Waveguide Characteristics and Measurement Errors

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Agenda

• Background
• Characteristics
• Conclusion
Waveguide

• Waveguide = hollow metal pipe
• Rectangular, 2:1 aspect ratio

• Advantages
  – Conducts millimeter signals
  – Low loss
  – High power
  – Good shielding
  – Can "flare" end into horn antenna

• Disadvantages
  – Bandwidth < 1 octave
  – Rigid, heavy, large
  – Expensive
  – No DC connection
  – Dispersive

\[ a = 2 \times b \]

Waveguide dimensions
## Millimeter Bands

<table>
<thead>
<tr>
<th>Std Name</th>
<th>US EIA Name</th>
<th>P1785(1) Name</th>
<th>Fcutoff (GHz)</th>
<th>Fmin (GHz)</th>
<th>Fmax (GHz)</th>
<th>a(2) (inches)</th>
<th>b(2) (inches)</th>
<th>a(2) (um)</th>
<th>b(2) (um)</th>
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(1) Proposed naming convention, IEEE working group P1785  
(2) US EIA series waveguide dimensions (in inches) and P1785 waveguide dimensions (in micrometers) vary by as much as 3% for waveguide smaller than WR-03 due to standards differences.
Propagation Modes

- Electromagnetic wave modes
  - TEM
  - TE & TM
  - Hybrid

- Rectangular waveguide
  - Supports TE and TM
  - For $\text{TE}_{mn}$, $m$ & $n$ give the "order" of mode
  - Mode propagates above its "cutoff frequency"
Waveguide Frequencies

- Standard millimeter waveguide is 2:1
- \( F_{\text{cutoff}1} = \frac{c}{2 \times a} \)
  - No propagation below \( F_{\text{cutoff}1} \)
  - TE10 propagates between \( F_{\text{cutoff}1} \) and \( 2 \times F_{\text{cutoff}1} \)
  - Other modes propagate above \( 2 \times F_{\text{cutoff}1} \)

- Operating range
  - \( F_{\text{min}} = 1.25 \times F_{\text{cutoff}1} \)
  - \( F_{\text{max}} = 1.89 \times F_{\text{cutoff}1} \)
  - \( F_{\text{LinearMean}} = 1.57 \times F_{\text{cutoff}1} \)
  - \( F_{\text{GeometricMean}} = 1.54 \times F_{\text{cutoff}1} \)
Dispersion

- Wave propagation depends on frequency
- Below $F_{\text{cutoff1}}$, no propagation
- Above $F_{\text{cutoff1}}$, the wave "ping-pongs"
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Propagation Velocity

- Wave velocity: Free space propagation
- Group velocity: Energy propagation
- Phase velocity: Phase propagation

\[
V_{\text{wave}} = c \\
V_{\text{group}} = c \sqrt{1 - \left(\frac{f_{\text{cutoff1}}}{f}\right)^2} \\
V_{\text{phase}} = \frac{c}{\sqrt{1 - \left(\frac{f_{\text{cutoff1}}}{f}\right)^2}} \\
c^2 = V_{\text{phase}} \times V_{\text{group}}
\]
Group Delay

\[
\text{GD} = \frac{\text{GD}_{\text{freespace}}}{\sqrt{1 - \left(\frac{F_{\text{cutoff1}}}{f}\right)^2}}
\]

\[
\text{GD} = \frac{\text{Physical Length}}{V_{\text{group}}}
\]

\[
\text{GD} = 1\text{ns / foot, in free space}
\]

- GD is infinite at \(F_{\text{cutoff1}}\) & approaches GD_{freespace}
Guide Wavelength

\[ \lambda_{\text{guide}} = \frac{\lambda_{\text{freespace}}}{\sqrt{1 - \left(\frac{f}{F_{\text{cutoff1}}}\right)^2}} \]

\[ \lambda_{\text{guide}} = \frac{V_{\text{phase}}}{f} \]

\[ \lambda_{\text{freespace}} = 1\text{mm @ 300GHz} \]

- \( \lambda_{\text{guide}} \) is infinite at \( f_{\text{cutoff1}} \) & approaches \( \lambda_{\text{freespace}} \)
Impedance

\[ Z_{TE} = \frac{Z_{freespace}}{\sqrt{1 - \left(\frac{F_{cutoff1}}{f}\right)^2}} \]

\[ Z_{Freespace} = 377\,\Omega \]

- \( Z_{TE} \) is infinite at \( F_{cutoff1} \) & approaches \( Z_{freespace} \)
- Network analyzers assume \( Z_0 = "1" \)
Loss

Loss is due to skin effect & surface roughness
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- Waveguide is dispersive
- \( Zo = 444\Omega - 628\Omega \)
- Set \( Zo = "1" \) in VNA
- Group delay is 18~67% longer than free space
- Wavelength is 18~67% longer than free space
- Skin effect loss is high (6.5dB/meter for WR7)