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

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Contents

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

- various VNA calibration schemes recently proposed for rectangular waveguides in mm and sub-mm bands
  - using of traditional λ/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?

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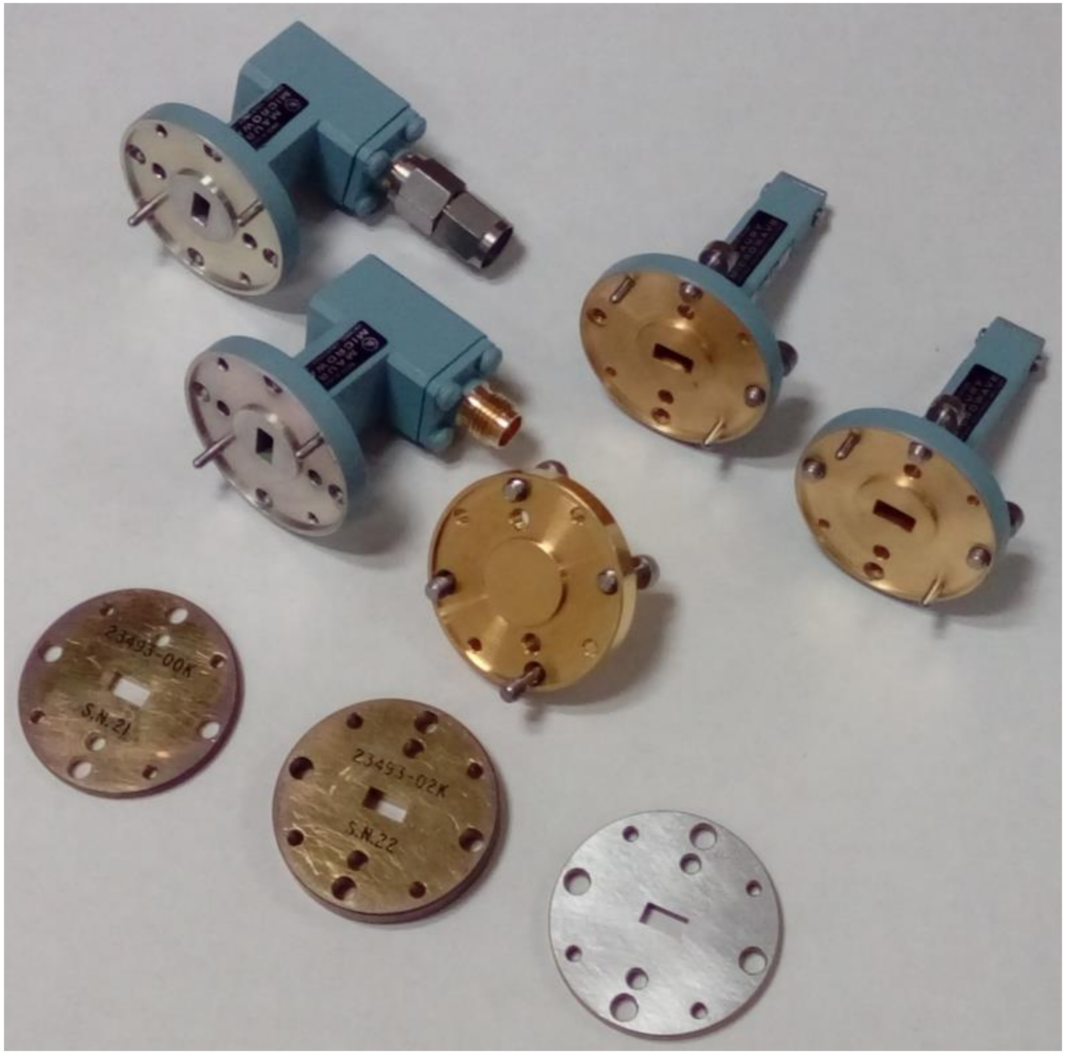
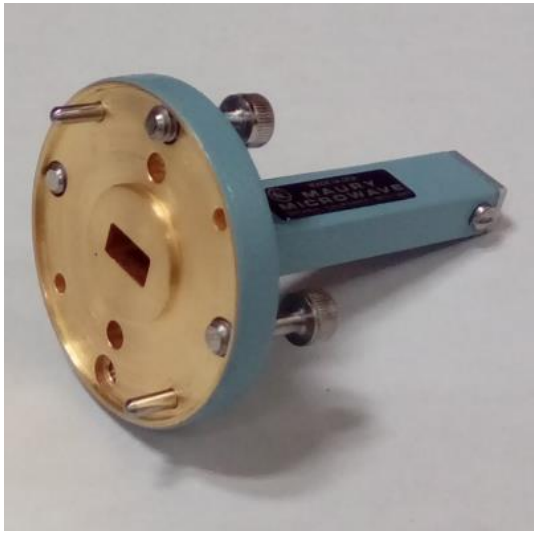
- VNA setup
  - Agilent PNA series E8364B
  - 2.4 mm flexible test port cables
  - 2.4 mm to waveguide adapters
  - Maury Microwave calibration kit model J7007H

- Calibration standards
- ❑ parts of cal kit J7007H
  - flush short
  - λ/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



- 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



- Calibration methods + schemes

VNA firmware

- **TRL** (reference calibration scheme)
- **SSLL** (short, offset short, load, offset load)
- **TRL2** (calibration using two roughly ¾-λ 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)

offline calibration

suitable for mm & sub-mm

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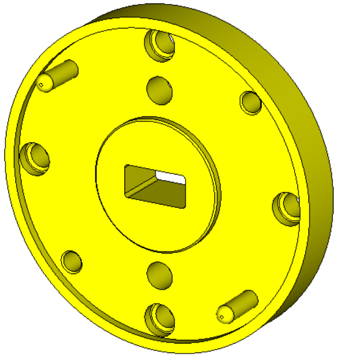
- **2.4 mm to waveguide adaptors (model J236A3) with Maury Microwave Precision WR22 Flange (MPF22), 2 pcs.**
- **3 different ways of the radiating open characterization**

  - **infinite flange model**
    - measurements: approximation not appropriate for used flanges

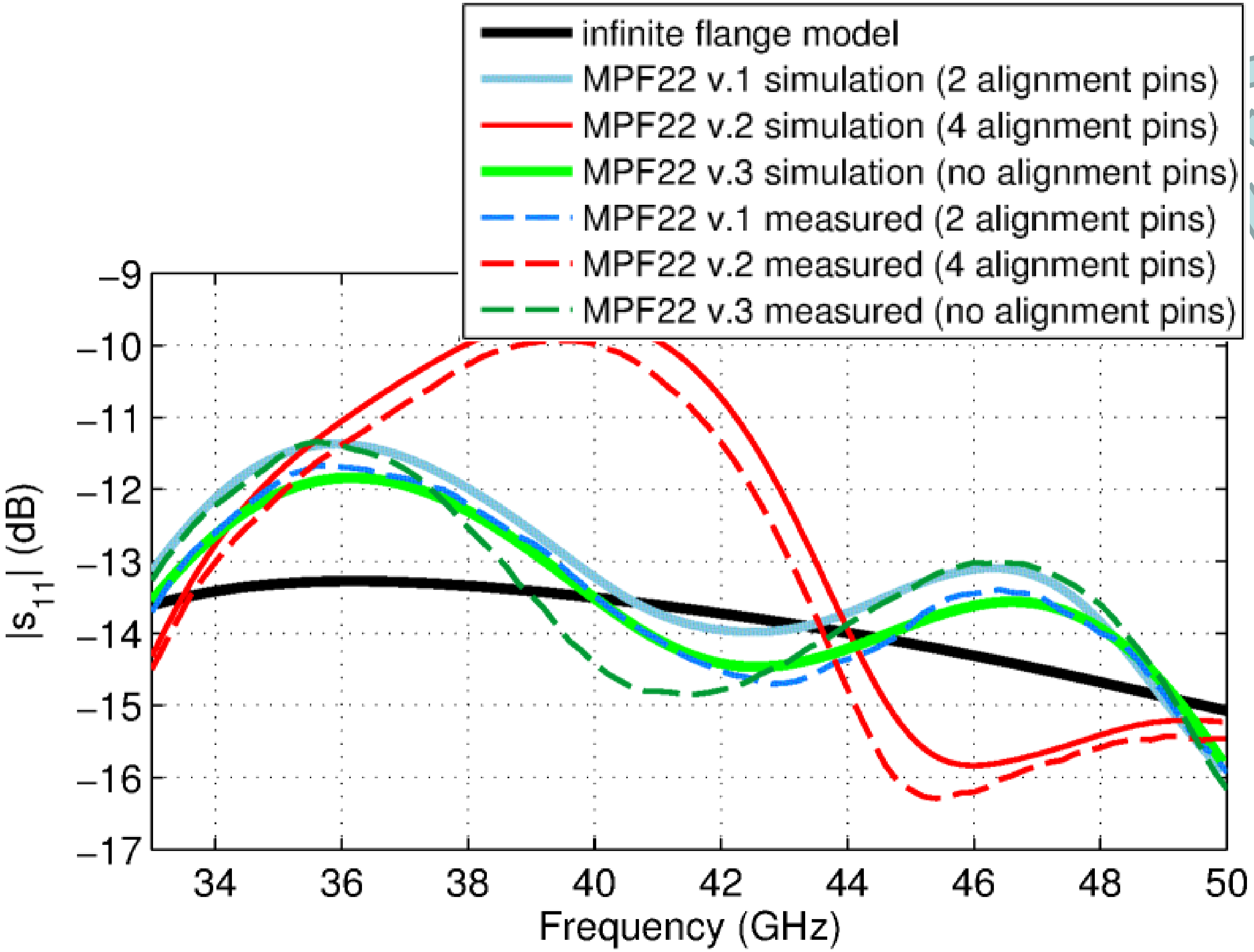


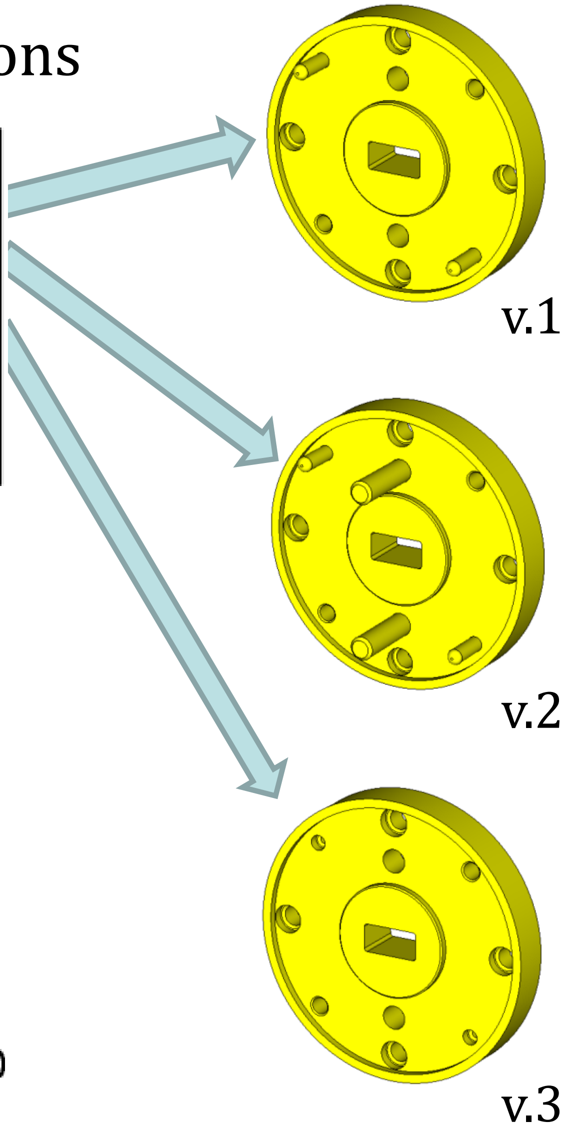
J. H. Kim, B. Enkhbayar, J. H. Bang, B. C. Ahn, E. J. Cha, "New Formulas for the Reflection Coefficient of an Rectangular Waveguide Radiating into Air including the Effect of Wall Thickness or Flange," *Progress In Electromagnetic Research M*, Vol. 12, pp. 143–153, 2010

