Performance assessment of VNA calibration schemes for millimeter-wave and submillimeter-wave frequencies, using the 33 GHz – 50 GHz band

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• Introduction
• Measurement setup
• Open-ended WG reflection standard
• Experimental results
• Conclusion
Introduction

• various VNA calibration schemes recently proposed for rectangular waveguides in mm and sub-mm bands
  – using of traditional $\lambda/4$ TRL line may cause problems (e.g. waveguide operating at 500 GHz ... 0.2 mm TRL line)
  – using of longer lines is preferred because of better mechanical robustness resulting in better repeatability
  – calibration accuracy is degraded by the flange misalignment
  – suitable are standards not suffering from flange misalignment (radiating open waveguides and flush shorts)

• how do these calibration schemes work at lower frequencies?
Introduction

- motivation: comparison of VNA calibration schemes suitable for traceable S-parameter measurements at mm- and submm-wave frequencies with well-established “low frequency” techniques
- comparison performed in the frequency band 33 GHz–50 GHz (WR-22 rectangular waveguide)
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Measurement setup

- **VNA setup**
  - Agilent PNA series E8364B
  - 2.4 mm flexible test port cables
  - 2.4 mm to waveguide adapters
  - Maury Microwave calibration kit model J7007H
Measurement setup

- **Calibration standards**
  - parts of cal kit J7007H
    - flush short
    - $\lambda/4$ shim, length 2.4 mm
    - waveguide load (2 pcs.)
    - adapter 2.4 mm to WR22 (2pcs., used as test ports and radiating open standards)
  - additional standards
    - precision shim, nominal length 2 mm
    - precision shim, nominal length 4.4 mm
    - combinations of the above standards
Measurement setup

- **Devices under test**
  - 8.8 mm offset short
  - matched waveguide load
  - 6.8 mm airline
  - 20 dB attenuator
  - mismatched load
  - direct connection of waveguide test ports
Measurement setup

- **Calibration methods + schemes**

  - **TRL** (reference calibration scheme)
  - **SSL** (short, offset short, load, offset load)
  - **TRL2** (calibration using two roughly $\frac{3}{4}\lambda$ lines, *one line cannot cover the whole frequency band*)
  - **LRL** (line, reflect, line, *ref. plane set using flush short measurement*)
  - **SSM** (short, offset short, match = *radiating open*)
  - **SSMT** (+ thru for 2-ports)
  - **TRM** (thru, reflect, match = *radiating open*)
  - **SSMU** (short, offset short, match = *radiating open, unknown thru*)

VNA firmware

suitable for mm & sub-mm

offline calibration
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Open-ended WG reflection standard

- 2.4 mm to waveguide adaptors (model J236A3) with Maury Microwave Precision WR22 Flange (MPF22), 2 pcs.
- 3 different ways of the radiating open characterization
  - **infinite flange model**
    - measurements: approximation not appropriate for used flanges
  - **more detailed simulation of the flange**
    - full-wave electromagnetic field simulator based on FDTD (for nominal dimensions)
  - **VNA measurements (TRL calibration)**
    - considered to be the most accurate in the frequency band 33 GHz – 50 GHz

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Open-ended WG reflection standard

• reflection coeff. measurements and simulations
Open-ended WG reflection standard

- open flanges with two pins (most common configuration) used as calibration standard for reported comparison measurements only
- other configurations presented here used for evaluation of the accuracy of the simulation only
Open-ended WG reflection standard

- deviations of the measured and simulated reflection coefficient too big for accurate characterization of calibration standard
• Repeatability of radiating open standards
  – standard deviation about 0.003 for repeated measurements, each after new calibration
  – difference between reflection coefficient (complex valued) measurements of two MPF22 flanges <0.005
  – difference in reflection coefficient measurements of the waveguide radiating against the pyramidal absorbers and “just into lab” in order of 0.001
Conclusions for WR22 waveguide with MPF22 flange

- good repeatability
- reflections of both flanges almost identical
- accuracy of the simulation not sufficient (open flange unsuitable as calculable standard)
  - complicated shape of the flange
  - simplification (e.g. no threaded holes)
  - nominal flange dimensions used in simulation
Conclusions and expectations for higher frequency bands

- In contrast to lower frequency bands, design of the flange used for bands from 75 GHz to 1100 GHz is typically the same.
- With increasing frequency, the problematic structures (pins, alignment holes etc.) are electrically further from the waveguide aperture → better accuracy of electromagnetic simulation can be expected.

