# Single-Flange 2-Port TRL Calibration for Accurate THz S-Parameter Measurements of Waveguide Integrated Circuits

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***Abstract*—This paper describes a single flange 2-port measurement setup for S-parameter characterization of waveguide integrated devices. The setup greatly reduces calibration and measurement uncertainty by eliminating vector network analyzer (VNA) extender cable movement and minimizing the effect of waveguide manufacturing tolerances. Change time of standards is also improved, reducing the influence of VNA drift on the uncertainty. A TRL calibration kit has been manufactured and measurements are demonstrated in WR-03 (220–325 GHz).**

***Index Terms*—Membrane, S-parameter, TRL, waveguide integrated.**

## I. Introduction

Terahertz components are often built in a waveguide integrated environment, for example membrane monolithic diode circuits [1], [2]. The development towards more complex and highly integrated circuits for use at THz frequencies yields a strong need for characterization and testing of single devices in the waveguide integrated environment [3]–[5], because the packaging in itself may be a part of the device. In addition, the recent development of vector network analyzer (VNA) extenders into the THz frequency range makes THz S-parameter characterization possible [6].

At THz frequencies measurement and calibration become more sensitive to dimensional errors and instrument related uncertainties. Much effort has been put into investigating the waveguide interface and its connection repeatability, for example [7], [8]. However, it is also important to consider the sources of uncertainties that are particular for waveguide integrated membrane S-parameter characterization [4], [9], [10], or more general, waveguide integrated circuits [11]. In [9]–[11] it has been shown that the width tolerance of the access waveguides causes large phase uncertainties, and that these uncertainties can be minimized by reducing the access waveguide length. Furthermore, investigations of VNA THz extender calibrations show that another large source of measurement uncertainty is extender movements [12].

We demonstrate a novel single flange 2-port setup that minimizes the mentioned effects by shortening the access waveguides and keeping the extenders fixed during calibration and measurement. The setup uses Thru-Reflect-Line (TRL) standards for calibration [13] and provides improved measurement uncertainty. It is verified with S-parameter measurements on passive waveguide integrated membrane circuits.

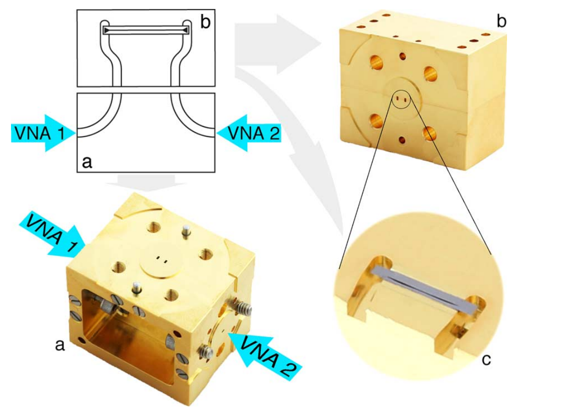


Fig. 1. Concept illustration and photographs of the waveguide blocks used in the setup: (a) The adapter block puts two regular rectangular waveguide single flanges from opposite sides into one single-flange 2-port on top of the block. (b) Interchangeable standard and DUT block, with a single-flange 2-port. (c) Open half of standard and DUT blocks with a 3 $\mu$m membrane mounted upside down.

## II. Design and Manufacturing

The proposed setup is designed in an E-plane rectangular waveguide split-block and consists of two main parts: First, an adapter block, see Fig. 1(a), converting the two VNA ports into a single 2-port flange. This keeps the VNA-extenders locked in position throughout calibration and measurements. Second, interchangeable blocks carrying the TRL standards and device under test (DUT), see Figs. 1(b), (c), and 2, all with single 2-port flanges.