  - **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

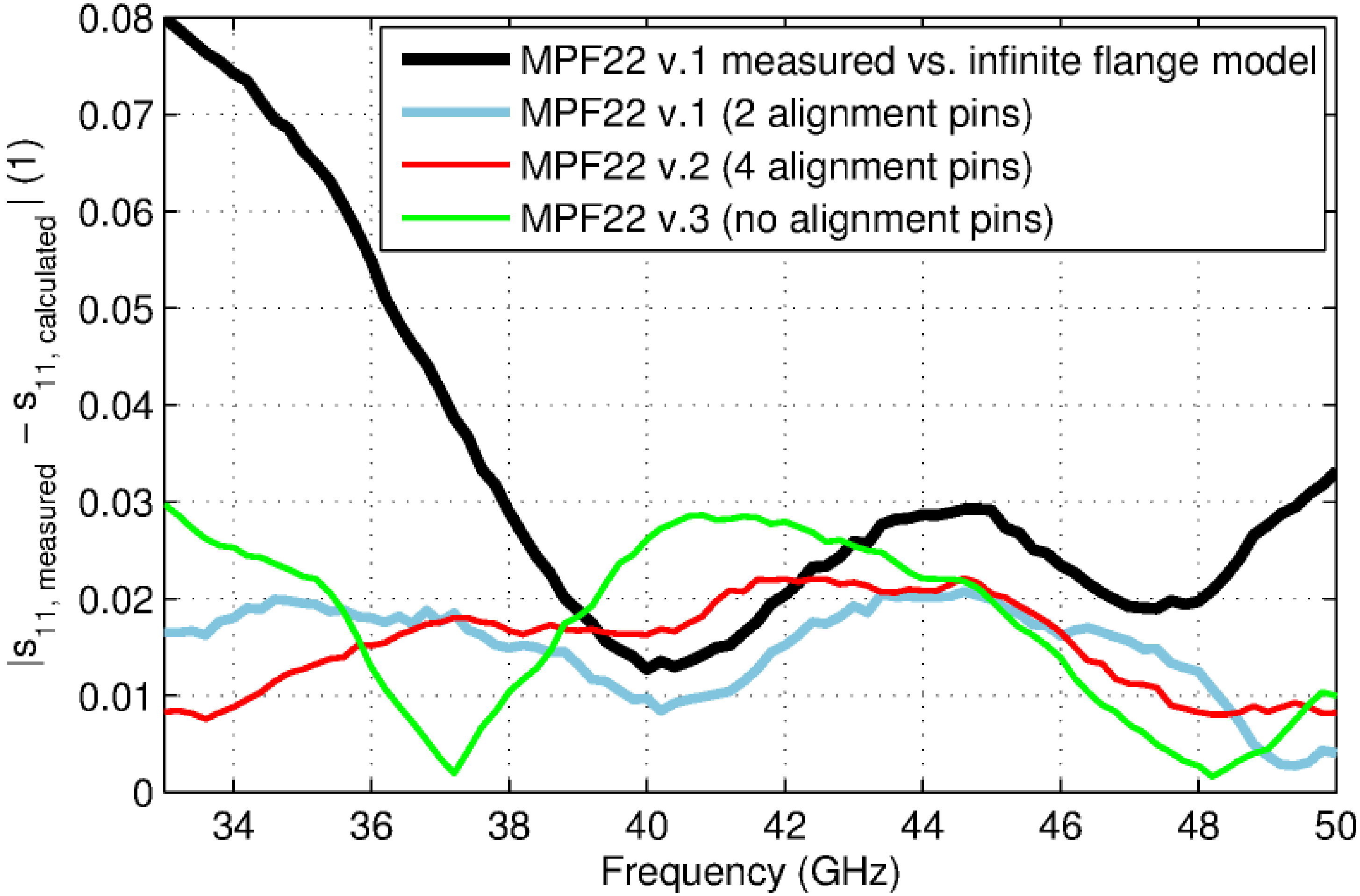
- reflection coeff. measurements and simulations





- 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

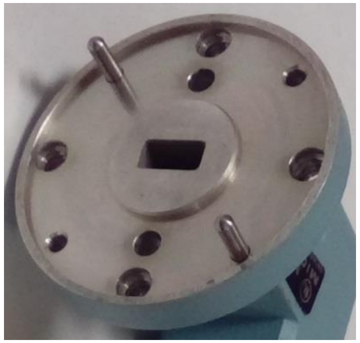
- deviations of the measured and simulated reflection coefficient too big for accurate characterization of calibration standard

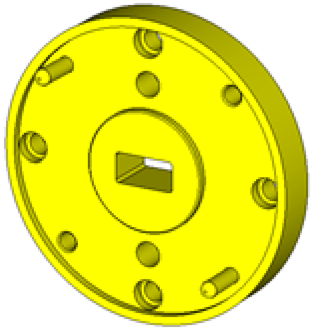


- Repeatability of radiating open standards
  - standard deviation about 0.003 for repeated measurements, each after new calibration
  - difference between reflection coefficient (complex valued) measurements of two MPF22 flanges <0.005
  - difference in reflection coefficient measurements of the waveguide 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



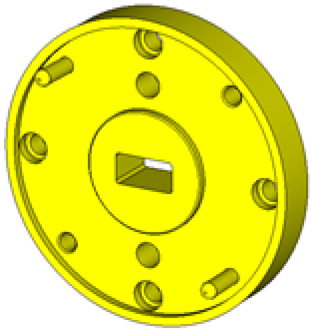


Conclusions and expectations for higher frequency bands

- 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

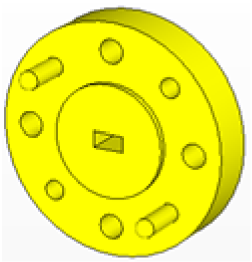
MPF22 flange

WR22 33-50 GHz

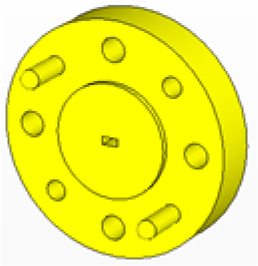


UG387 flange

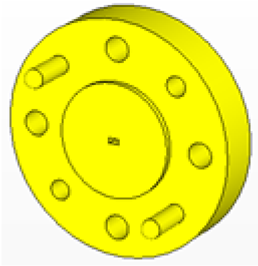
WR10 75-110 GHz



WR05 140-220 GHz

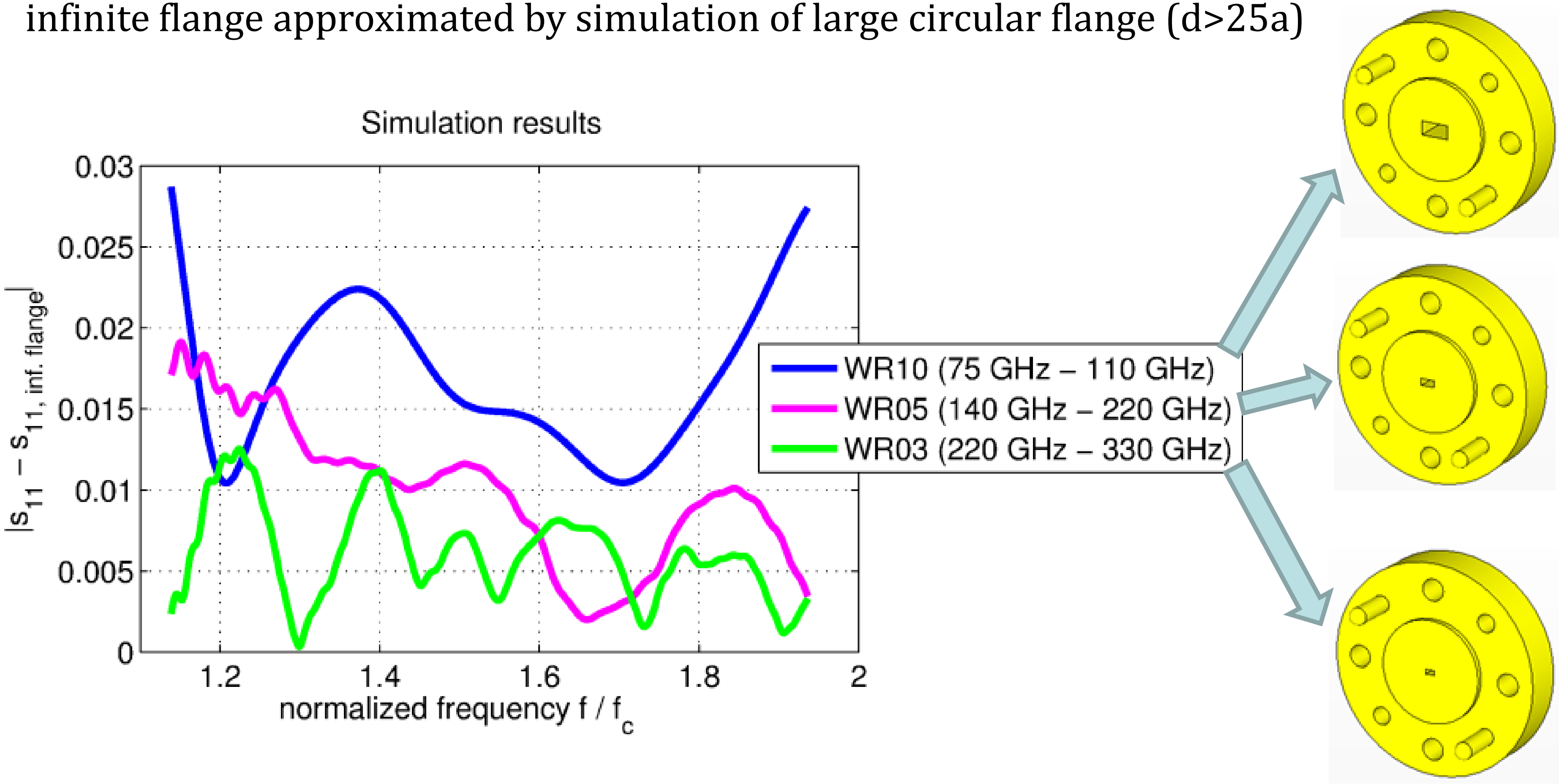


WR03 220-330 GHz



deviations of the UG387 flange and infinite flange refl. coefficient

infinite flange approximated by simulation of large circular flange (d>25a)