<table>
<thead>
<tr>
<th>Flange</th>
<th>Frequency Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>MPF22 flange</td>
<td>WR22 33-50 GHz</td>
</tr>
<tr>
<td>UG387 flange</td>
<td>WR10 75-110 GHz</td>
</tr>
<tr>
<td>WR05 140-220 GHz</td>
<td>WR03 220-330 GHz</td>
</tr>
</tbody>
</table>
Open-ended WG reflection standard

deviations of the UG387 flange and infinite flange refl. coefficient
infinite flange approximated by simulation of large circular flange (d>25a)
Open-ended WG reflection standard

• for each waveguide size both simulations done under exactly the same conditions (mesh, solver, other parameters)
• systematic errors of the simulation can be reduced when only differences are taken into account
• combining with published methods suitable for accurate infinite flange modelling can improve the accuracy
• we suppose that this approach can yield sufficient accuracy of the open-ended WG reflection standard characterization at higher frequency bands
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Experimental results

- results of calibration schemes under test (CSUT) compared to the “reference” TRL method (together or as a ratio)
- calibration schemes based on open-ended waveguide standard (OEWG) usually presented in separate pictures
- only some of the results shown due to time limit
Matched load - differences of measurements at port 1 and port 2
Experimental results

Matched load – differences of CSUT and TRL results

![Graph showing differences between CSUT and TRL results](image)
Matched load – differences of CSUT with OEWG and TRL results
Offset short – comparison of CSUT and TRL results (VRC magnitude)
Experimental results

Offset short – differences of CSUT and TRL results (VRC phase)

![Graph showing differences in VRC phase between CSUT and TRL results](graph_image)

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Experimental results

Offset short – comparison of CSUT and TRL results (VRC magnitude)
Experimental results

Offset short – differences of CSUT and TRL results (VRC phase)
Experimental results

Mismatched load – differences of CSUT and TRL results
Mismatched load – comparison of CSUT with OEWG and TRL results
Mismatched load – differences of CSUT with OEWG and TRL results
Experimental results

Line 6.8 mm – differences of CSUT and TRL results
Experimental results

Line 6.8 mm – differences of CSUT with OEWG and TRL results

![Graph showing differences of CSUT with OEWG and TRL results.](image)
Experimental results

Line 6.8 mm – comparison of CSUT and TRL results
Experimental results

Line 6.8 mm – comparison of CSUT with OEWG and TRL results

![Graph showing comparison of TRL, SSM, TRM results across frequency bands.](image_url)
Experimental results

20 dB attenuator – differences of CSUT and TRL results

![Graph showing differences of CSUT and TRL results with frequency (GHz) on the x-axis and |S21| / |S21, ref| (dB) on the y-axis. The graph compares TRL2 and LRL.]
Experimental results

20 dB attenuator – differences of CSUT with OEWG and TRL results

![Graph showing differences of CSUT with OEWG and TRL results](image-url)
Thru – comparison of results of Unknown thru method
note: difference between pink and light green traces due to 12 μm change in offset short length definition
Experimental results

Thru – comparison of results of Unknown thru method

![Graph showing comparison of results of Unknown thru method]
Experimental results

20 dB attenuator – differences of Unknown thru and TRL results

![Graph showing frequency response](image-url)
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Summary of results in frequency band 33 GHz – 50 GHz

• TRL (λ/4 line)
  – chosen as a reference cal. scheme (well-established at this band)
  – smallest differences of low-refl. load measurements at both VNA ports
  – no significant ripple observed on offset short VRC trace

• TRL2 (two roughly ¾ λ lines 6.4 mm, 8.8 mm)
  – slightly worse results for low-reflection measurements
due to worse uniformity of longer lines (assembled from shims)

• LRL (lines 6.4 mm, 8.8 mm, set ref: reflect)
  – reference plane setting by flush short (better characterization of flush short in comparison with 6.4 mm line presumed)
  – slightly worse results for low-reflection measurements
  – deviations for transmission and high reflection measurements observed
can indicate discrepancy between flush short definition and reality
Conclusion

- **SSLL (short – offset short – load – offset load)**
  - slightly worse results in comparison with TRL based methods for both low reflection and high reflection devices

  - accuracy significantly dependent on accuracy of characterization of used standards, mainly OEWG

- **TRM**
  - accuracy significantly dependent on accuracy of characterization of used standards, mainly OEWG
  - for low-reflective devices comparable results with SSMT
  - for high-reflective devices and transmission measurements slightly better results in comparison with SSMT

- **SSMU (short – offset short – match/OEWG/ – unknown thru)**
  - transmission measurements very sensitive to inaccurate definition of reflection standards
  - another characteristics similar as for SSMT
Conclusions

- TRL calibration scheme with $\frac{3}{4} \lambda$ lines works very well
- Good accuracy of methods using OEWG can be expected at higher frequency bands
- Maybe, the accuracy of the methods using OEWG (mainly TRM) as calculable standard can be similar (or better?) in comparison with TRL at higher frequency bands
- Investigation of TRM method with intentionally misaligned thru standard can be useful
EMRP project “SIB62 Metrology for new electrical measurement quantities in high frequency circuits”
http://www.hfcircuits.org/

Thank you for attention