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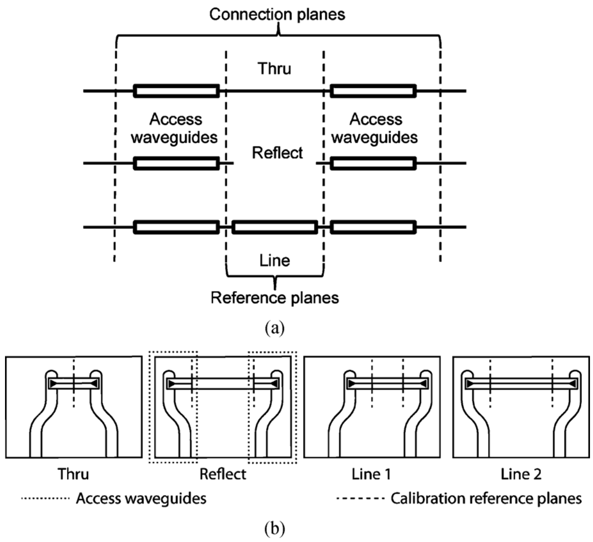


Fig. 2. (a) Principle of TRL standards where reference planes and connection planes are separated by access waveguides. (b) Illustration of the four different calibration standards, demonstrating how two bends in each access waveguide is used in different orientations, in order to accomplish different line lengths.

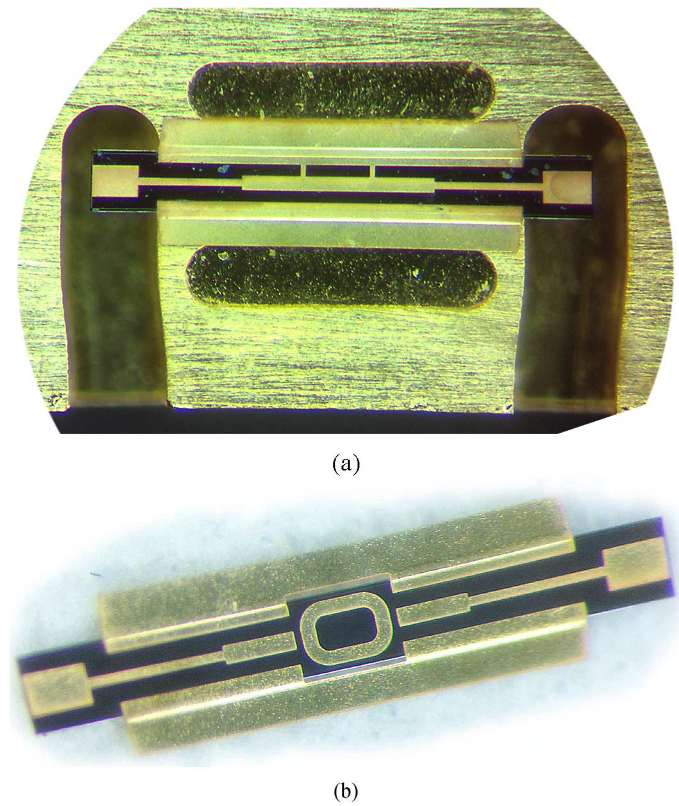


Fig. 3. Photographs of the DUTs. (a) Shorted stub structure mounted inside the waveguide block. (b) Ring resonator membrane circuit.

Because the access waveguides in the standard and DUT blocks are placed in the same flange (single-flange 2-port), they can be made very short without making the block unpractically thin. For conventional $\mathrm{E}$-plane split blocks the corresponding distance between the flanges on opposite sides of the block would be in the range of 2 mm in WR-03. This would be difficult to handle when aligning screw and guidepin holes, and fitting them in the block halves.

However, since both ports are in the same flange, the distance between them is now fixed. To allow for different thru, line and DUT lengths, two bends turned either outward or inward are introduced in each of the two access waveguides, see Fig. 2. Although the bends are made physically equal there will be a small difference in the coupling to the membrane circuit when turning the bends in opposite orientations. This is because the bends disturb the waveguide mode. Making the bends longer will relax this error but the sensitivity to errors in the waveguide width will increase. This trade-off was studied in [10] and the optimum bend radius was determined to be $6 \times w_y$, where $w_y$ is the waveguide height.

