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Submillimeter Wave S-Parameter Characterization of Integrated Membrane Circuits

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***Abstract* —We demonstrate S-parameter characterization of membrane circuits in the WR-03 frequency band (220-325 GHz) utilizing thru-reflect-line (TRL) -calibration technique. The TRL calibration kit design features 3 µm thick GaAs membrane circuits packaged in E-plane split waveguide blocks with the reference planes inside the membrane circuit structure. A 300 GHz membrane ring resonator filter circuit has been characterized by applying the proposed calibration kit, showing good agreement with simulations.**

***Index Terms*— Membranes, Monolithic integrated circuits, Scattering parameter measurements, Submillimete wave measurements, THz circuits, Calibration.**

I. Introduction

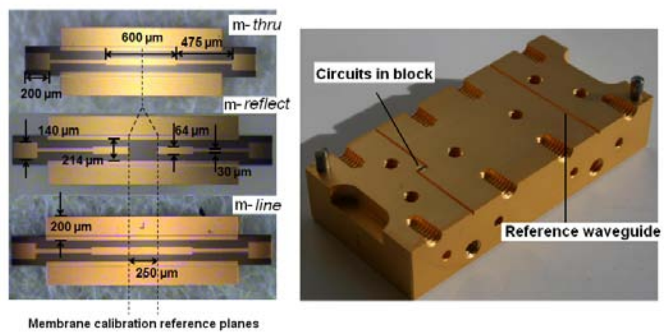
Terahertz (THz) technology has attracted much interest recently, due to its applications in remote sensing, radio astronomy, medical diagnostic and security imaging. However as circuit operating frequency increases, the difficulty of assembly increases due to the reduced chip dimensions and alignment tolerances. Furthermore, high frequency circuit designs are usually limited by the thickness of the support substrate, due to the onset of higher order electromagnetic modes [1]. To overcome these drawbacks, membrane supported monolithic integrated circuits (MICs) have been proposed [2]. Up to date, numerous ground-breaking results based on this technique have been reported. For instance, a 2.5 THz GaAs monolithic membrane-diode mixer and a 1.2 THz membrane frequency tripler have been demonstrated [2]-[3]. However, little has been reported about full S-parameter characterization of membrane circuits, although this is significant for circuit modeling and design verification.

For high frequency S-parameter characterization, traditional on wafer probing measurements [4] become very challenging due to contacting tolerances of probes, radiation and coupling effects, and it is unsuitable for fragile membrane circuits. A method for waveguide-embedded calibration has been proposed before for the characterization of MIC structures at millimetre -wave frequencies [5]. The solution is a fixture containing a waveguide to planar transition that connects the device to the network analyzer waveguide flanges. The systematic errors introduced by the embedding structure could be removed using a TRL calibration procedure.

In this paper, a TRL calibration kit for waveguide-embedded membrane circuits is presented for the first time and demonstrated by S-parameter characterization of membrane circuits in the WR-03 frequency band (220-325 GHz).

II. Design And Experiment

TRL standards are favourable for high frequency characterization, since the standards need only to be partly known. Furthermore, this technique can set the reference plane at the device under test (DUT), which eliminates the discontinuity between the measurement plane and the device plane [6], and the need for extra de-embedding procedures [7].



(a) (b)

Fig.1. (a) Microscope pictures of the membrane TRL standards and (b) a photo of the E-plane split block used for the thru standard in which a reference waveguide was included for evaluation of the waveguide losses.

In this work, the membrane TRL standards and filters were designed using a three-dimensional electromagnetic simulator (Ansoft HFSS) and a microwave circuit simulator (Agilent ADS). The design principle of the TRL standards is described in [8]. All of the TRL standards, denoted as m-*thru*, m-*line* and m-*reflect* in Fig.1 (a), have the same waveguide to planar transitions at each end. The simulated return loss is better than 15 dB over the WR-03 band for a single waveguide transition. The m-*line* is 250 µm longer than the m-*thru*, corresponding to a phase difference of 90 degrees at 300 GHz. The width of the transmission line is 64 µm, corresponding to a nominal characteristic impedance of approximately 100 Ω. An *open* standard was chosen as the *reflect* standard since it has a very good response characteristic and should be less sensitive than a *short*, which has a stronger dependence on mounting tolerances and good ground contact. To minimize the number of different mechanical block types, the membrane length for the m-*line*, the

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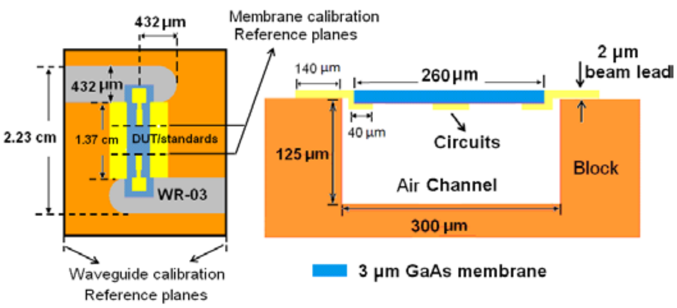
m-*reflect* and all the DUTs are the same.