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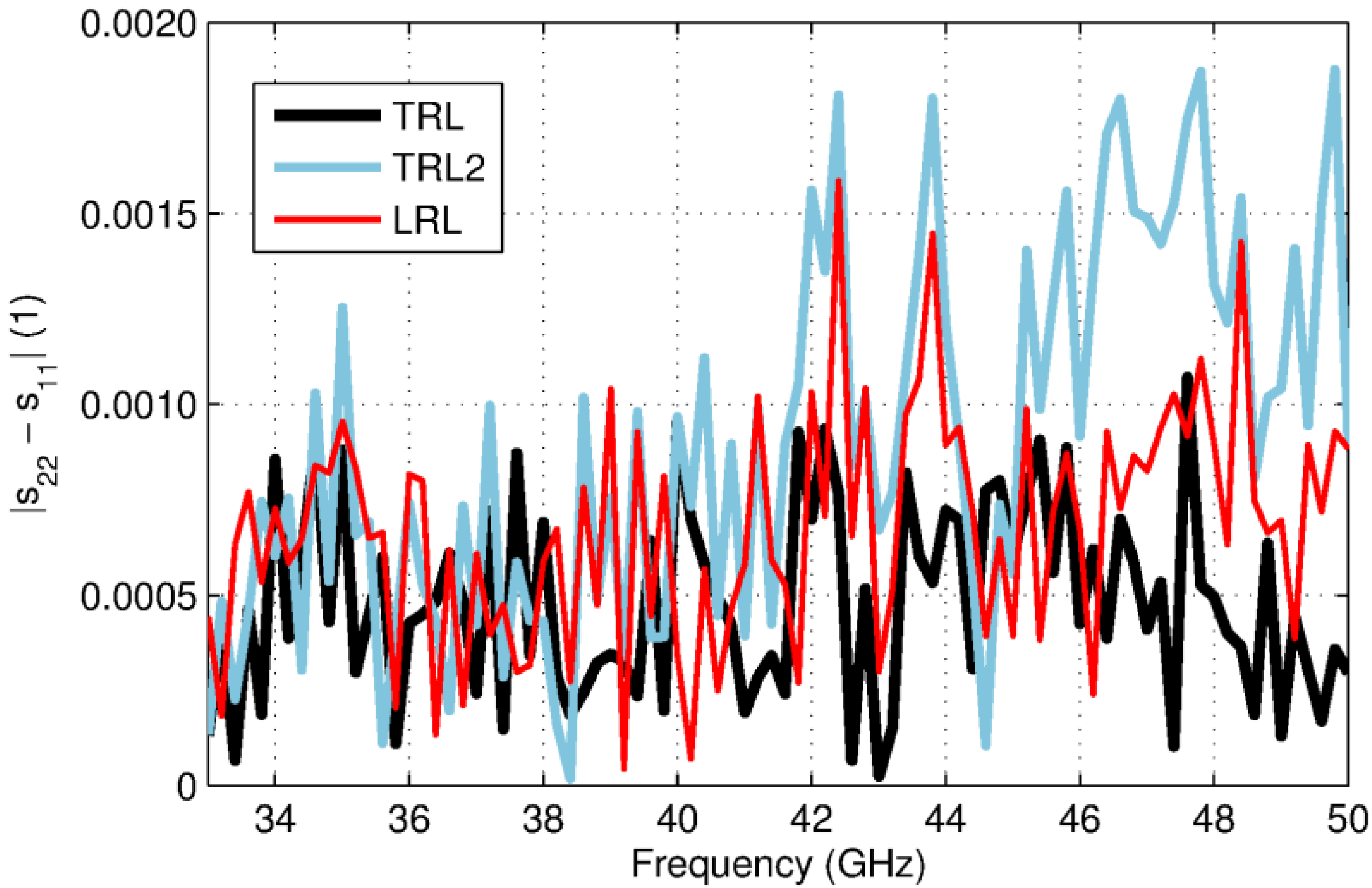
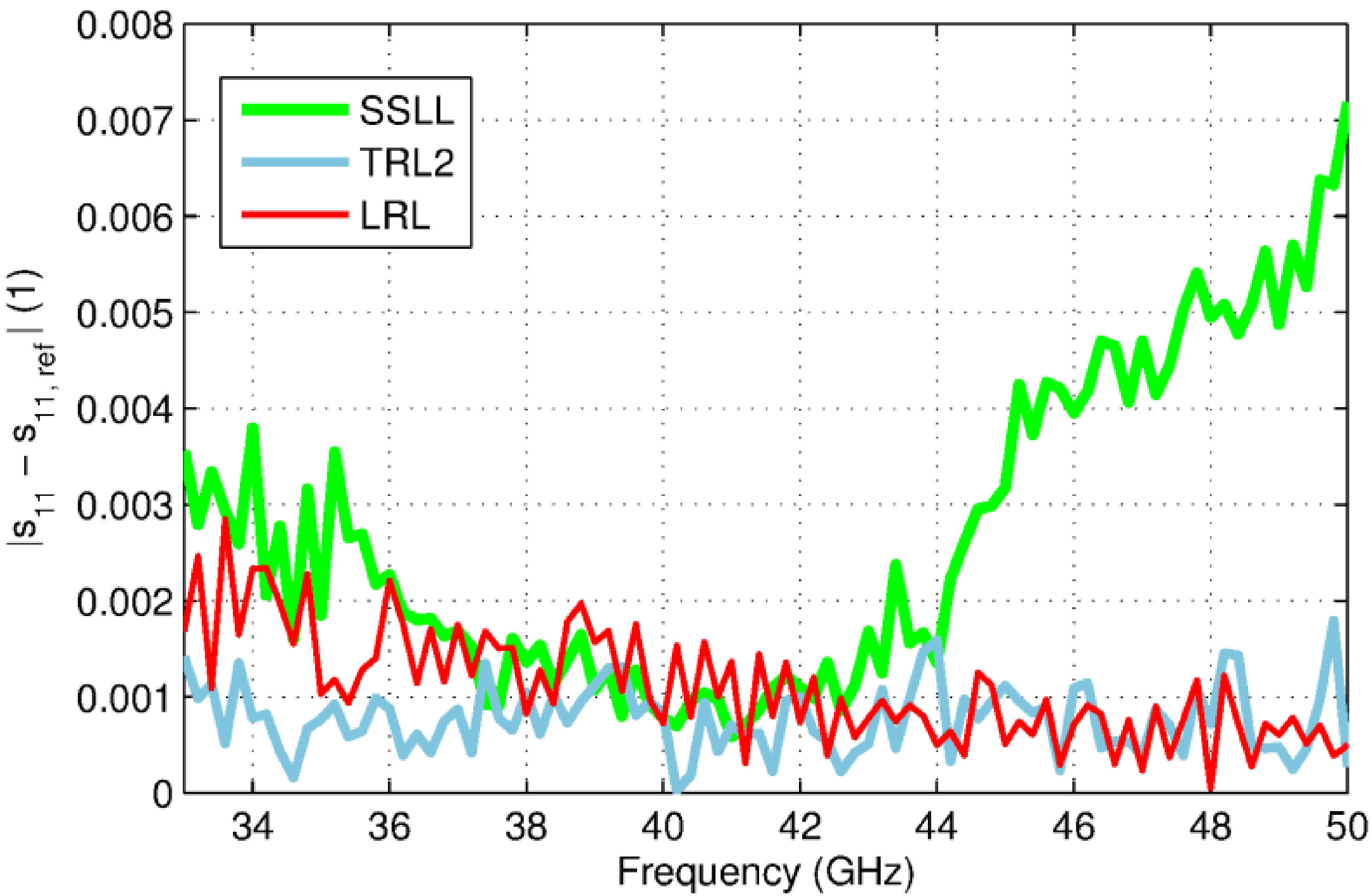
- results of calibration schemes under test (CSUT) compared to the “reference” TRL method (together or as a ratio)
- calibration schemes based on open-ended waveguide standard (OEWG) usually presented in separate pictures
- only some of the results shown due to time limit

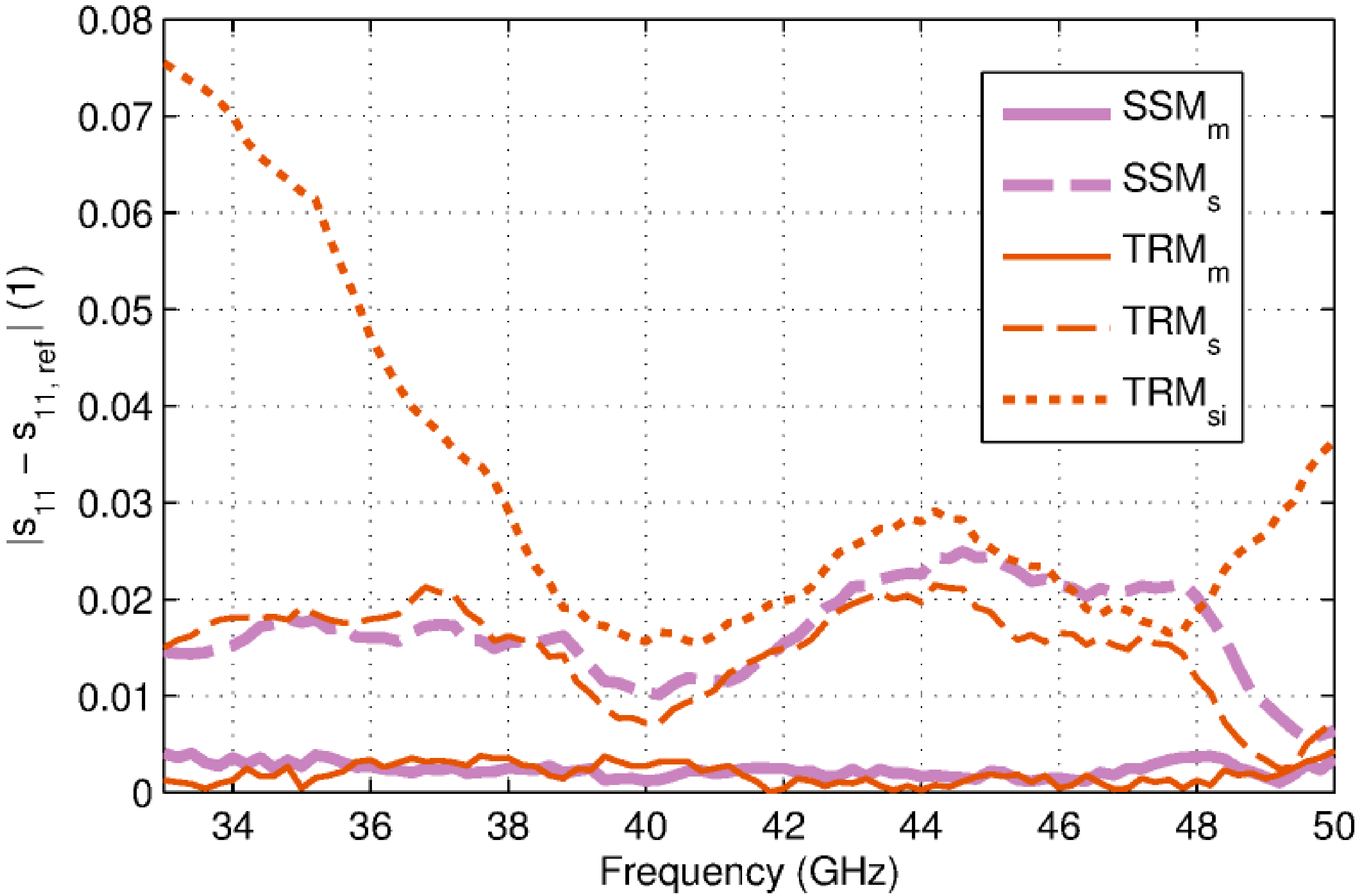
Matched load - differences of measurements at port 1 and port2