To compare the results of the new design with old results, we use the membrane circuit designs in [4] and [5]. $\mathrm{E}$-plane probes and circuit dimensions for calibration standards and the two DUTs, a ring resonator and a shorted stub filter structure, see Fig. 3, are the same as in [4] and [5]. Furthermore, the membrane material and membrane circuit fabrication process is also the same.

Although the TRL algorithm only requires one delay line for a waveguide band we have included two delay lines (Lines 1 and 2) to investigate the impact of the bend orientations on the calibration. Due to the symmetry of the bends, Line 2 is twice as long as Line 1. Line lengths are designed so that the first line (Line 1) nominally has a delay from 45° to 67° (0.57 ps or 142 $\mu$m) and the second line (Line 2) nominally has a delay from 90° to 134° (1.14 ps or 284 $\mu$m).

The block is manufactured in gold plated brass. The bottom block surface is recessed to provide a good electrical contact between the surfaces around the waveguides. The measured difference in width between the access waveguides of the manufactured standards is less than 7 $\mu$m.

## III. Measurements

Measurements are made with an Agilent N5222A PNAX 4-port network analyzer, with two OML WR-03 VNA frequency extenders having a multiplication factor of 18. Each measurement sweeps the frequency range 220–325 GHz, with an IF bandwidth of 100 Hz. Non-calibrated raw measurement data is read from the VNA, with no smoothing or averaging performed. The raw data is then processed in an external TRL calibration algorithm, where either the Line 1 or Line 2 standard is used.

The external calibration makes it possible to use and compare several combinations of measurements (reconnections) of both calibration standards and the DUT.

Each measurement consists of three consecutive sequences (sets) of calibrations standards and DUT measurements $(\mathrm{R}, \mathrm{T}, \mathrm{Line\ 1}, \mathrm{Line\ 2}, \mathrm{DUT}, \ldots \times 3)$, where the adapter block is connected to the VNA extenders during the entire measurement sequence.

We have also performed measurements using the Agilent built in TRL calibration, using our calibration standards, with good results. However in that case, only one combination of standards can be used at a time.

