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Multiline TRL Calibration Standards for S-parameter Measurement of Planar Goubau Lines from 0.75 THz to 1.1 THz

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Abstract—We present a multiline Thru-Reflect-Line (TRL) calibration standard for Planar Goubau Line (PGL) which allows setting the calibration plane along the PGL and thus removing the effect of the embedding structure. This opens the possibility of characterizing PGL-circuits. The presented structures were used for calibrating S-parameters measurements between 0.75 THz and 1.1 THz to characterize a 1 mm long and 10 µm wide PGL. The line shows negligible dispersion with an effective relative permittivity of 2.0 and an attenuation constant lower than 0.35 Np/mm (0.65 dB/λ).

Index Terms— Calibration, Multiline TRL, On-wafer THz measurements, Planar Goubau Lines, S-parameter characterization, Terahertz circuits.

I. INTRODUCTION

The Planar Goubau Line (PGL) [1]-[4] is a groundless single conductor waveguide consisting of a metal strip supported by a dielectric substrate (see Fig. 1 a). This waveguide is the two-dimensional counterpart of Goubau's dielectric coated single wire waveguide [5]-[6], which in turn is based on the finite-conductivity wire waveguide studied by Sommerfeld [7] in 1899. In both the Goubau and the Sommerfeld lines, the field propagates as a surface wave [8]-[9].

As the Sommerfeld and Goubau line, the PGL's propagating mode is transverse magnetic and has a quasi-radial electric field around the conductor. Due to its single-conductor nature, the field in the PGL has a large extension compared to other multi-conductor transmission lines used at teraherz (THz) frequencies, such as Coplanar Waveguide (CPW), while it exhibits negligible dispersion across a wide bandwidth. This makes the PGL a suitable candidate for sensing applications [2], where interaction with a larger volume is required. Additionally, its physical geometry favors liquid sample deposition around the line.

To excite the PGL using ground-signal-ground probes, a CPW to PGL transition [3] is needed (Fig. 1 b)). Therefore, unless the calibration plane is set after the CPW-PGL transition, the measurements will include the impact of the transition, which might be undesirable. To the best of the authors' knowledge, no reported calibration structures exist which allow to de-embed these transitions.

In this paper, we present multiline Thru-Reflect-Line (TRL) calibration standards which allow setting the calibration plane at the PGL, and thus opening the possibility to accurately characterize PGL based circuits [4]. Using the aforementioned TRL calibration structures, a 10 µm wide and 1 mm long PGL
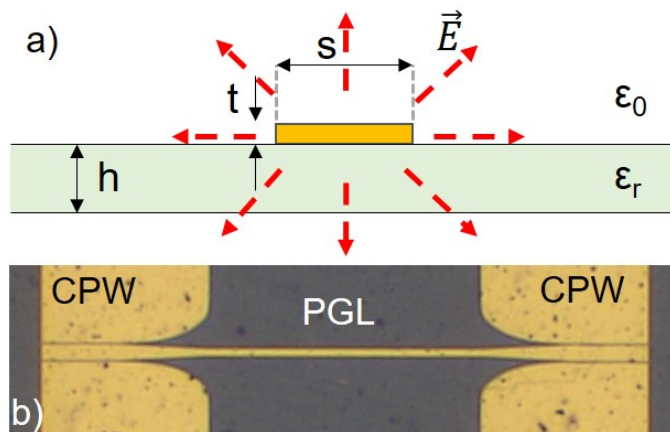

Fig. 1   a) Sketch of the cross-section of the PGL where the electric field is represented by dashed arrows. b) Microscope picture of a PGL showing the CPW-PGL transition needed to contact with ground-signal-ground probes.

on a 23 µm thin polyethylene terephthalate (PET) film was characterized from 0.75 THz to 1.1 THz.

II. METHOD

A. PGL Design

To efficiently excite a PGL with ground-signal-ground probes, one first needs to excite a CPW due to its suitable probing geometry. This CPW can then change its dimensions to progressively couple its even mode into a PGL's propagating mode. This can be done by separating the CPW's ground planes while changing the width of the CPW's central conductor (Fig. 1 b)) [3]. However, this change in the CPW's gap and conductor width dimensions will produce a change in impedance, which will cause reflections. In the transition used, the conductor and gap dimensions were designed to vary its impedance value using a geometric progression to minimize reflections, while simultaneously avoiding using small CPW strip and gap widths, which increase line losses.

