Calibration on the Fly—A Novel Two-Port S-Parameter Measurement Method for On-Wafer Leaky Systems

Aihua Wu, Chen Liu, Faguo Liang, Xuefeng Zou, Yibang Wang, Peng Luan, Chong Li, Senior Member, IEEE, and Nick Ridler, Fellow, IEEE

Abstract—In this article, we present a two-port on-wafer scattering parameter measurement method to tackle the issue of crosstalk between probes. The proposed method treats the crosstalk separately during the system calibration and the device measurement stages because the crosstalk during these stages is often different due to changes in the measurement conditions after the probes have been calibrated. For example, device under test (DUT) and calibration standards are often situated on different substrates, or the distance between probes during calibration is different from that during DUT measurement. Based on this concept, we develop a new error model in which the crosstalk is treated as a standalone two-port error network in parallel with the two-port calibration standards or DUTs. The two-port crosstalk error generated during probing, $E_{CT}$, is removed in the system calibration and corrected during the measurement of the DUT by using a dummy pair of open-circuit standards that are fabricated on the same substrate as the DUT. Since the crosstalk is corrected while measuring the DUT, rather than during system calibration, we call this method “calibration on the fly” (COF). The method is demonstrated using measurements of a 10-dB attenuator between 140 and 220 GHz.

Index Terms—Calibration, error model, millimeter-wave measurement, on-wafer measurement, scattering parameter (S-parameter).

I. INTRODUCTION

OVER the past 30 years, system error models for scattering parameter (S-parameter) measurement have been developed and implemented in coaxial, waveguide, and on-wafer measurement systems. The most widely used calibration methods, such as short-open-load-thru (SOLT) [1], thru-reflect-line (TRL) [2], and line-reflect-match (LRM) [3], are based on either 8-term or 12-term error model and do not contain corrections for crosstalk, because it is either nonexistent or negligibly small.

For on-wafer measurements, the limitations in using the conventional error models become significant at high frequencies, e.g., 100 GHz and above. This is mainly due to the nonnegligible crosstalk or leakage generated when probes are brought closer together in order to reduce system losses at these frequencies. The fringing effect between the probes leads to a leakage path from one probe to the other when the probes are in close proximity to each other. This is the case when testing components and transistors in monolithic millimeter-wave-integrated circuits.

The presence of crosstalk in S-parameter measurements is a well-documented problem. To address the probe-to-probe coupling issue, Speciale [4] introduced a 16-term error model, as shown in Fig. 1. The eight conventional error terms (plotted with solid lines in Fig. 1) and eight crosstalk error terms (plotted with dotted lines) are treated as a four-port network in cascade between the vector network analyzer (VNA) and the device under test (DUT). Sixteen errors can be solved by using at least five two-port standards whose S-parameters are fully known, and at least one of them is asymmetric (e.g., an open-load pair [5], [6]). Since then, several developments have been proposed to improve and optimize the original 16-term error model.

In 1997, Silvonen [7] developed a thru-match-reflect/line-match-reflect (TMR/LMR) self-calibration method which reduces the number of calibration standards and therefore simplifies the calibration procedure. In 2012, a short-open-load-reciprocal (SOLR) calibration method for multiport on-wafer measurement was introduced [8]. Subsequently, a method enabling the calibration of the full 16-term errors was developed using only four calibration standards [9]. In 2014, Dahlberg and Silvonen [10] proposed to define the calibration standards for the line-reflect-reflect-match (LRRM) method in a reciprocal 16-term error network. More recently, Williams et al. [11] used the 16-term error model as a second-tier calibration to determine the crosstalk error terms (plotted with dotted lines in Fig. 1) provided that the other eight error terms had been solved by a multiline-TRL
calibration [12], [13]. In 2018, Liu et al. [14] showed that two leakage paths, i.e., $e_{21}$ and $e_{12}$, actually represent the probe-to-probe crosstalk and the other six error terms are negligibly small and so can be ignored. In all the previous cases, the crosstalk generated between probe tips, i.e., $e_{21}$ and $e_{12}$, is always treated as a constant. However, this is generally not the case. In practice, the crosstalk changes as probe separation changes, especially at high frequencies.