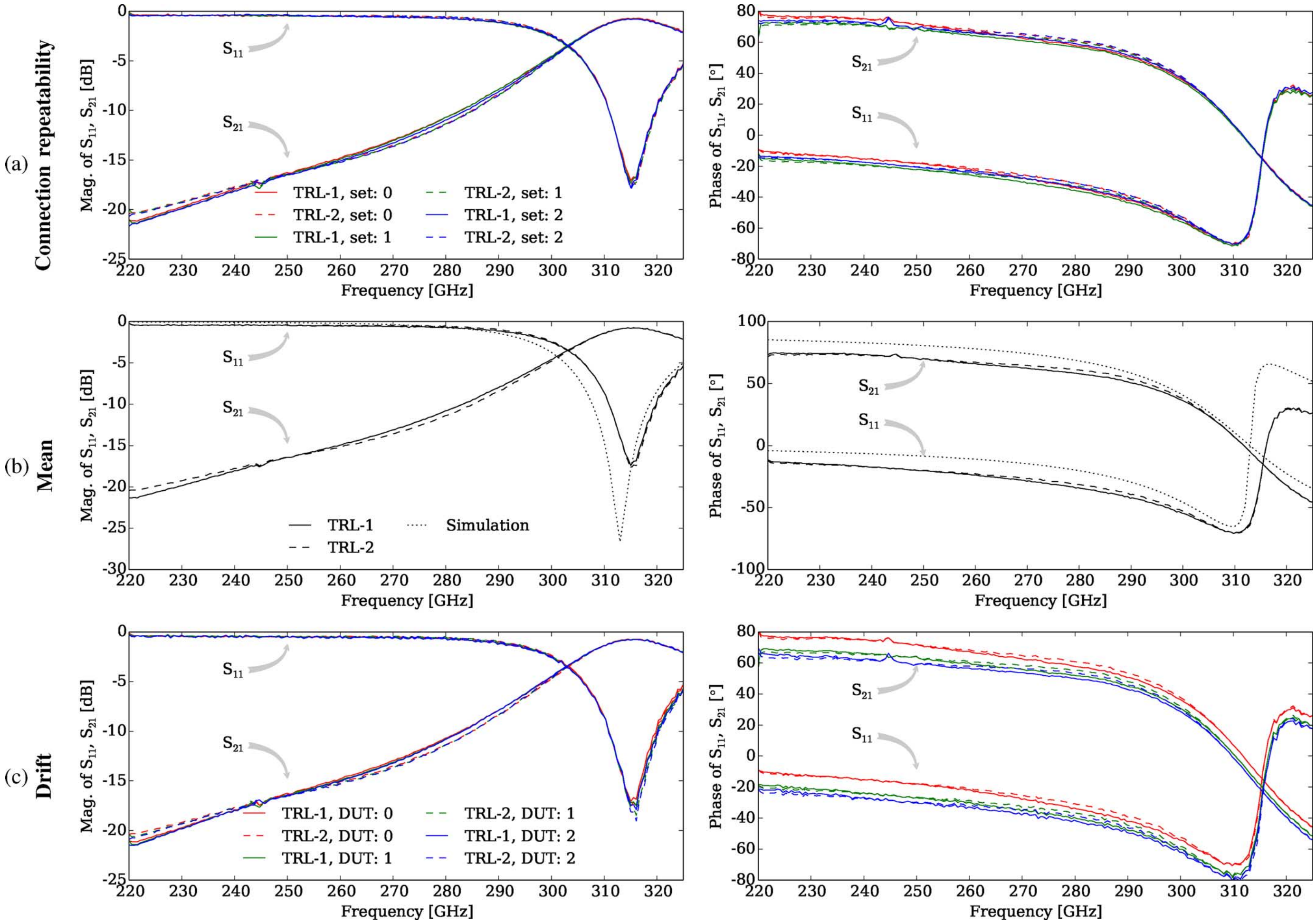


Fig. 4. Measured $S_{11}$ and $S_{21}$ of a ring resonator. (a) Six sets of calibrations and measurements, three using Line 1 and three using Line 2. (b) Mean of the three sets, comparing calibrations with Line 1 (TRL-1) to Line 2 (TRL-2). (c) Three different DUT measurements, calibrated with the same calibration set.

## IV. Calibration Analysis

To assess the uncertainty introduced by the different bends in the access waveguides in the Line 1 and Line 2 standards, we compare the two resulting calibrations.

Each calibration results in a calibration set represented by two 2-port S-parameter error matrices, $e_a$ and $e_b$, one on each side of the two reference planes surrounding the deembedded DUT

$$e_{ai} = \begin{bmatrix} e_{ai,11} & e_{ai,12} \\ e_{ai,21} & e_{ai,22} \end{bmatrix} \text{ and } e_{bi} = \begin{bmatrix} e_{bi,11} & e_{bi,12} \\ e_{bi,21} & e_{bi,22} \end{bmatrix} \quad (1)$$

where $i = 1$ or 2 depending on which line standard was used in the calibration. The difference between the two calibration sets is found by de-embedding them from each other:

$$\Delta e_a = e_{a2}^{-1} \otimes e_{a1} \text{ and } \Delta e_b = e_{b1} \otimes e_{b2}^{-1} \quad (2)$$

where $\otimes$ denotes cascading of the S-matrices.

This will result in the residual errors [14]: directivity ($D_a$ and $D_b$), match ($M_a$ and $M_b$), reflection tracking ($R_a$ and $R_b$), and transmission tracking ($T_{21}$ and $T_{12}$), where

$$D_a = \Delta e_{a,11} \text{ and } D_b = \Delta e_{b,22} \quad (3)$$

$$M_a = \Delta e_{a,22} \text{ and } M_b = \Delta e_{b,11} \quad (4)$$

$$R_a = \Delta e_{a,12} \Delta e_{a,21} \text{ and } R_b = \Delta e_{b,12} \Delta e_{b,21} \quad (5)$$

$$T_{21} = \Delta e_{a,21} \Delta e_{b,21} \text{ and } T_{12} = \Delta e_{b,12} \Delta e_{a,12}. \quad (6)$$

Because of the reciprocity of the calibration, $T_{12} = T_{21}$.