To maximize the power delivered to the PGL, the length of the transition was optimized resulting in a trade-off between reflections and line losses. Additionally, if the transition length is a multiple of one half-wavelength it will produce minimum reflections, thus the length was chosen as the multiple of half-wavelength (at the center of the band) which maximized the power delivered to the PGL.
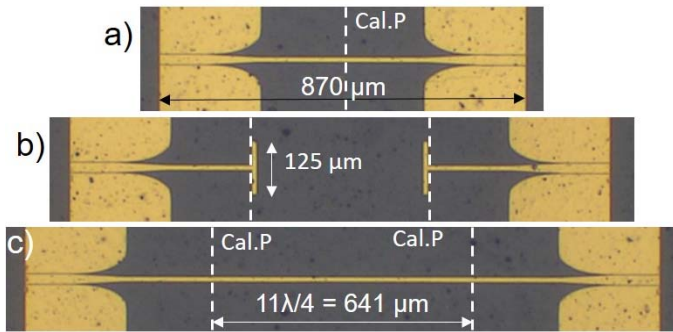
Fig. 2   Microscope image of the fabricated calibration standard, showing: a) thru, b) reflect and c) 11λ/4 line. Dashed lines indicate the calibration plane. Figures are shown to scale.

To design the transition, electromagnetic simulations of the structure were performed using commercial finite integration technique software.

To decrease substrate modes, which cause dispersion and radiation losses, it is recommended to use thin and low permittivity substrates, since they increase the substrate mode's cutoff frequency [10]. Thus a 23 μm thin PET film ($\varepsilon_r = 3.15$ and $\tan(\delta) = 0.017$ at 1 THz [11]) was selected as the supporting substrate.

B. Multiline TRL Calibration Standard Design

The TRL calibration method [12] is a widely used approach at THz frequencies [13]-[14] since it requires no loads, which are challenging to fabricate with precision at THz frequencies. To minimize the effects of random errors, and improve the accuracy and bandwidth of the TRL calibration, multiple lines with different electrical lengths can be included in the calibration substrate [15].

In the case of the PGL, the design of the thru and line standards is straightforward after the CPW-PGL transition has been designed (see Fig. 2 a) and c)). The thru standard had a probe-to-probe distance of 870 μm and the calibration lines had an additional PGL length of 58 μm (λ/4), 175 μm (3λ/4) and 641 μm (11λ/4) at 910 GHz (considering an effective dielectric permittivity of $\varepsilon_{eff} = 2$, obtained from simulations).

However, the design of a PGL-reflect is not as straightforward as it consists of a single conductor. The reflect was designed as a T-shaped structure by adding a λ/2 long perpendicular conducting strip (10 μm × 125 μm) at the end of an open PGL, as shown in Fig. 2 b). It should be noted that, despite resembling a dipole antenna, this structure has a single conductor and a wideband reflective behavior, thus not acting as an antenna.

The PGL and the calibration substrates were fabricated on the same substrate using e-beam lithography. A 350-nm thick layer of gold was evaporated on top of the 23-μm thick PET substrate, forming the conductor layer.
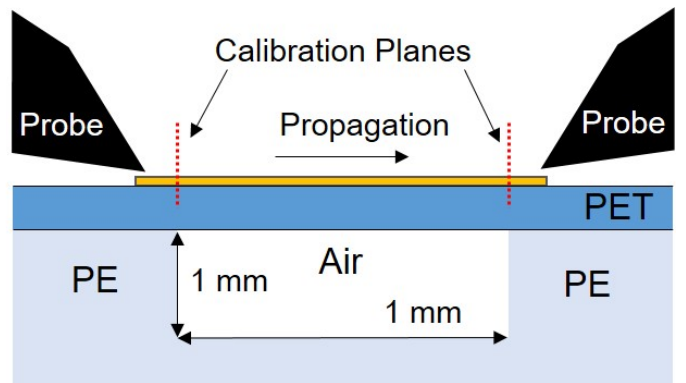

Fig. 3   Cross section sketch of the measurement procedure with the 1 mm long PGL deposited on the thin film of PET and suspended in the PE substrate holder. The PGL calibration planes are marked as discontinued red lines. Figure is not to scale.
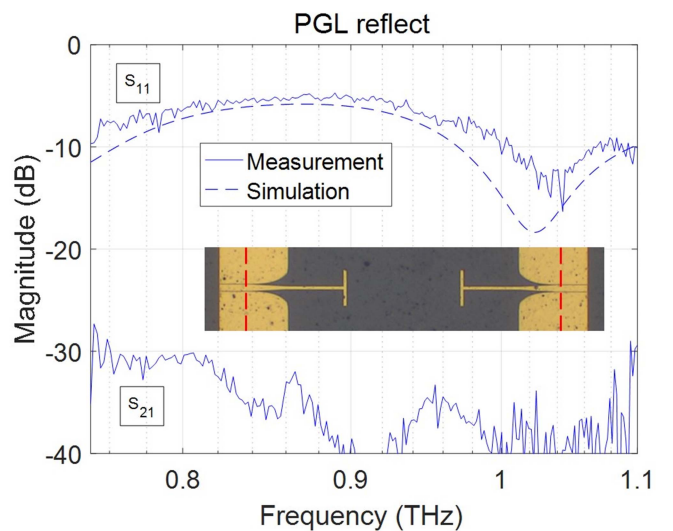