The epitaxial structure and the membrane circuit fabrication are similar as in [9]. Fig.1 (b) shows a photo of an E-plane type split block with circuits mounted. A 26 mm long reference waveguide was designed for a comparison of waveguide and membrane losses. The circuits are aligned to a predefined channel which is formed by two symmetrical block halves. Fig. 2 shows the top view and cross section of the membrane circuits in the split block. The channel is designed to be 40 µm wider than the membrane, to accommodate manufacturing tolerances of mechanics and circuits. The circuits on a 3 µm GaAs membrane are suspended in air in the channel. The beam leads that are clamped in the block provide mechanical support as well as electrical connections.



(a) (b)

Fig. 2. Schematic pictures of the membrane circuits in blocks (a) top view and (b) cross section (The pictures are not to scale).

III. Design Verification of Membrane TRL Kit

For verification of the membrane TRL standards, a calibration was performed using standard Oleson Microwave Labs (OML) waveguide TRL standards. Upon calibration, the reference planes were set at the flanges of the two frequency extenders and the performance of the complete waveguide embedded membrane standards could in this way be verified. The WR-03 setup consists of OML V03VNA2-T/R frequency extension modules with an Agilent E8361A PNA S-parameter test set.

Fig. 3 shows $|S_{21}|$ and $|S_{11}|$ of the reference waveguide, m-*line* and an HFSS simulation of the m-*line*. The HFSS simulation has included the waveguide embedded structure. $|S_{21}|$ of the reference waveguide and the m-*line* are approximately -0.7 dB and -1 dB, respectively. The difference of the $|S_{21}|$ between the reference waveguide and the m-*line* ranges between 0.1-1 dB. The loss is mostly attributed to the waveguide transition and the membrane circuits. The envelope of the measured $|S_{11}|$ of the m-*line* has a reasonable agreement with the smooth response from HFSS simulations.

Fig.4 shows $|S_{21}|$ and $|S_{11}|$ of the m-*thru* and m-*reflect*. Compared to the m-*line*, a slightly larger loss at the band edges is observed in the m-*thru*, which is probably due to different transitions between the two waveguide probes separated by different distances and due to inequalities in the circuit assembly. For m-*reflect*, $|S_{11}|$ is around -0.7 dB and $|S_{21}|$ is below -40 dB, indicating the two ports are well isolated.

The low insertion loss in the m-*thru* and m-*line* and high reflection in the m-*reflect* indicate that the membrane TRL standards are adequate for use as calibration standards. However a spread in insertion loss was observed, which is probably due to inequalities in the assembly coming from imperfect grounding of the beam lead. The membrane TRL kit was selected by measuring several membrane TRL standards and selecting the ones with the lowest loss.

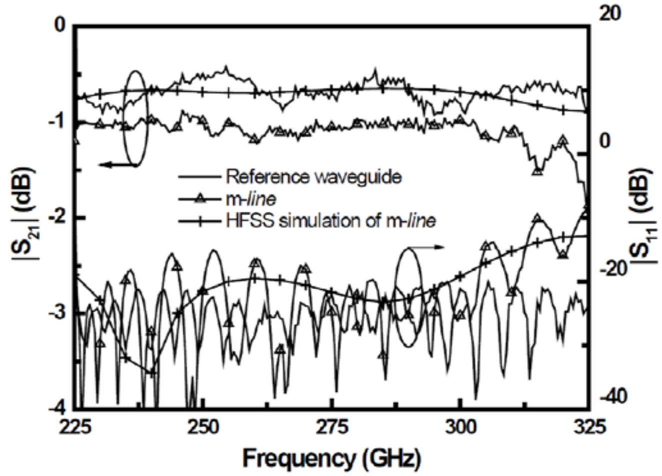


Fig.3. $|S_{21}|$ and $|S_{11}|$ of the reference waveguide, m-*line* and an HFSS simulation of the m-*line*, measured at waveguide calibration reference planes.

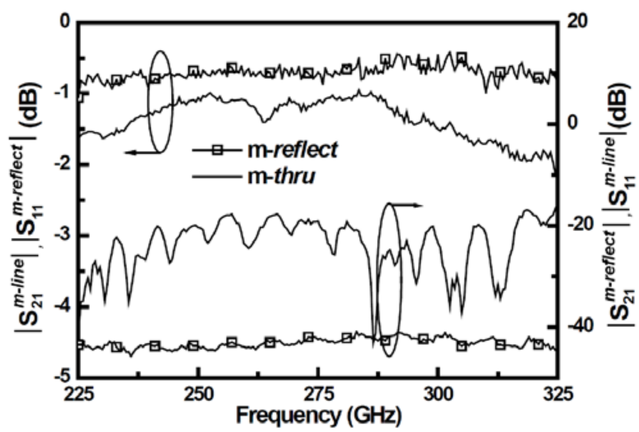


Fig.4. $|S_{21}|$ and $|S_{11}|$of the m-*reflect* and m-*thru*, measured at waveguide calibration reference planes.