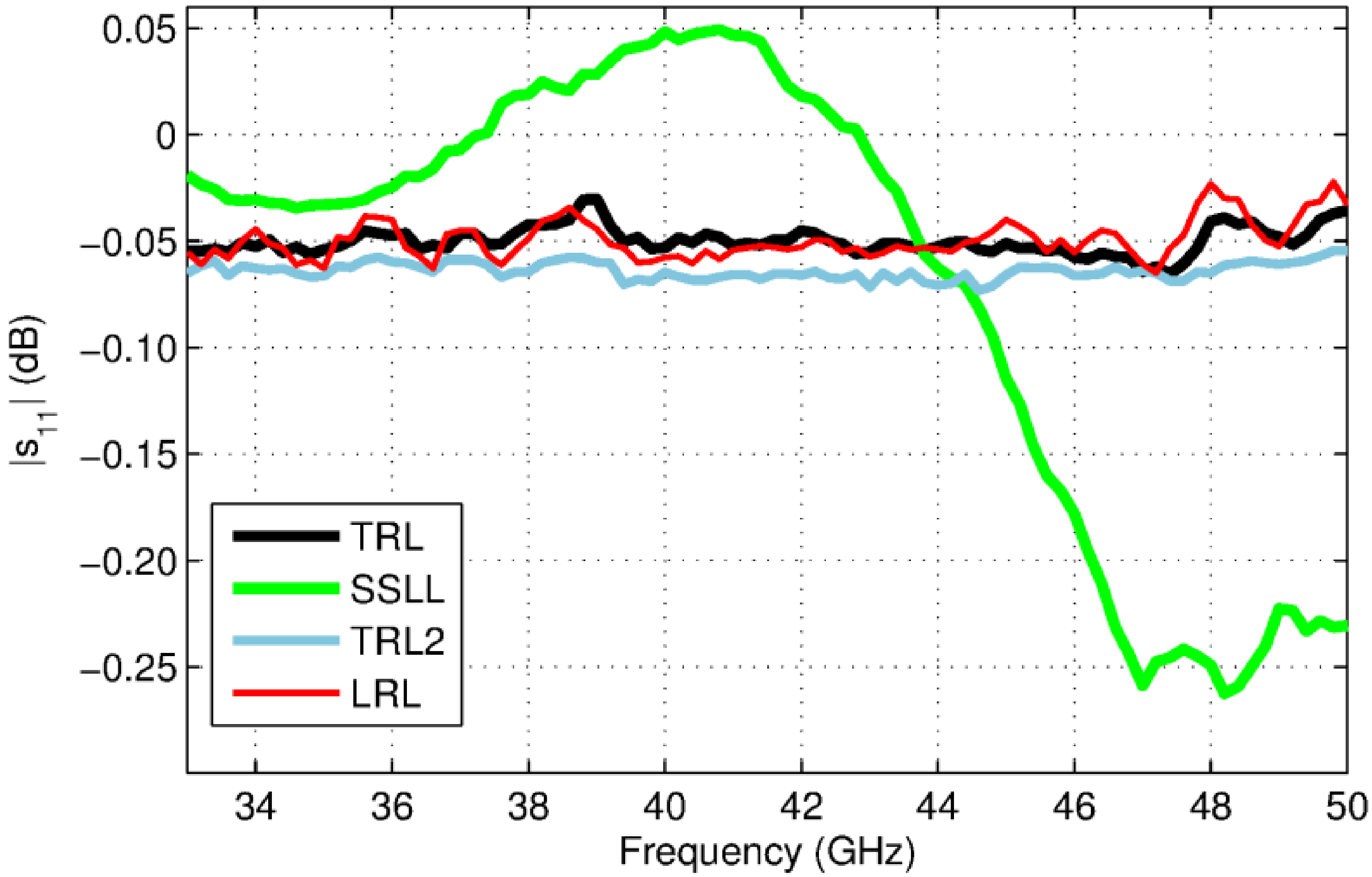
Matched load – differences of CSUT and TRL results



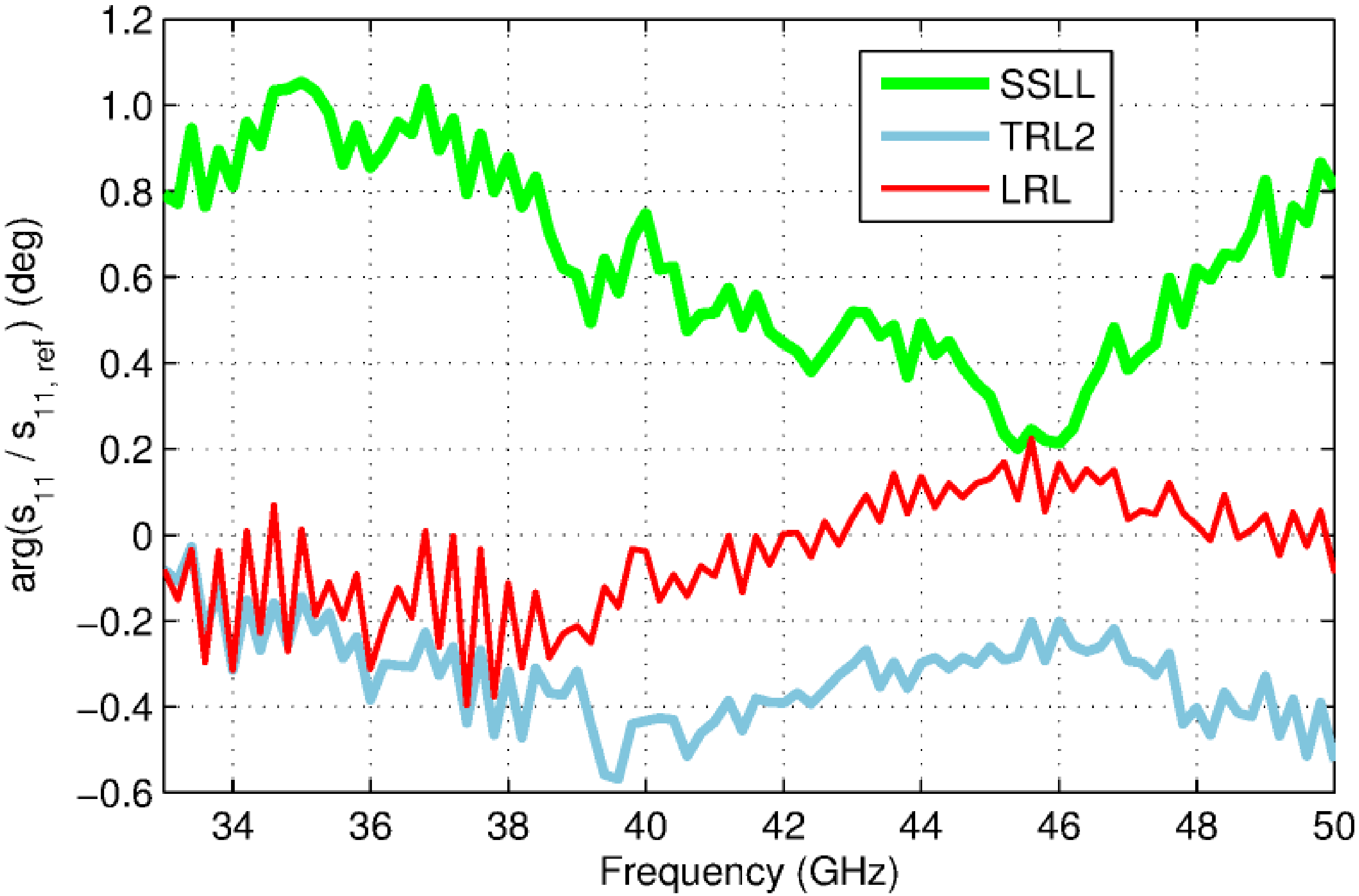
Matched load – differences of CSUT with OEWG and TRL results



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



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



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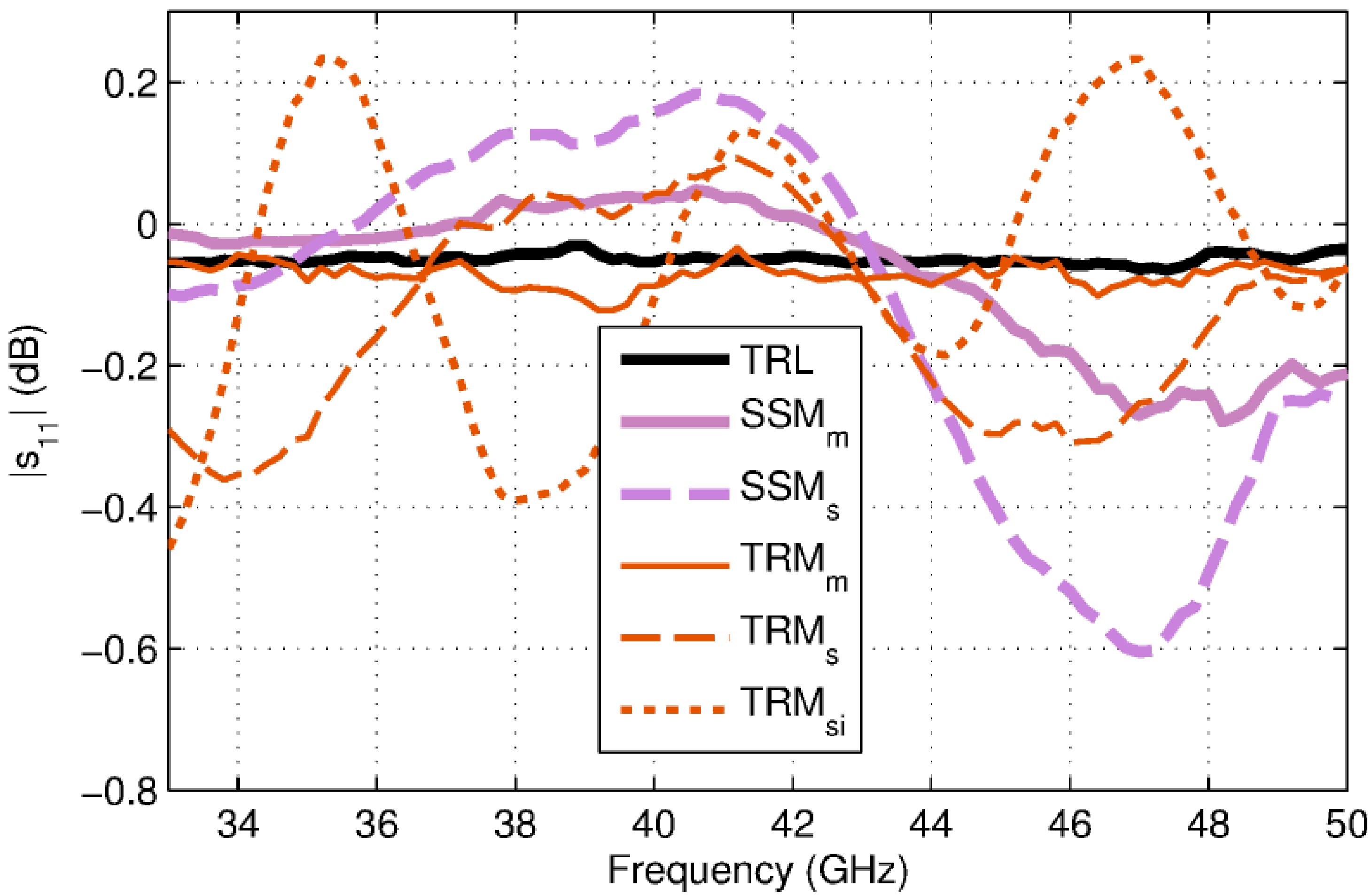