Fig. 4   S-parameter simulation (dashed line) and measurement (solid lines) from 0.75 THz to 1.1 THz of CPW-PGL transition followed by reflect element. Simulated S_{21} was bellow -95 dB in all the band. A CPW multiline TRL standard was used to calibrate the measurements. Inset shows the layout of the simulated and measured structure. Dashed line in inset indicates the location of the calibration plane, 105 μm into the 50 Ω CPW line of the CPW-PGL transition.

C. Measurement Set-up

The 2-port S-parameter measurements from 0.75 THz to 1.1 THz were performed using an Agilent N5242A PNA-X Network Analyzer connected to two VDI WR1.0SAX frequency extenders. The IF bandwidth of the VNA was set to 50 Hz. To probe the structures, ground-signal-ground Cascade T-Wave probes were used [16]. To minimize the phase noise to achieve a higher dynamic range in the measurements, external RF and LO sources were used (Keysight E8257D).

The fabricated wafer was placed on a polyethylene (PE) holder ($\varepsilon_r = 2.3$ and $\tan(\delta) = 0.004$ at 1 THz [11]). This PE holder separates the structures from the metal chuck of the
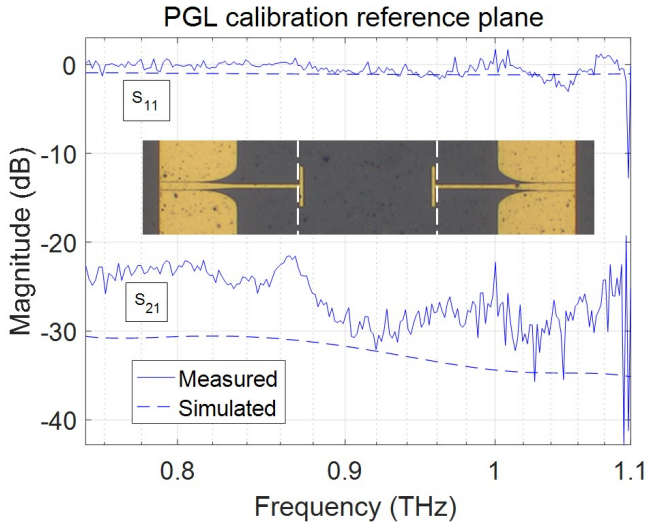
Fig. 5 — S-parameter simulation (dashed lines) vs. measurement (solid lines) of reflect element using the proposed PGL multiline TRL standard. Simulation results give S_{11} values higher than -1.1 dB in all the band. Inset shows the layout of the simulated and measured structure. Dashed line in inset indicates the location of the PGL calibration reference plane.

Fig. 6 — a) S-parameter simulation (dashed lines) and measurements (solid lines) between 0.75 THz and 1.1 THz of a 10 µm wide and 1 mm long PGL using the proposed PGL multiline TRL calibration standard to calibrate the measurements. Simulated |S11| results lied bellow -30 dB in all the band. b) Microscope image of the 1 mm long PGL. Dashed lines indicate PGL calibration reference plane. The probes can be seen making contact at the edge of the CPWs.

Fig. 7 — Simulated (dashed line) and measured (solid line) insertion loss of the 180 µm long CPW-PGL transition. Inset shows the considered transition where dashed lines indicate its span.

probe station avoiding field coupling and ensuring the PGL mode propagation.

To avoid substrate modes in the PE holder and minimize the losses while keeping the mechanical support, 1 mm deep and 1 mm wide holes were micromachined in the PE holder (Fig. 3). With this configuration, the 1 mm long PGL has air as dielectric under the PET while maintaining the mechanical support under the probing area.

Two different calibration standards were included in the wafer for comparing measurements: the proposed PGL multiline TRL, that sets the calibration plane along the PGL, and a customized CPW multiline TRL standard, with a calibration plane set 105 µm into the 50 Ω CPW line (with a 23.5 µm wide conductor strip and 1.5 µm wide gap) of the CPW-PGL transition.

