Realizing Dielectric Waveguide Network Analyzers for Millimeter-wave Frequencies

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Overview

• Why Dielectric Waveguide?

• VNA Design

• Standards & Calibration

• NPL’s Realized Systems & Applications (to date)

• Summary
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Dielectric Waveguide – some background

‘Common’ transmission lines above 100 GHz:

• Rectangular Metallic Waveguide

• On-wafer (CPW)

• Dielectric Waveguide
For accurate measurements, we would like transmission lines with (amongst other things):

- Low insertion loss (i.e. low attenuation)
- Good interconnectability (i.e. low return loss)
- Easy and reliable traceability of measurement (to SI)
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Why dielectric waveguide??

Compared to metallic waveguide at millimeter wavelengths:

- Better Connections – more repeatable; lower loss
  - can be non-contacting (to some extent)
  - junctions can be inspected visually

- Standards easier to characterise (using mechanical measurements)
  - defined by external guide dimensions (height & width)

- Better electromagnetic properties
  - lower dispersion
  - lower loss
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VNA design

- Choice of Dielectric Waveguide Material
- Choice of VNA
- Test Port Design
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Choice of Dielectric Waveguide Material

Six materials considered:
- PEEK = Polyether Ether Ketone
- PTFE = Polytetrafluoroethylene
- HDPE = High-density Polyethylene
- Rexolite® = Cross linked Polystyrene
- TPX® = Polymethylpentene
- PP = Polypropylene
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PEEK – very lossy
PTFE & HDPE – low loss but too flimsy
Rexolite – rigid, but ‘high’ loss
PP & TPX – rigid, and low loss

Therefore, TPX (and PP*) chosen as the dielectric material
(* PP is not easy to glue to other materials)
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Choice of VNA

• Use a commercial (waveguide) VNA
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Test Port Design

Horn

Metal Waveguide

Taper

Dielectric Waveguide
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Transition taper design

![Diagram of transition tapers](image)

Plot of $S_{11}$ vs. Frequency (GHz)

- No Taper
- Case (a)
- Case (b)
- Case (c)
- Case (d)
- Case (e)
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5 mm taper – E field (100 GHz)
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5 mm taper – H field (100 GHz)
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5 mm taper – return loss (dB)

![Graph showing return loss in dB as a function of frequency.](image-url)
10 mm taper – E field (100 GHz)
10 mm taper – H field (100 GHz)
10 mm taper – return loss (dB)
Standards and Calibration

• One-port
  • standards
  • calibration

• Two-port
  • standards
  • calibration
One-port standards

• Offset short-circuits

• Use different lengths, \( l \), of dielectric waveguide

• Terminate each with a ‘mirror’

\[ |\Gamma| = 1; \quad \varphi_i = f(\beta, \ l_i) \]
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- Computer-driven motorised standards wheel
- Containing up to six standards
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One-port calibration: six offset short-circuits

@ 75 GHz

@ 110 GHz
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One-port calibration

Uncertainty estimated from:

- Random errors (connection repeatability)
- Systematic errors (cal stds imperfections)

Typical VRC uncertainty ≈ 0.006 (44 dB return loss), 75 to 110 GHz
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Two-port standards

• Lines
  – $\lambda/4$ at midband (?)
  – $3\lambda/4$ at midband
  – $5\lambda/4$ at midband
  – $7\lambda/4$ at midband

• Reflect
  – ‘flush’ short-circuit using a ‘large’ copper sheet
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Line standards
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VNA Test Ports and connection platform
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VNA test ports and line holder
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Adding a line to the line holder
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‘Connecting’ a line standard – close up
The line in place (suspended between test ports)
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Connecting the Reflect Standard
Two-Port calibration

• Thru-Reflect-Line

• Connecting all three standards is easy!

• But $\lambda/4$ line standards are getting short, as $f > 110$ GHz !!
## TRL Line lengths

<table>
<thead>
<tr>
<th>Waveguide</th>
<th>λ/4 (mm)</th>
<th>3λ/4 (mm)</th>
<th>5λ/4 (mm)</th>
<th>7λ/4 (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WR-10 75 – 110 GHz</td>
<td>(0.7)</td>
<td>2.2</td>
<td>3.6</td>
<td>5.0</td>
</tr>
<tr>
<td>WR-06 110 – 170 GHz</td>
<td>(0.5)</td>
<td>1.4</td>
<td>2.3</td>
<td>3.2</td>
</tr>
<tr>
<td>WR-05 140 – 220 GHz</td>
<td>(0.4)</td>
<td>1.1</td>
<td>1.8</td>
<td>2.5</td>
</tr>
</tbody>
</table>

These are too short!
NPL’s Realised Systems & Applications (to date)

• One- and Two-port Systems in WR-10 (75 – 110 GHz)

• Two-port System in WR-06 (110 – 170 GHz)

• Two-port System in WR-05 (140 – 220 GHz)
Applications – Some Sample Measurements

What shall we measure??

• Lines (as calibration verification devices)

• Materials (as devices under test)
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Measurements of a line: $|S_{11}|$

![Graph showing $|S_{11}|$ vs Frequency (GHz)]
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Measurements of a line: $|S_{21}|$

![Plot of $S_{21}$ vs Frequency (GHz)]
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3.6 mm line: \( S_{21} \) phase measurement, expressed as a length

![Graph showing phase measurement as a function of frequency for a 3.6 mm line.](image-url)
5.0 mm line: $S_{21}$ phase measurement, expressed as a length
Material measurement

- YAG: Yttrium Aluminium Garnet
- $\varepsilon_r = 10.6$
- 10 mm square; 0.53 mm thick
- Designed to be a ‘Beatty’ standard
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YAG Measurement Set-up

Dielectric waveguide
Test ports

YAG Sheet
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YAG Reflection: model versus measurement

![Graph showing the comparison of measured and predicted S11 and S22 values against frequency.](image)
YAG Transmission: model versus measurement

![Graph showing measured and predicted S12 and S21 values across different frequencies.](image-url)
Summary

• Dielectric Waveguide VNAs can be built around existing hardware

• Standards are easy to make and easy to use

• Calibration is similar to conventional methods (e.g. TRL)

• Measurement results look promising and offer a method of characterising materials at millimeter and submillimeter wavelengths

• Measurement Traceability to SI is straightforward and reliable
Bibliography

• K Lees, C Eio, M J Salter, N M Ridler and R N Clarke, “Investigation of the use of dielectric waveguide reflectometry for measuring complex permittivity at millimetre-wave frequencies” 29th URSI General Assembly, Chicago, IL, August 2008.


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