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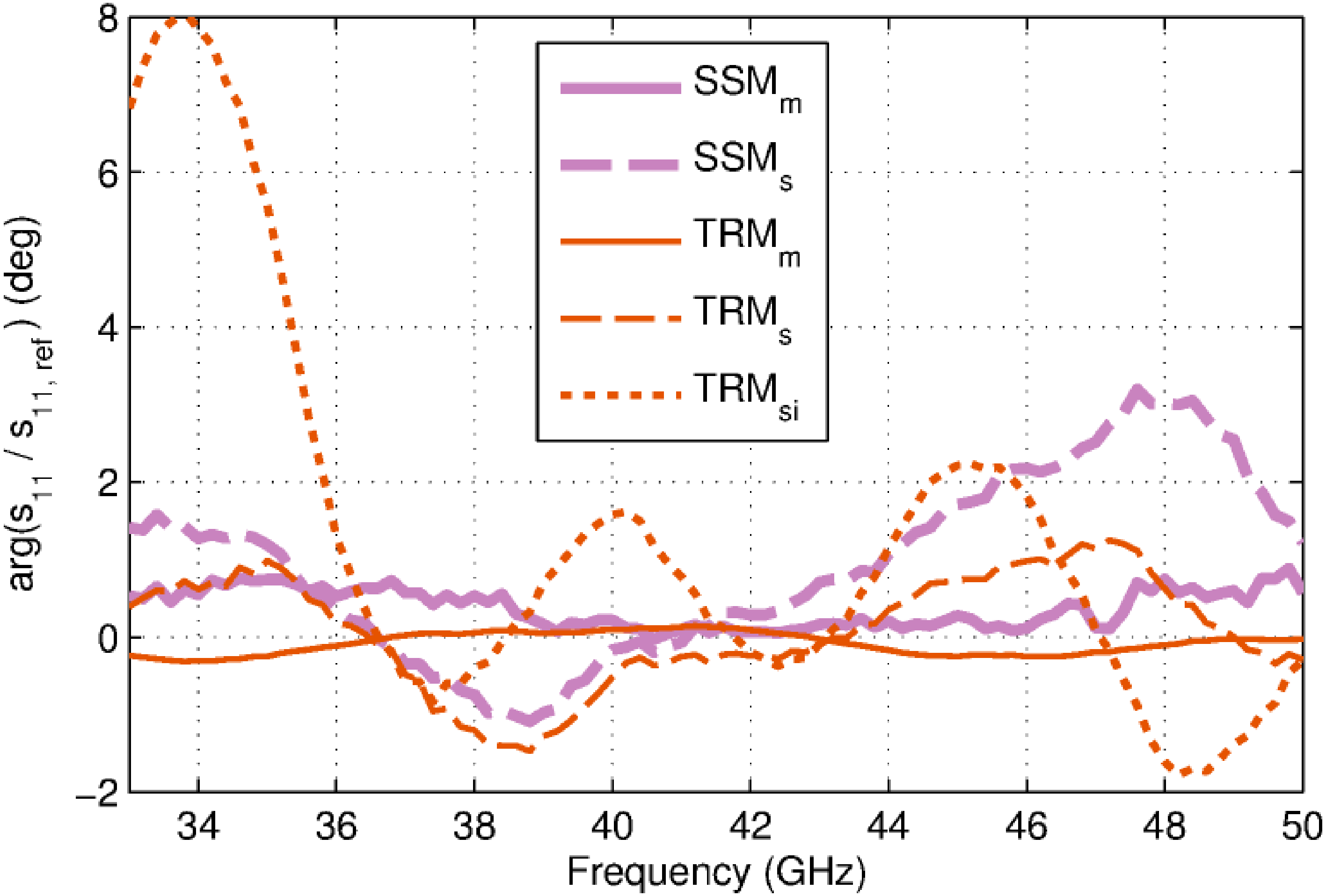
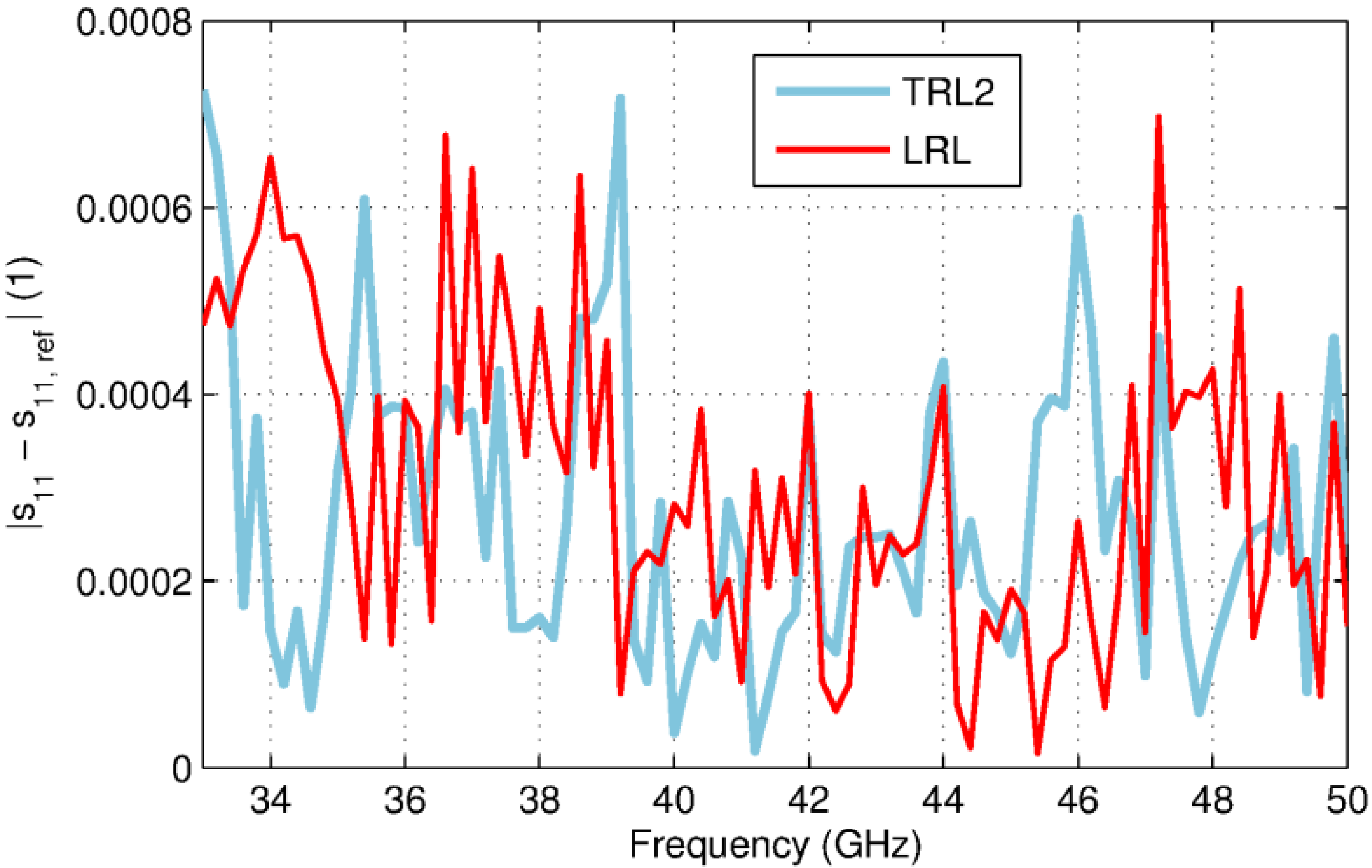
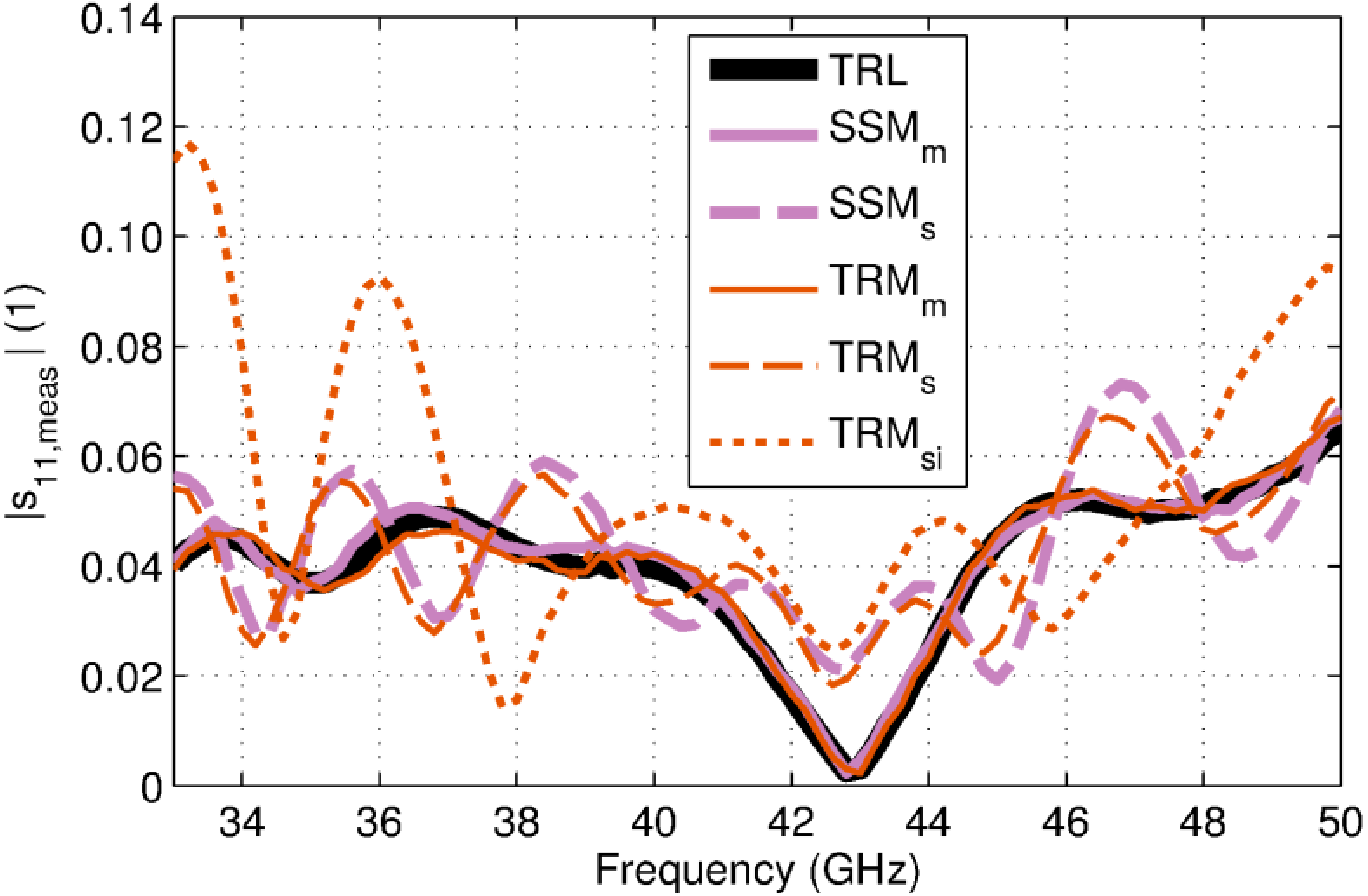


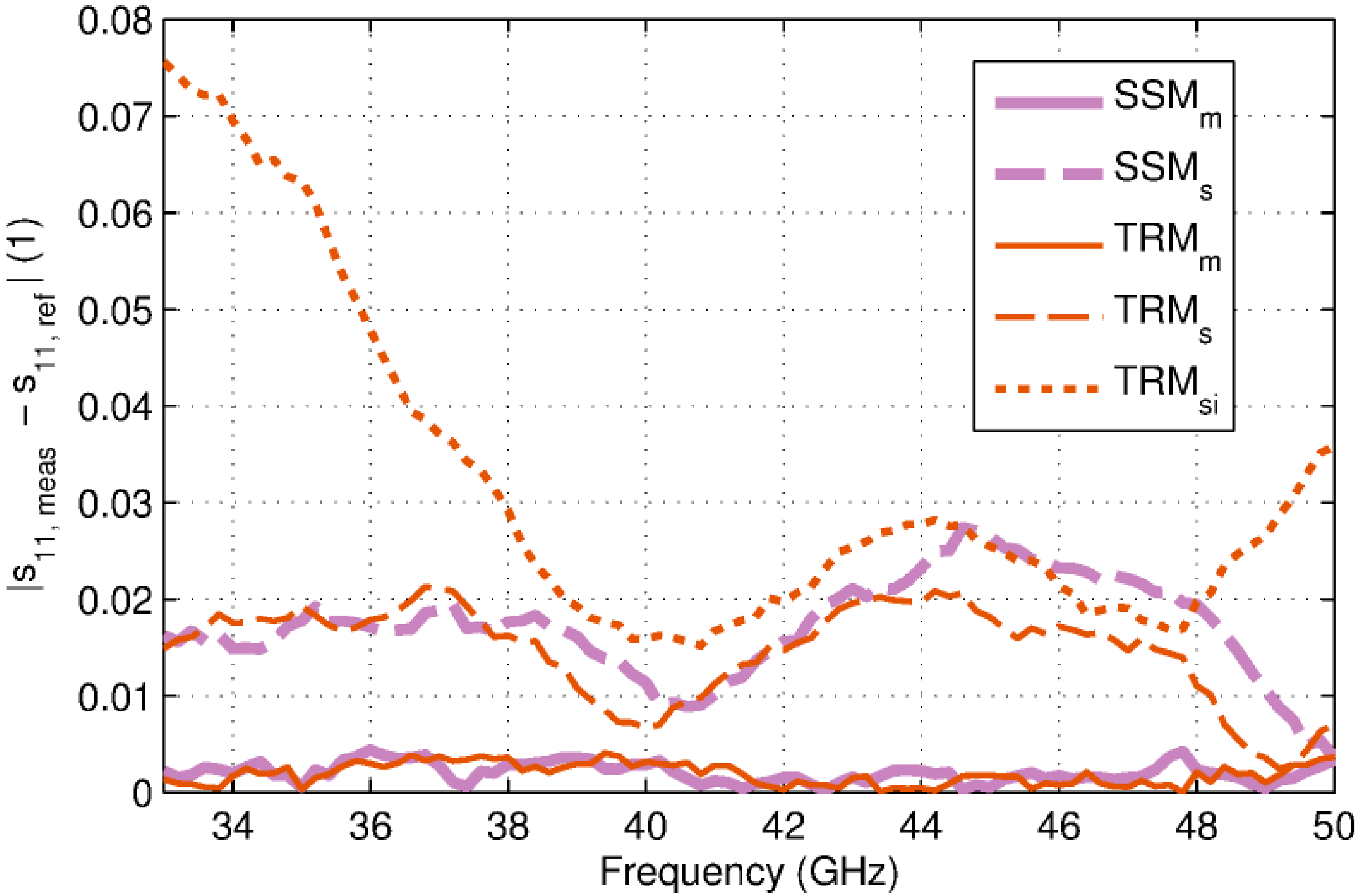
Mismatched load – differences of CSUT and TRL results