III. RESULTS

First, to verify the behavior of the reflect of the proposed PGL TRL calibration substrate, the reflect structure was measured using the CPW multiline TRL standard. Measurements were compared with simulation results showing good agreement between the S_{11} and S_{21} (Fig. 4). The same S-parameter reflect simulation and measurements were repeated using the proposed PGL multiline TRL standard. Therein both simulated and measured S_{11} yielded high reflection results in all the band, having simulated S_{11} results higher than -1.1 dB in all the band (Fig. 5). Simulation and measurement results of S_{21} showed to have a desirable isolation and good agreement between them. Overall, the reflect standard is functional and behaves as expected.

Using the proposed PGL multi-line TRL standards, which allows the de-embedding of the CPW-PGL transition, a 1 mm
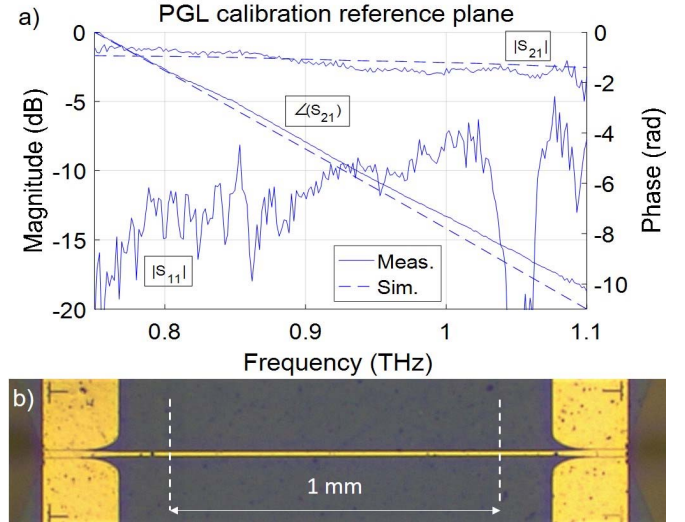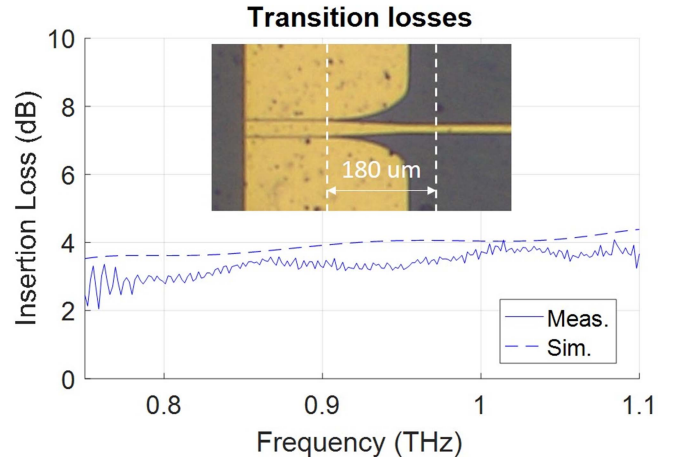
long and 10 µm wide PGL on a 23 µm thick PET film suspended on air was measured. The S-parameter measurement results show S_{21} between -1.1 dB and -3.0 dB (Fig. 6) from 0.75 THz to 1.1 THz, which corresponds to an attenuation constant between 0.13 Np/mm and 0.35 Np/mm. Additionally, the phase and group velocity of the PGL showed to be approximately 71% of the speed of light ($\varepsilon_{\text{eff}} = 2.0$), with negligible dispersion across the band. Reflection (S_{11}) measurements exhibit a higher uncertainty than the transmission (S_{21}) due to its high dependence on probing conditions.

The proposed PGL multi-line TRL standards allowed to experimentally estimate the insertion loss of the designed CPW-

PGL transition, which has a length of 180 μm (Fig. 7). Insertion loss resulted in values between 2 dB and 4 dB in the entire band, which are considered to be low taking into account the operating frequency.

IV. CONCLUSION

A set of multiline TRL calibration standards has been designed, fabricated and used to characterize a PGL from 0.75 THz to 1.1 THz. Measurement results of the reflect element have shown to have a wideband high-reflective behavior, which allows the multiline TRL standard to de-embed all elements behind the PGL calibration reference plane. This opens the possibility of studying in detail this waveguide, circuit elements included in it and to enhance the PGL's sensing capabilities.

The measured 10 μm wide and 1 mm long PGL has shown to have low line losses (between 0.13 Np/mm and 0.35 Np/mm in the range 0.75 - 1.1 THz), negligible dispersion, and wide-band characteristics.

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