To tackle this problem, we propose a new error model to represent the system errors in a modern two-port on-wafer $S$-parameter measurement system. The varying probe-to-probe crosstalk is considered as a standalone two-port error network in parallel with any two-port standard or DUT. Since the crosstalk generated during system calibration and device measurement stages is different, it is treated separately. We first remove the crosstalk error in the system calibration and then correct the crosstalk generated during the device measurement stage. We, therefore, call this method “calibration on the fly” (COF).

In addition, we will limit our study to coplanar waveguide (CPW) with ground-signal-ground topology in this article. Other topologies such as leakage in multimode waveguides for multiport or differential measurements [15], [16] are beyond the scope of this article.

II. PROBE-TO-PROBE CROSSTALK

In Speciale’s 16-term error model [4], crosstalk is treated as a constant and corrected during system calibration. However, the crosstalk often changes as the measurement environment changes whether it is for off-chip calibration, where DUTs and calibration standards are on different substrates, or for on-chip calibration where DUTs and calibration standards are on the same substrate. For the former, different substrates have different dielectric properties therefore different coupling; for the latter, the distance between probes during calibration is often different from that during the measurement of the DUTs. This also applies to the off-chip calibration scenario. To demonstrate how crosstalk is affected by the conditions of the measurement, we undertook the two experiments described below.

In the first experiment, we measured raw (uncorrected) forward transmission coefficients ($S_{21}$), which represents the crosstalk, between two G-band (140–220 GHz) probes when placed in air and separated by various distances. As shown in Fig. 2, $|S_{21}|$ is close to $-20$ dB at 220 GHz when the probes were separated by 200 $\mu$m and decrease as the distance between the probes increases. When the two probes are separated by 30 mm, the coupling is as low as $-80$ dB, and even $-100$ dB when a microwave absorber (Cascade PN 116-344) is inserted between the probes. From this experiment, we conclude that the crosstalk varies greatly with the distance between probes.

In another experiment, we investigated how probe-to-probe crosstalk is influenced by the type of DUT being measured. To do this, we measured three pairs of standards—open-open, short-short, and load-load—on a commercial CS-15 impedance standard substrate (ISS) from GGB Industries, Inc. Each pair has the same separation distance, i.e., 150 $\mu$m. The measured $|S_{21}|$ is plotted in Fig. 3. From these results, we can see that the crosstalk changes with both frequency and the type of DUT. The reflection coefficient of the DUTs has a
significant influence on the crosstalk. Therefore, we conclude that it is inappropriate to treat crosstalk for calibration and measurement as a constant.

To truly represent the crosstalk, we propose a new error model. As shown in Fig. 4, the probe-to-probe crosstalk is treated as a standalone two-port error network in parallel with the DUT during measurement. The crosstalk error, generated when probing, is removed during the system calibration and characterized using a dummy open-open pair that are fabricated on the same substrate as the DUTs. Then the crosstalk can be removed from the DUT measurements.

III. PROPOSED ERROR MODEL

As discussed in Section II, crosstalk exists between probes in a two-port on-wafer  S -parameter measurement system due to signals leaking from one probe tip to the other both in the substrate and in the air. The crosstalk varies depending on the loads being probed. We treat the crosstalk as a “virtual two-port network” (e.g., as an attenuator with high attenuation and high impedance) which is in parallel with a DUT during measurement, or a pair of standards during calibration. As shown in Fig. 4, all errors in the error model can be decomposed into three types: system errors, probe errors, and crosstalk errors. This assumption is based on a modern VNA which has very low internal leakages [17]. The S -parameters of the “virtual network” are marked as $E_{CT,ij}$, where $i, j = 1$ or 2, separately. If there is no crosstalk, the “virtual network” can be treated as an ideal pair of ideal open standards, i.e., $E_{CT,11} = E_{CT,22} = 1$, and $E_{CT,21} = E_{CT,12} = 0$. In this case, this error model becomes the conventional eight-term error model which is widely used in TRL and LRM calibration methods for coaxial and rectangular waveguides.