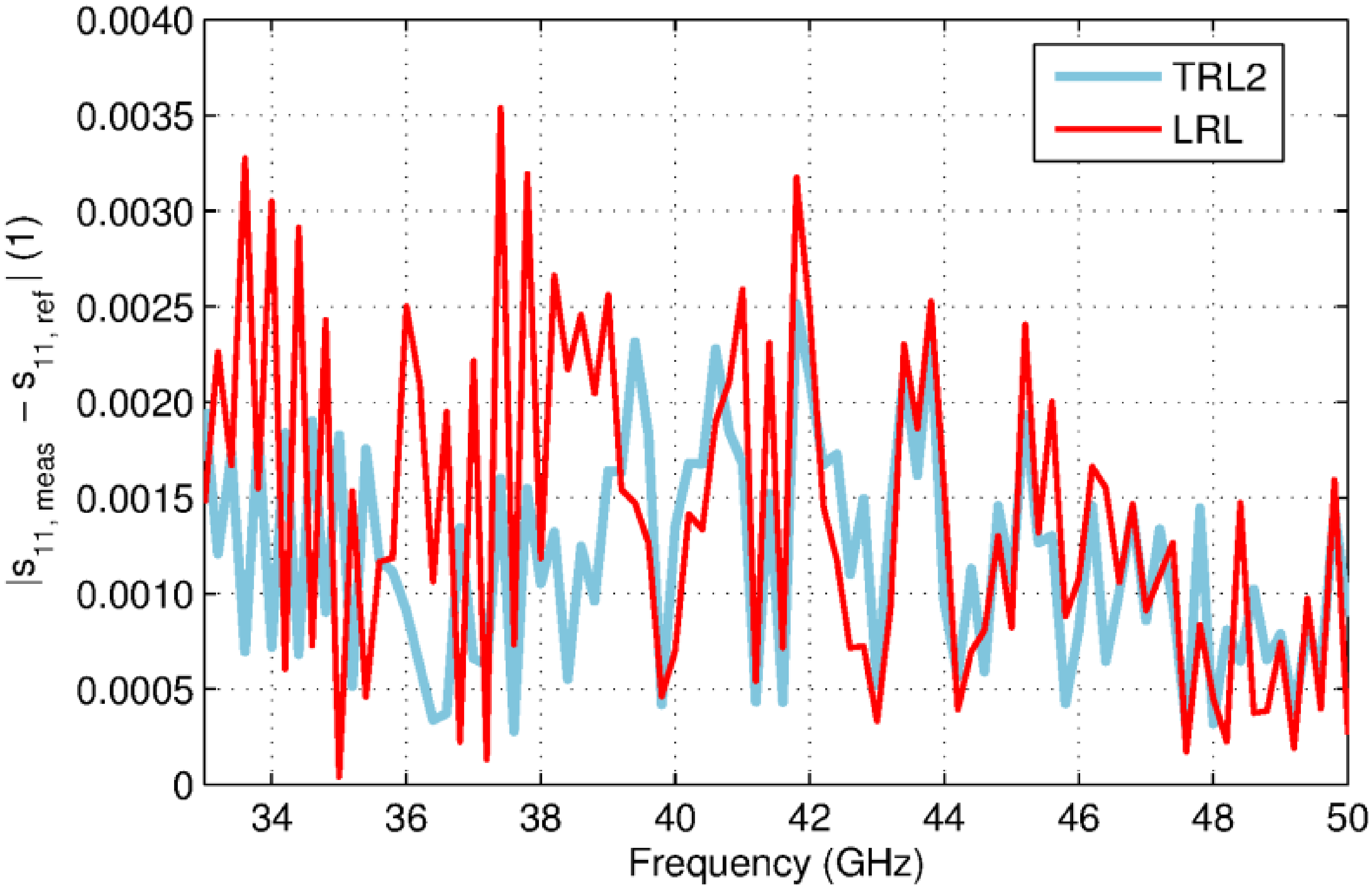
Mismatched load – comparison of CSUT with OEWG and TRL results



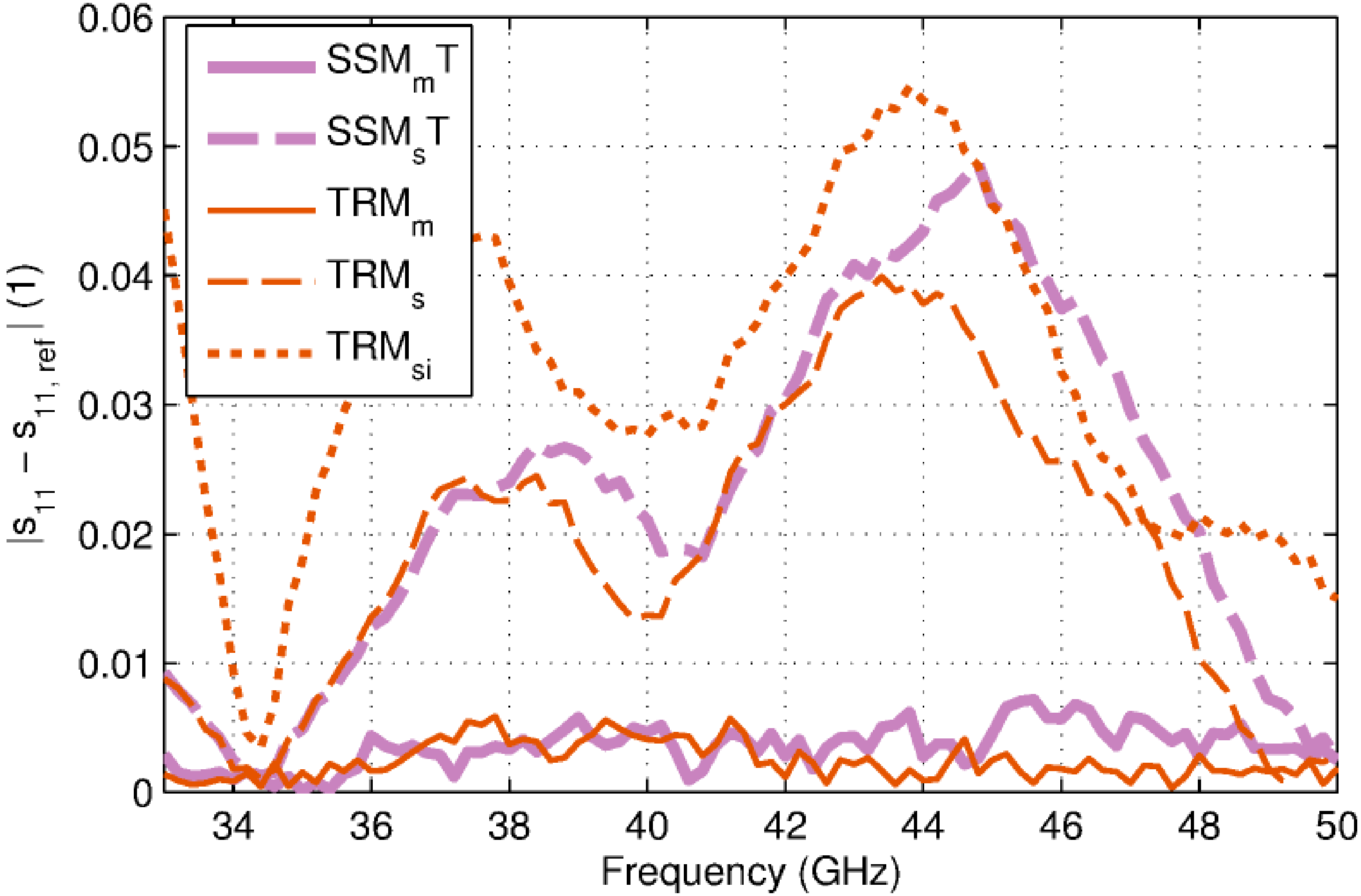
Mismatched load – differences of CSUT with OEWG and TRL results



