRH)
- Single-Ring-Bar (SRB)

**Phase velocity**

Dimensions:
- $a = 4 \text{mm}$
- $p = 20 \text{mm}$
- $w = \delta = 1 \text{mm}$

**Group velocity**

- $K_0 = \frac{E_z^2}{2 \beta^2 W v_g}$

- None of the above give large $\nu_p$ and $K_0$ concurrently
- However, SRB is attractive because largest $K_0$ and moderate $\nu_p$
- **SRB is an attractive structure for high power!!**
**Parametric study of SRB**

**Effect of cylinder radius, b**
- Two controlling parameters (i.e., \( p \) and \( b \))
- \( p \uparrow \rightarrow v_p \uparrow \)
- \( p \uparrow \rightarrow K_0(\Omega) \downarrow \)
- \( b \) has very less effect

\[ K_0 = \frac{Ez^2}{2\beta^2Wv_g} \]

**Effect of pitch, \( p \)**
- Lower \( p \rightarrow \) more slowdown
- Lower \( p \rightarrow \) High \( K_0 \)

\[ K_0 = \frac{Ez^2}{2\beta^2Wv_g} \]

**\( v_p \) and \( K_0 \) are competing parameters!**

Not much change in \( v_p \)
Improving phase velocity ($\nu_p$)

Dimensions:
- $a=4\text{mm}$
- $p=20\text{mm}$
- $w=\delta=1\text{mm}$

- Inserting second bar increases $\nu_p$ by 1.5 times.
- $K_0$ reduces by 6 times!!

- Desirable $\nu_p$ by increasing conducting path
- Need to increase E-field at the center so that $K_0$ increases concurrently

Phase velocity

Interaction impedance

Comparison of E-field Profile(V/m)
Improving Interaction Impedance ($K_0$)

**Top view**

Phase velocity

**Side view**

Group velocity

Dimensions:
- $a=4\text{mm}$
- $p=20\text{mm}$
- $w=\delta=1\text{mm}$
- $h_1=h_2=5\text{mm}$

Interaction impedance

- Larger $K_0$ than Double Bars
- Desirable $\nu_p$
- Curved bar is an attractive geometry!!
New Control Parameter, Axial Ratio (m)

Dimensions:
- a=4mm
- p=20mm
- w=δ=1mm
- h₁=8mm
- h₂=h₁ x m

Axial ratio, m can be used to control \( v_p \) and \( K_0 \)

Next step: design optimization

Deign goals:
- \( V_p > 0.8c \)
- \( K_0 > 50\Omega \)

Interaction impedance

Normalized Phase velocity

Normalized Group velocity

\[
K_0 = \frac{E_z^2}{2\beta^2Wv_g}
\]
Curved Ring-Bar with Rippled Wall: Comparison

Deign goals:
\(\nu_p > 0.8c\)
\(K_0 > 50\Omega\)

E-field Profile (V/m)

More Aligned and strong axial field

Phase velocity

Slow Wave region

Dispersive

Interaction impedance

Interaction impedance

Curved Ring-Bar TWT

Dimensions:
\(a = 4\text{mm}\)
\(b = 30\text{mm}\)
\(p = 20\text{mm}\)
\(w = \delta = 1\text{mm}\)
\(h_1 = 8\text{mm}\)
\(h_2 = 4.8\text{mm}\)

Interaction impedance

Curved Ring-Bar TWT

Curved Ring-Bar has Strong E-field at center (suitable for bunching)

Better control for Curved Ring-bar Structure

Dispersive

\(K_0 = \frac{E_z^2}{2\beta^2W_v}\)

More Aligned and strong axial field

Curved Bar has good dispersion and almost flat impedance (>48\(\Omega\)) profile

Ripple wall can generate large impedance with high dispersion

Concluding Remarks

Curved Ring-Bar (CRB) Structure

- Designed a new Curved Ring-Bar that provides $v_p > 0.75c$
  - Operates with $v_e = 0.86c$.
  - Operates at relativistic velocity with moderate interaction impedance, $K_0$
  - Good impedance profile across S-band

- Next Steps:
  - Simulate Curved Ring-Bar using PIC and CST codes to investigate beam-wave interaction (hot beam test)
  - Choose materials and support layout for high power realization
  - Conduct thermal and structural analysis
  - Transition to UNM to fabricate design for testing
  - Adapt design approach to Backward Wave Oscillators (BWO).