To apply this error model to a real on-wafer S -parameter calibration, we need to separate the crosstalk, or the “virtual network,” from the DUT. Fig. 5 illustrates a possible implementation of the new technique at frequencies from 140 to 220 GHz (G-band). We define the reference planes at each waveguide port as Plane I and Plane II, respectively, and the reference planes at the probe tips as Plane III and Plane IV, respectively.

Like a two-tier calibration, the correction procedure requires two calibrations. The first calibration is a waveguide calibration, which is performed at Plane I and Plane II. Since there is no crosstalk between two waveguide ports, a standard SOLT calibration in the waveguide can be implemented. The second calibration, i.e., probe calibration, is performed at Plane III and Plane IV, which are probe tips to remove probe errors, therefore an ISS is used. To characterize the crosstalk generated when measuring DUTs, an open-open pair on the same wafer as the DUTs and having the same physical length as the DUTs is required. A detailed calibration procedure, showing how the errors in the new model are solved, is described below.

A. Waveguide Calibration

A VNA is first calibrated as its waveguide ports (i.e., Plane I and Plane II in Fig. 5) using the conventional two-port SOLT method with waveguide standards. This calibration solves the eight system error terms, i.e., $e_{00}$, $e_{10}$, $e_{01}$, $e_{11}$, $e_{33}$, $e_{23}$, $e_{32}$, and $e_{22}$, as shown in Fig. 4.

B. On-Wafer Calibration

After the two-port waveguide calibration, probes are installed and one-port SOL calibration is performed at the probe tips (i.e., Plane III and Plane IV in Fig. 5) individually using a commercial ISS (e.g., CS-15 from GGB Industries Inc.) to extract the S -parameters or probe error terms of the left probe, $E_{PL}$, and the right probe, $E_{PR}$. This extraction can be achieved using the built-in program “AdaptorChar Marco” in a Keysight PNA-X VNA (all of the major VNA vendors have a similar Bauer–Penfield utility [18]). We used the models provided by the vendor for the SOL standards. More accurate models, e.g., based on full-wave simulation of SOL standards [19], [20] can be used for the extraction. In addition, the SOL method can be replaced with an over-determined set of offset shorts for probe characterization [21]. Note when performing one-port SOL calibration on one probe, the other probe should be separated by at least 30 mm to avoid probe-to-probe crosstalk. Once the S -parameters of the two probes have been obtained, the reference planes can be moved from Planes I and II to Planes III and IV using deembedding.
techniques. Details about this deembedding process are given in Section III-C.

In fact, Steps A and B can be combined using an on-wafer SOLR calibration method which requires an additional thru.

C. Crosstalk Characterization

The crosstalk errors are corrected with a dummy open–open pair with the same physical length as the DUT fabricated on the same wafer. This is because open standards, as shown in Fig. 3, have increased crosstalk as the frequency increases and are believed to be the main source of the coupling between probes. If the open-open pair standard is ideal, i.e., \(|S_{11}| = |S_{22}| = 1\) and \(|S_{21}| = |S_{12}| = 0\), the measured \(S\)-parameters are the cascaded \(S\)-parameters of the left probe, crosstalk network, and the right probe. In reality, the open–open pair is nonideal and so its \(S\)-parameters \((S_{\text{open}})\) can be defined using \([22]\). Based on the waveguide calibration, the measured \(S\)-parameters \((S_M)\) are the cascaded \(S\)-parameters of the left probe, the crosstalk network in parallel with the open–open pair standard, and the right probe.

\(T\)-parameters are used to de-embed the left probe and the right probe from \(S_M\) \([23]\). The \(S\)-parameters of the open–open pair in parallel with the crosstalk network \((S_{\text{open}})\) can then be obtained. (Here the “\(|\rangle\) sign means “in parallel.”)