Line 6.8 mm – differences of CSUT and TRL results



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



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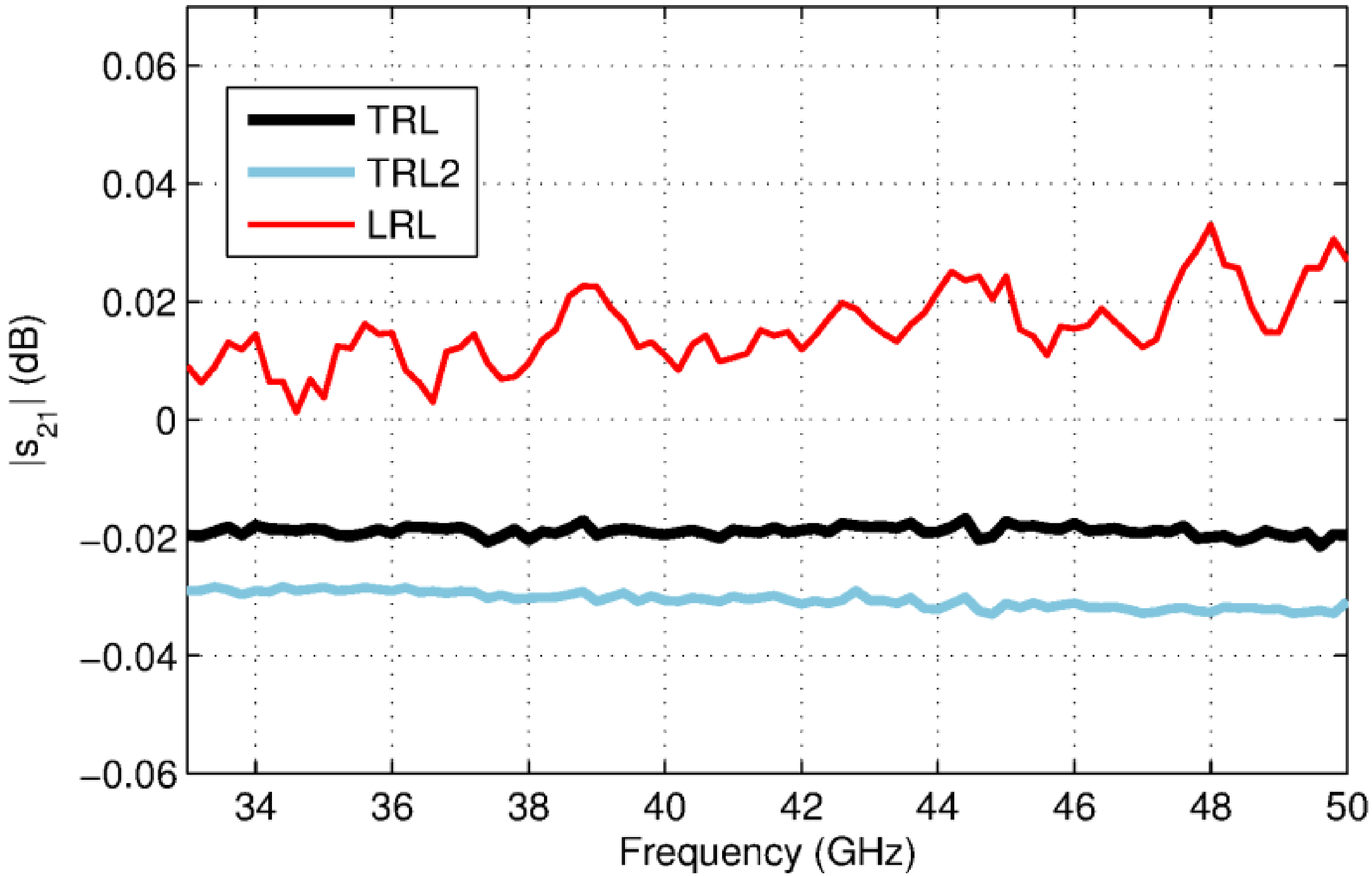
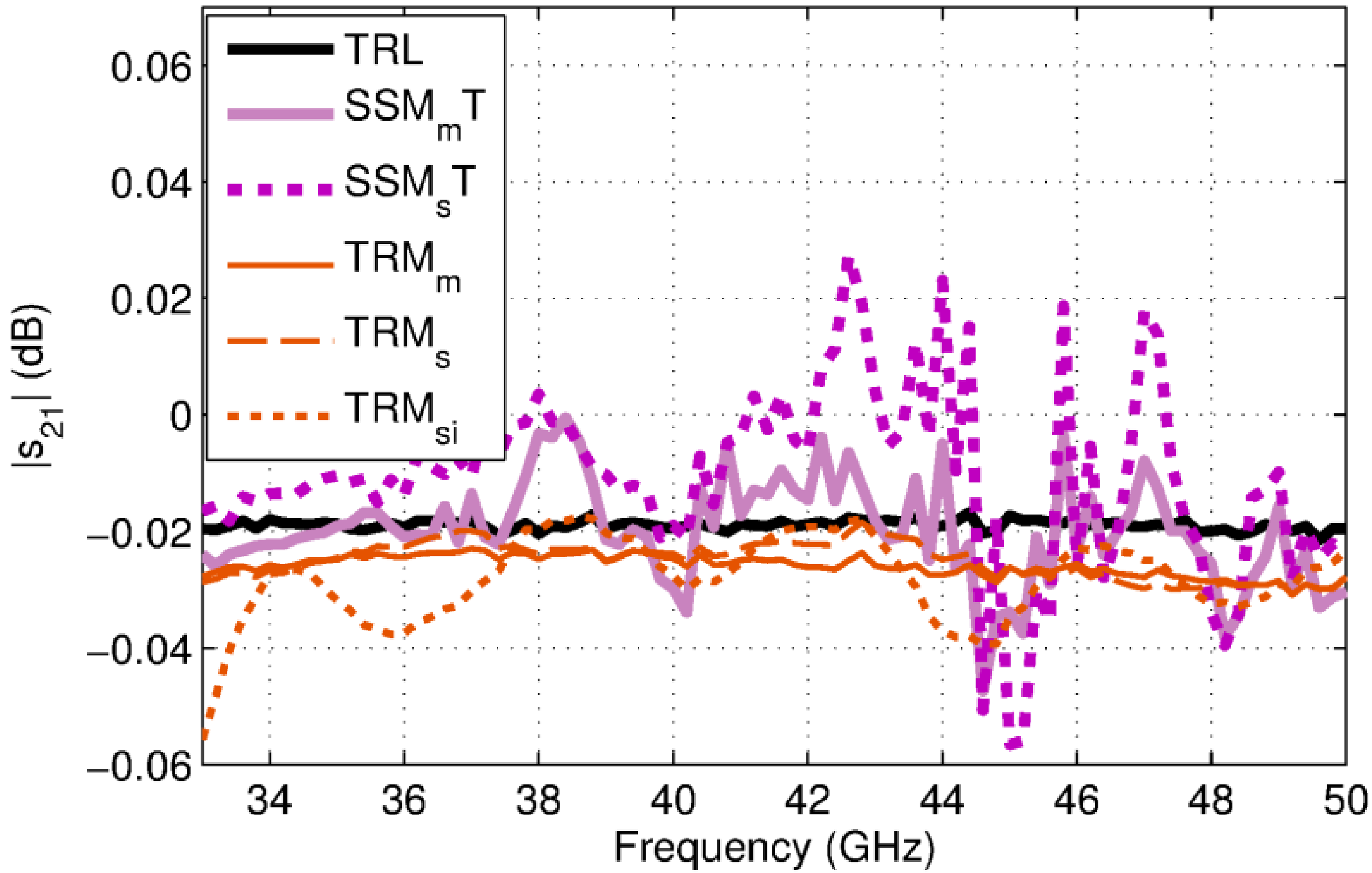
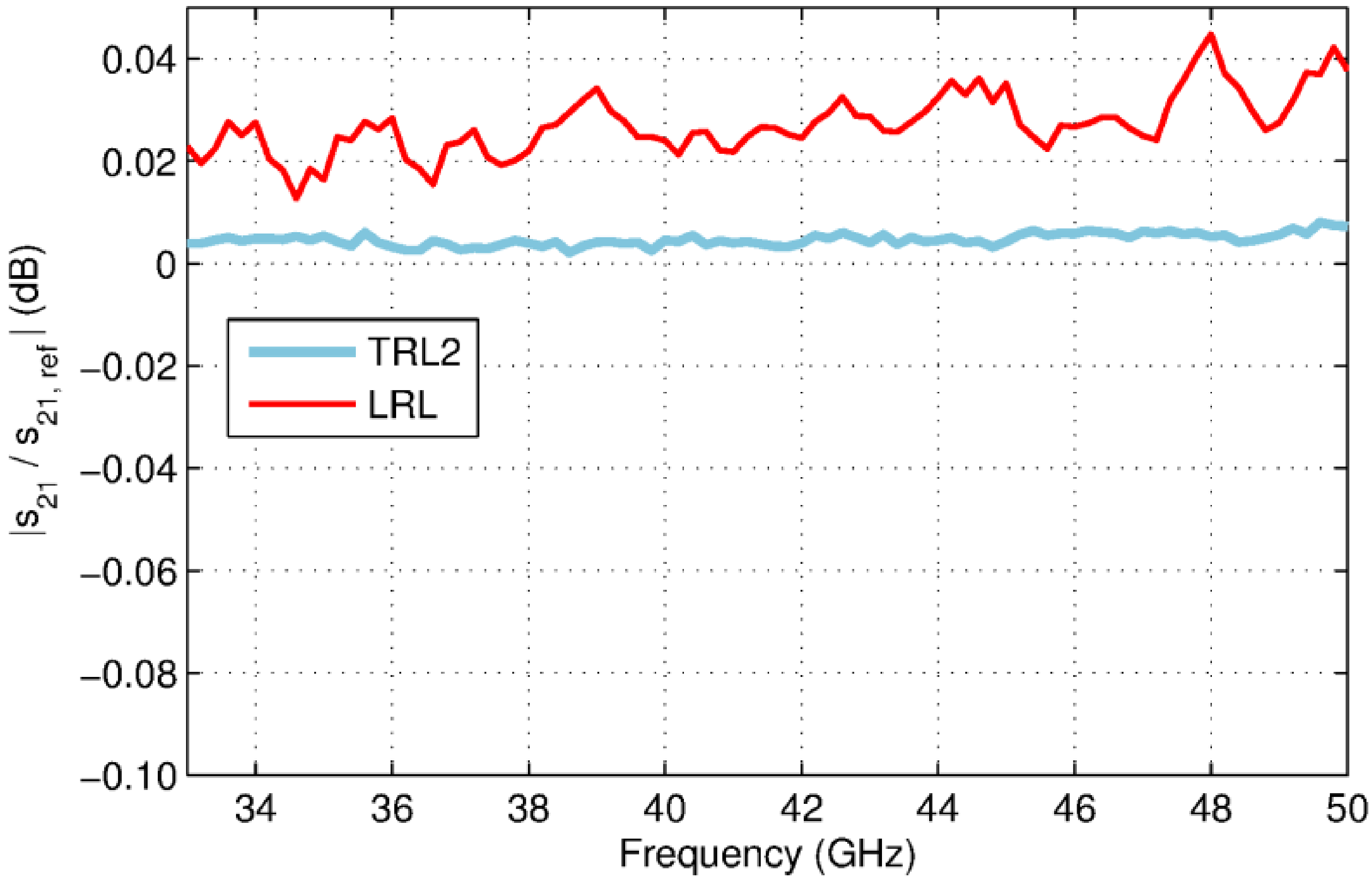