IV. Membrane TRL Kit Calibration

By performing a TRL calibration with the manufactured membrane TRL kit, the reference plane is set at the center of the m-*thru*. After the calibration, the m-*thru* shows an insertion loss magnitude and phase repeatability within ± 0.01 dB and ±1 degree respectively without reconnection. By reconnecting the waveguide flange interfaces, the repeatability of the membrane TRL kit was checked, see. Fig. 5. The variation in $|S_{12}|$ and $|S_{21}|$ of the m-*thru* is within ± 0.2 dB. $|S_{11}|$ and $|S_{22}|$ of the m-*thru* are well below -30 dB across the frequency band. Very small differences are observed in both magnitude and phase response between the two ports for all the membrane standards.

Finally, a ring resonator filter was measured using the membrane calibration, see Fig. 6. A 5 GHz frequency shift, between the simulation model and circuit measurements, corresponding to 1.5 % of the resonance frequency was observed. The small frequency shift is probably due to either modelling error or manufacturing tolerances. The ripples which are also seen in Fig. 3 and Fig. 4 may be due to imperfect repeatability of the waveguide flange connections or differences in waveguide to membrane transitions. The amplitude of the ripple indicates a residue error of 0.08 in the reflection measurement.

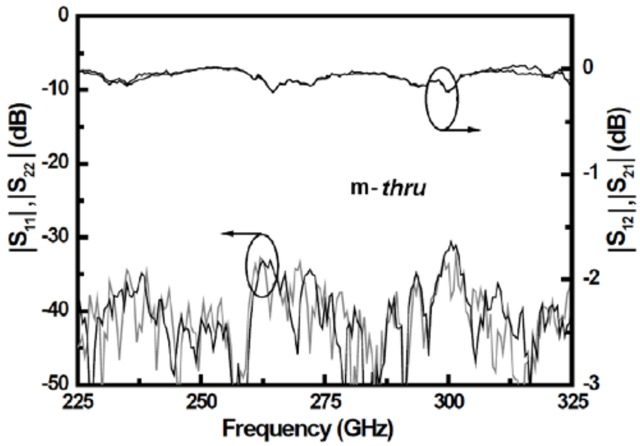


Fig.5. Repeatability measurement of full S-parameter of the m-*thru*, measured at membrane calibration reference planes.

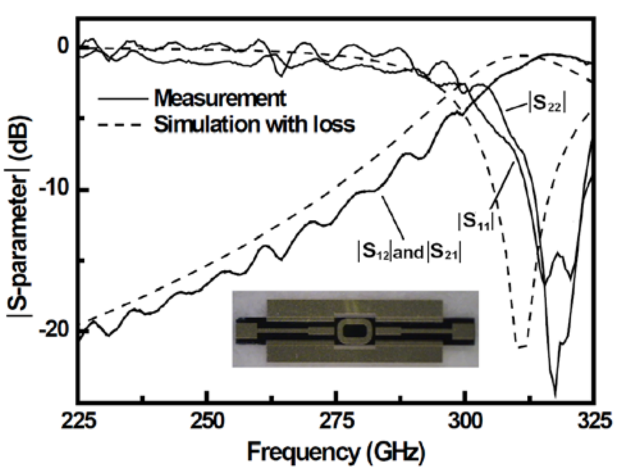


Fig.6. S-parameter characterization of a 300 GHz ring resonator filter, measured at membrane calibration reference planes.

V. Discussion

We have developed a practical waveguide integrated membrane TRL calibration kit for characterization of membrane circuits at submillimeter wave frequencies. This approach enables full S-parameter measurements with the reference plane directly on the membrane circuits, thus eliminating the need for de-embedding. However, several considerations should be made in the future to improve the accuracy and repeatability of the proposed calibration method:

(1) Misalignment of circuits in blocks, which affects the waveguide to membrane transitions, can be improved by decreasing the alignment tolerance from 20 µm to 10 µm or even smaller.

(2) Process repeatability such as non uniform waveguide transitions. In this work, all the TRL standards and DUTs were fabricated in the same batch. The plated Au for the circuits shows a 50 nm variation of the thickness and a root mean square (RMS) roughness of 21 nm across the wafer.

(3) The characteristic impedance of the reference transmission line setting the system impedance was designed and assumed to be 100 Ω; however the absolute value is difficult to verify experimentally.

(4) The repeatability of waveguide connections, which can be improved by using a ring-centred waveguide flange [10], and using a statistical measurement approach.

(5) A drift in both phase and amplitude in the VNA over time was observed. By re-measuring the membrane calibration kit again after DUT measurements, the drift effects can be estimated.

(6) The contacting between two half split blocks can be improved by recessing the contacting surfaces, thus improving the beam lead to ground connection and the yield of the circuit assembly.

In addition, the calibration error can be reduced by performing an averaged calibration making use of several sets of membrane standards.

VI. Acknowledgment

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