## V. Results

Figs. 4 and 5 show measured results of a ring resonator and a shorted stub structure respectively, first designed and measured in [4] and [5]. The resonance frequency shift of about 3 GHz compared to simulations for both circuits, is in line with the measurements in the previous articles.

With the conventional setup in [4], [5] and [9] we had a measurement ripple up to 5 dB which indicated large uncertainties. However, in this new setup we cannot distinguish any ripple from noise in the measurement and calibration. Furthermore, as we can see in Figs. 4(a) and 5, the repeatability between measured sets is between 0° and 10°, which can be compared to the stability of the frequency extenders which is ±8° [15]. To illustrate the difference between calibrations with Line 1 and Line 2, we plotted the mean of the three measured sets in Fig. 4(b), which shows there is very little difference both in magnitude and phase between calibrations using Line 1 or Line 2.

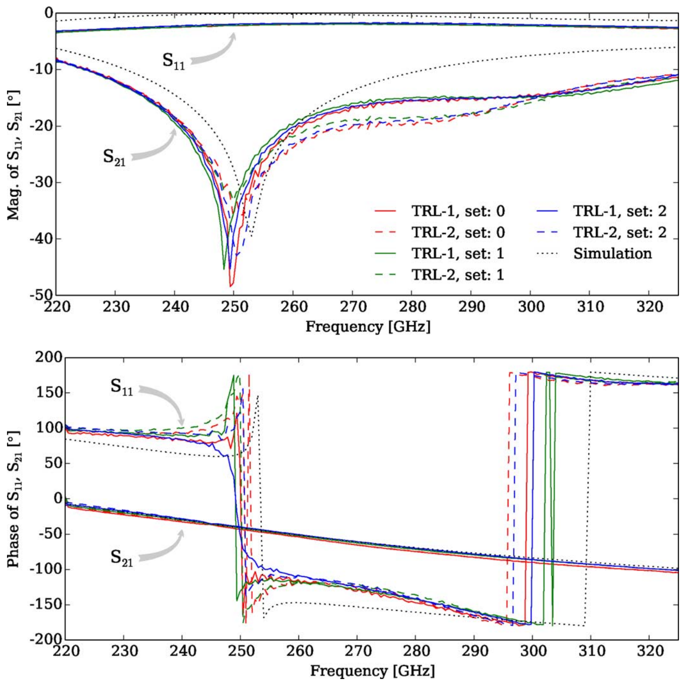


Fig. 5. Measured $S_{11}$ and $S_{21}$ of a double stub filter. Three measured sets (0–2) including T, R, Line 1, Line 2 and DUT, calibrated with either Line 1 (TRL-1) or Line 2 (TRL-2).

The drift over time is studied in Fig. 4(c), where the first calibration set is used for three different DUT measurements. The VNA drift is evident in the phase plot, with a phase shift as large as 13° in the lower end of the spectrum with 40 minutes between the first and the last DUT measurement. Thus the largest contribution to phase uncertainty is VNA drift over time, and measurements of the DUT made close in time to calibrations provides better repeatability. With this new setup, measurements are faster, reducing the sensitivity to drift. Due to the simplicity of the connection a set of measurements of the TRL calibration standards plus one DUT now takes about 15–20 min, as compared to about an hour in the old setup.

To further study the measurement uncertainty introduced by the different bend orientations in Line 1 and Line 2 (see Fig. 2) we compared the different calibration sets for Line 1 and Line 2 using the residual directivity, reflection tracking and transmission tracking according to (3), (5), and (6). The phase of the reflection tracking in Fig. 6 is used to measure how much the calibration reference plane is perturbed due to the different bend orientations in Line 1 and Line 2 and the waveguide width manufacturing tolerance. The results in Fig. 6 agree well with simulations in [10] and the errors introduced by the bends in the standards are less or comparable with the other uncertainty contributions. Thus making this inconsistency in the TRL standards acceptable, providing improved calibration quality.