Line 6.8 mm – comparison of CSUT with OEWG and TRL results



20 dB attenuator – differences of CSUT and TRL results



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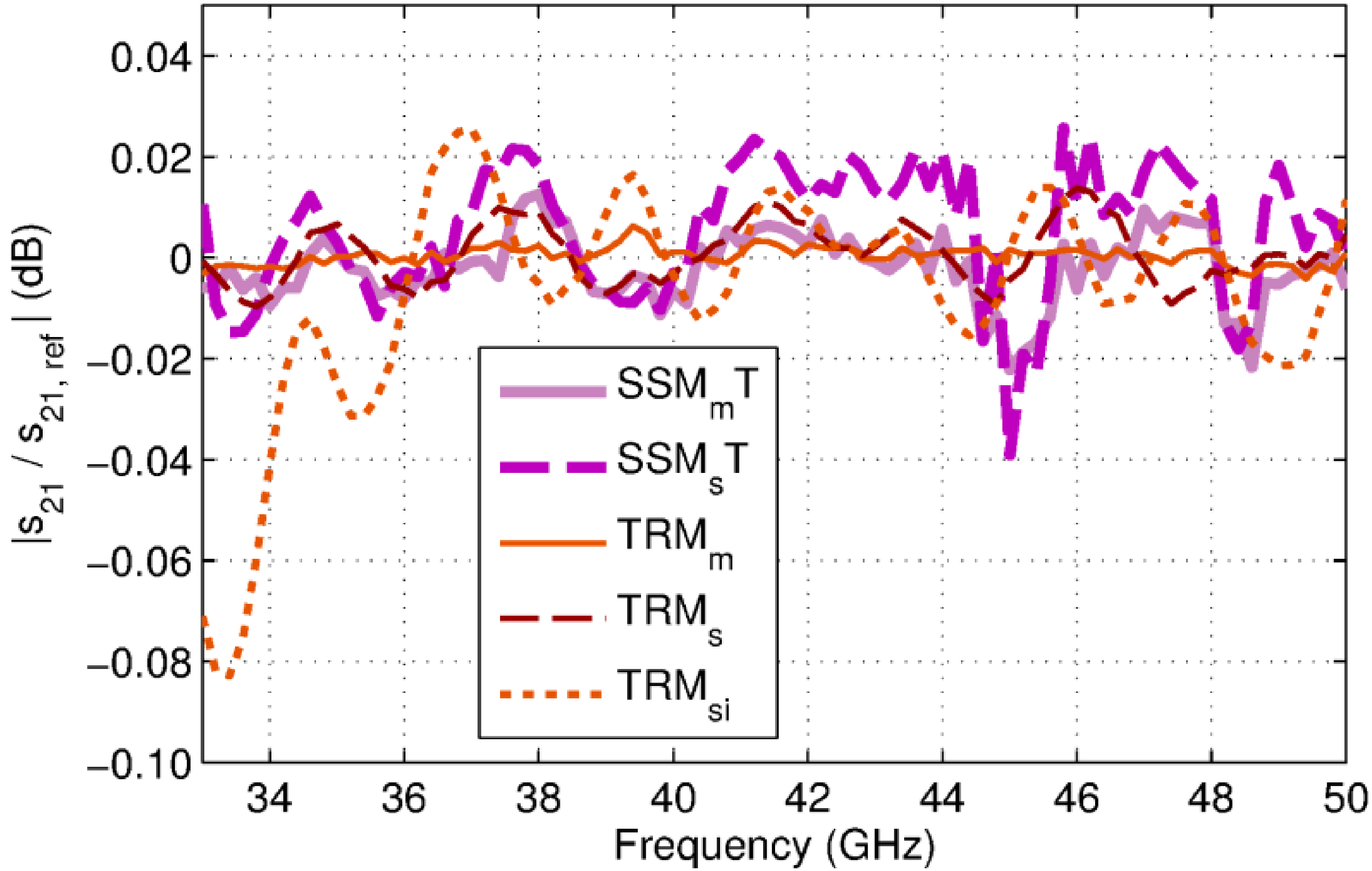
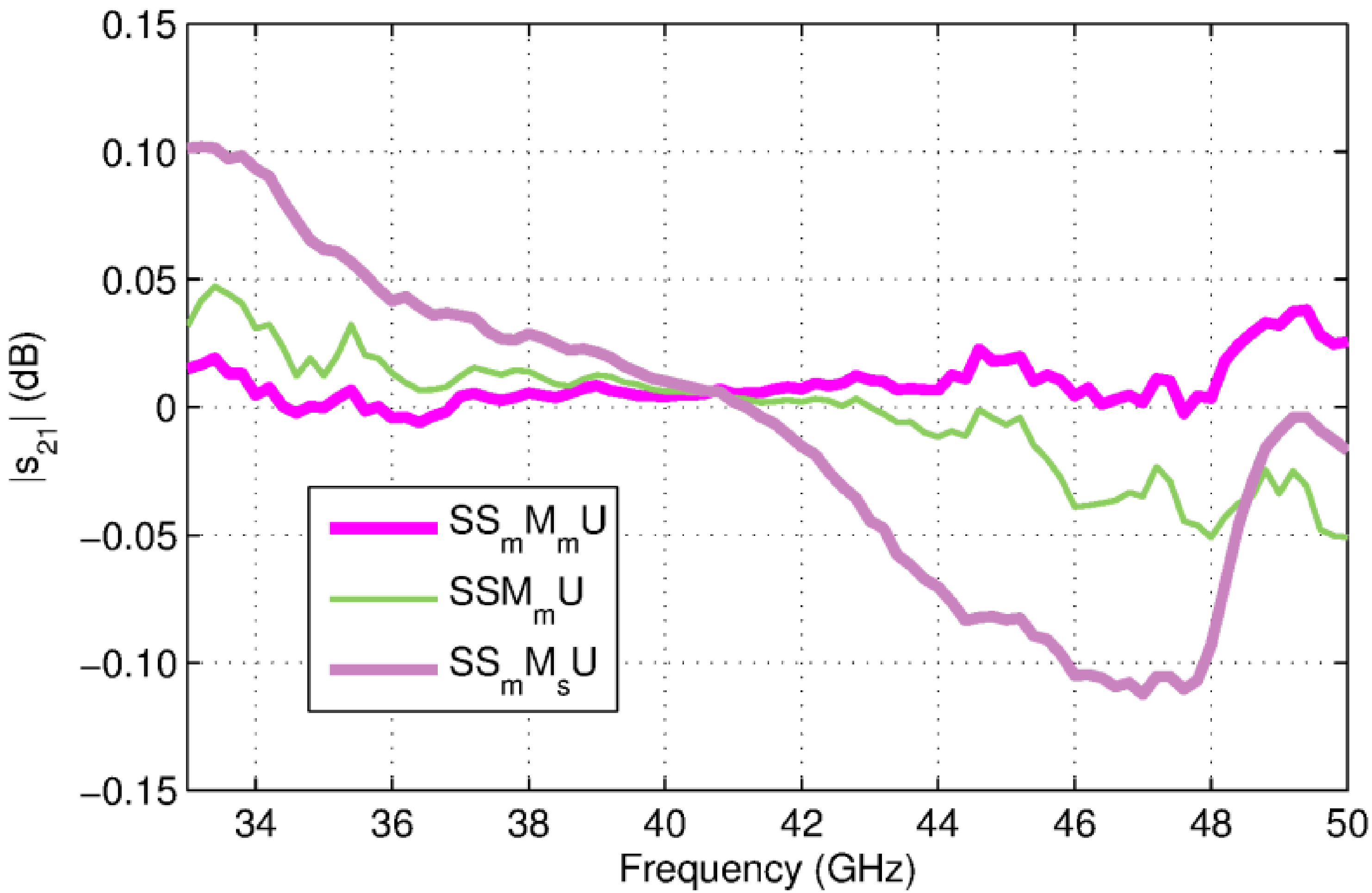
20 dB attenuator – differences of CSUT with OEWG and TRL results



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



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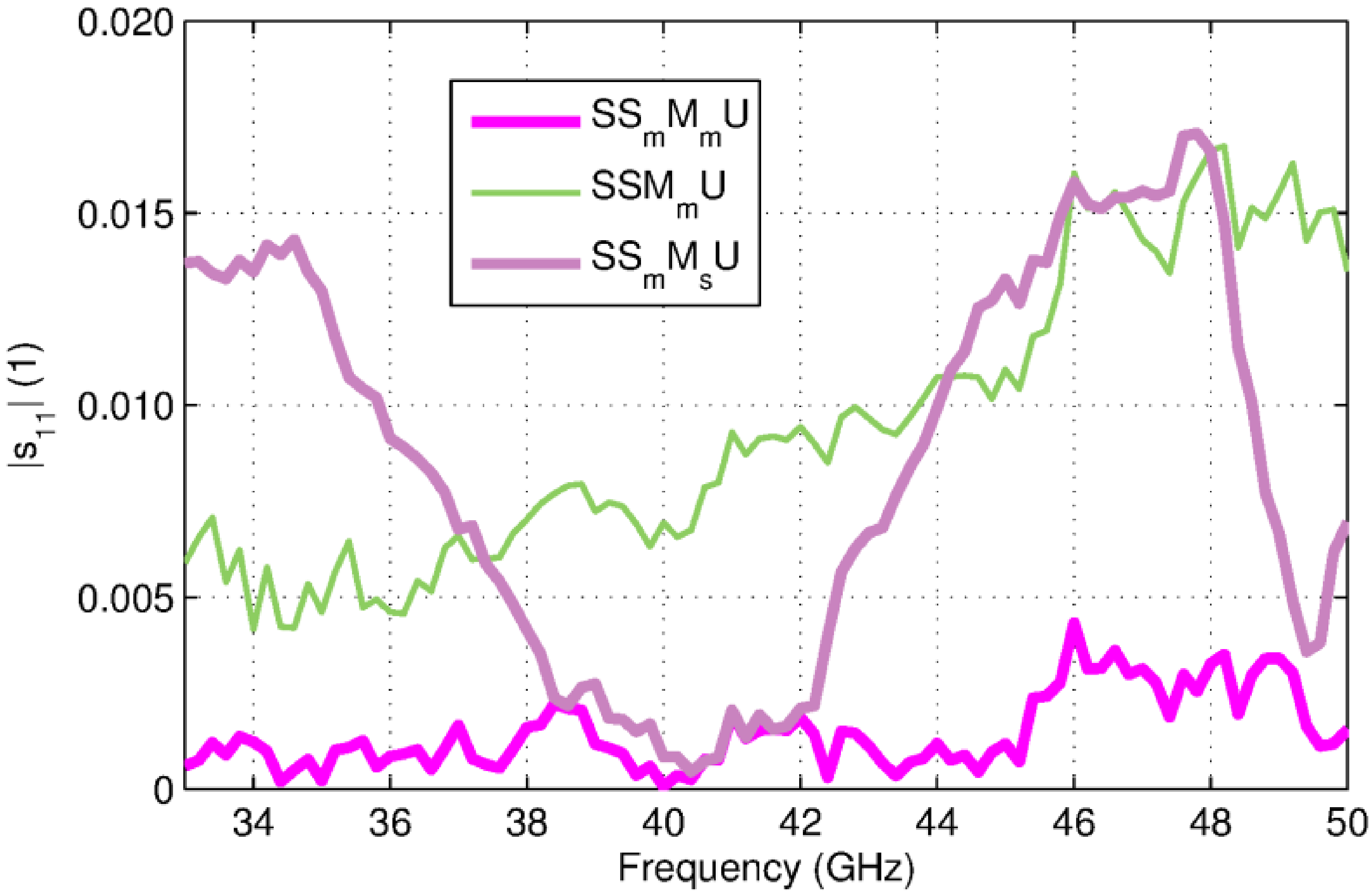
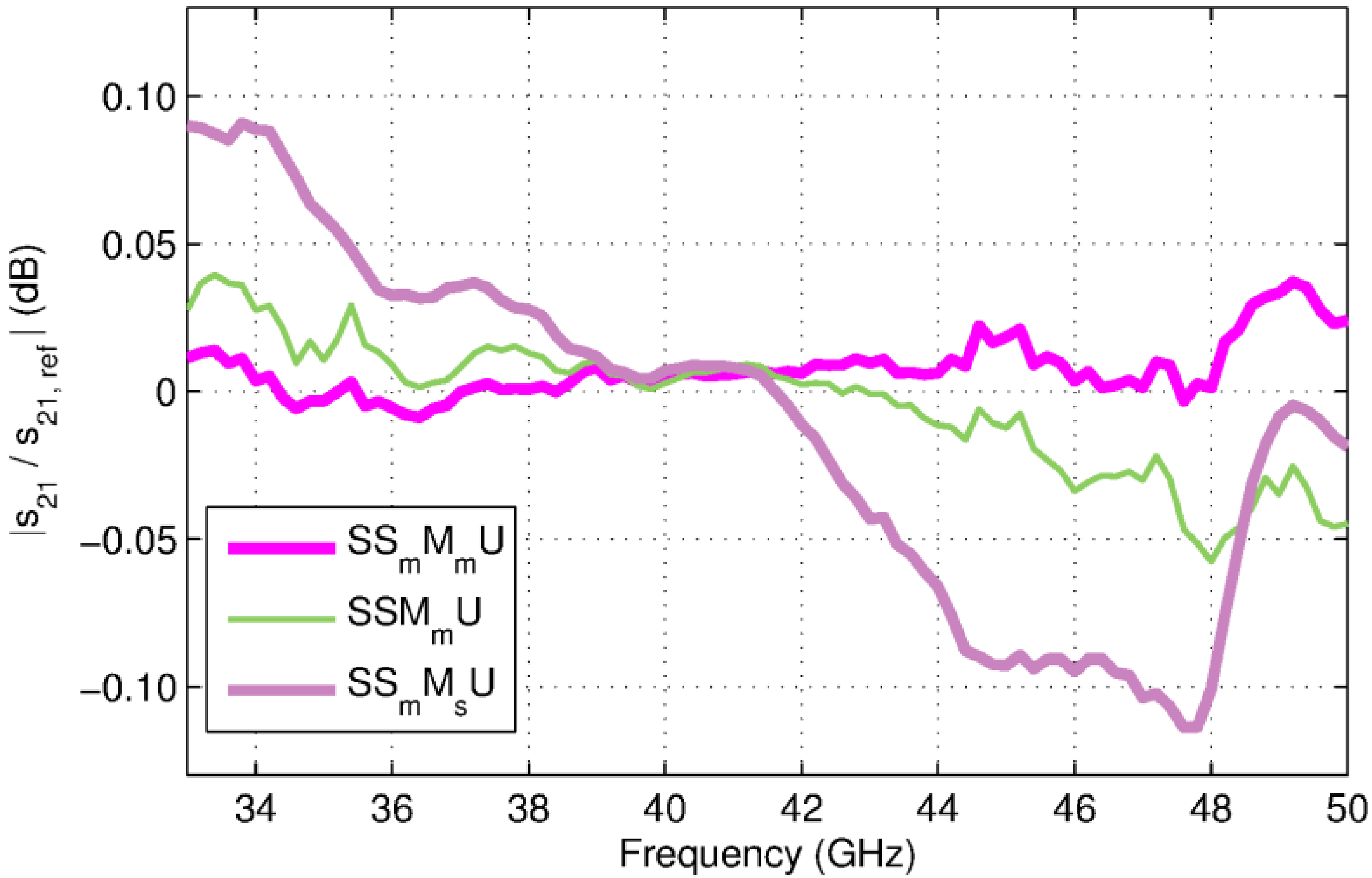


20 dB attenuator – differences of Unknown thru and TRL results



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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

- SSLL (short – offset short – load – offset load)
  - slightly worse results in comparison with TRL based methods for both low reflection and high reflection devices
- SSMT (short – offset short – match/OEWG/ – thru)
  - 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 ¾ λ 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

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Thank you for attention