A potential problem with two ports in one flange is cross coupling between the ports in the interface. We have, however, not observed this effect in our calibration and measurement data.

## VI. Conclusion

We have demonstrated a new single-flange 2-port measurement setup for S-parameter characterization, which has improved measurement uncertainty drastically. Much because the effect of cable flex which is now completely eliminated by fixing the extenders to the adapter block during the entire measurement sequence. The single-flange 2-port design also allows shortening the access waveguides giving a drastic improvement of the phase uncertainty. Since the errors introduced by the bends do not scale with frequency, we expect this method to be useful for characterizing components at THz frequencies.

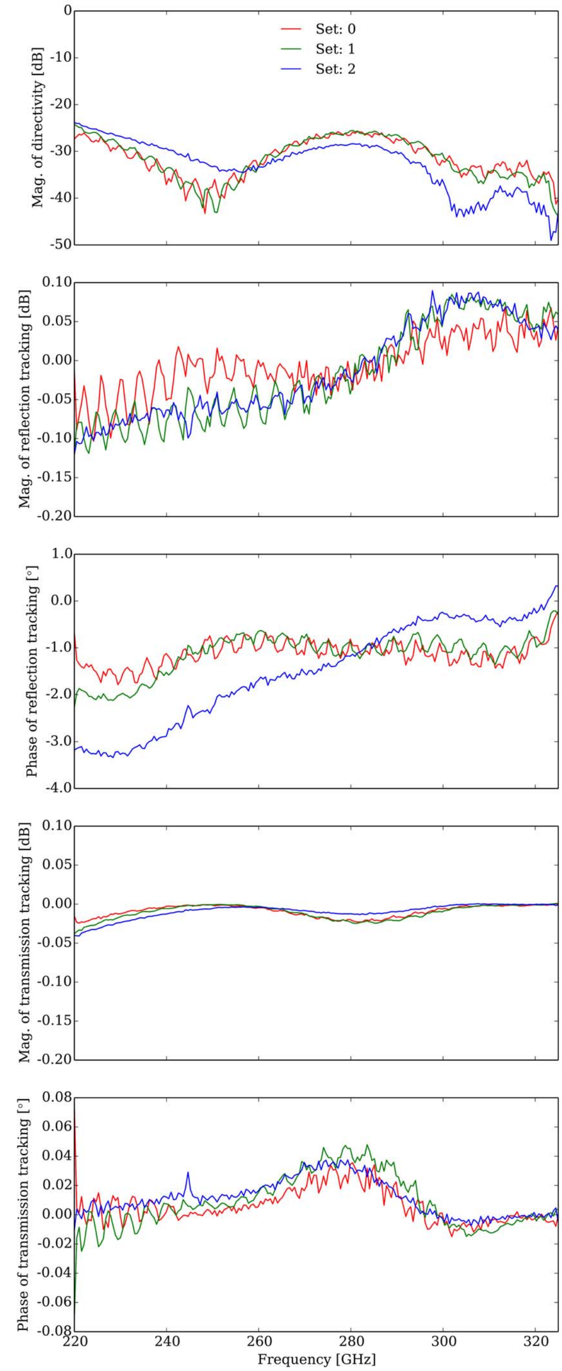


Fig. 6. Residual directivity and reflection tracking at calibration port 1 when comparing the Line 1 and Line 2 calibration standards for three measured sets. Transmission tracking in forward direction.

Earlier a TRL calibration could require a number of repeated measurements to succeed, whereas now, one is usually enough.

The uncertainty due to drift is also drastically improved due to the increased measurement speed. This is because the connection procedure of the waveguide block has been simplified, reducing the time for a complete measurement set to less than 20 minutes.

The improvement of the measurement uncertainty can be seen in the ripple in the measurements. In the earlier measurements we had a ripple up to 5 dB in transmission whereas now it is not distinguishable from the noise.

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