Converting \(S\)-parameters to \(Y\)-parameters, and then using \((1)\) to separate \(S_{\text{open}}\) from \(S_{\text{open}})\), we can obtain \(E_{\text{CT}}\) from \(Y_{\text{CT}}\)

\[
Y_{\text{CT}} = Y_{\text{open}} - Y_{\text{open}}\tag{1}
\]

The relationship between \(S\)-parameters and \(Y\)-parameters is given in \((2)–(5)\), as shown at the bottom of this page \([23]\), where \(Y_0\) is the system admittance (i.e., the inverse of the system impedance, \(Z_0\)).

We also investigated short–short and load–load pair standards at lower frequencies, i.e., below 50 GHz, and found that the load–load pair standard has a similar effect as the open–open pair standard; however, the short–short pair standard is not feasible due to a singularity generated in \((1)\). The singularity could perhaps be mitigated using a mathematical means.

D. DUT Test

Also, based on the waveguide calibration, the \(S\)-parameters obtained between Plane I and Plane II for a DUT are labeled as \(S_m\). Again, using \(T\)-parameters to de-embed \(E_{\text{pL}}\) and \(E_{\text{pR}}\) from \(S_m\), the \(S\)-parameters of the DUT in parallel with the crosstalk network \((S_{\text{DUT}})\) can be obtained. Then, using \(Y\)-parameters to separate the crosstalk network from \(Y_{\text{DUT}}\) in \((6)\), the \(S\)-parameters of the DUT are obtained from \(Y_{\text{DUT}}\)

\[
Y_{\text{DUT}} = Y_{\text{DUT}}(\text{CT}) - Y_{\text{CT}}\tag{6}
\]

When measuring other DUTs of different lengths, the crosstalk network will change and will need to be recharacterized. In this case, a corresponding open-open pair with the same length as the new DUT is required, and the same crosstalk characterization procedure described in Section III-C should be implemented for the actual \(S\)-parameters of the new DUT.

According to the above method, the crosstalk error is removed while measuring the DUT rather than during the system calibration—hence, this method is called “COF.”

IV. EXPERIMENTAL RESULTS

To evaluate the COF method, a 10-dB attenuator was designed with the aid of commercial software (i.e., CST Microwave Studio) and fabricated on a 600-μm-thick semi-insulating gallium arsenide substrate using standard photolithography technology. A 400-nm layer of gold was deposited for the conductors and a thin layer of the nickel-chrome alloy was used for the resistors. A two-port open–open pair was also fabricated on the same substrate. The spacing between circuits was kept to a minimum of 3λg, which is greater than that suggested in \([24]\). The substrate was then thinned down to 100 μm after all circuits were made.

Fig. 6 shows a scanning electron microscope (SEM) image of the fabricated attenuator. All aforementioned components have the same edge-to-edge distance (i.e., 160 μm) in order to keep the distance constant during calibration and measurement. We defined the offset of the standards with reference to \([22]\). A G-band (i.e., 140–220 GHz) on-wafer \(S\)-parameter measurement setup, including a manual probe station, at the

\[
\begin{bmatrix}
Y_{11} & Y_{12} \\
Y_{21} & Y_{22}
\end{bmatrix} = \frac{Y_0}{\Delta Y S} \begin{bmatrix}
(1 - S_{11})(1 + S_{22}) + S_{21} S_{12} & -2S_{12} \\
-2S_{21} & (1 + S_{11})(1 - S_{22}) + S_{21} S_{12}
\end{bmatrix}
\]

\(\Delta Y S = (1 + S_{11})(1 + S_{22}) - S_{21} S_{12}\)

\(\Delta Y = (Y_0 + Y_{11})(Y_0 + Y_{22}) - Y_{21} Y_{12}\)

Authorized licensed use limited to: National Physical Laboratory. Downloaded on August 07,2020 at 08:21:18 UTC from IEEE Xplore. Restrictions apply.
National Physical Laboratory (NPL), U.K., and two probes from GGB Industries, Inc., was used for the measurements. The system configuration is shown in Table I.

Fig. 7 shows the extracted S-parameters of the probes. Port 1 and Port 2 refer to the waveguide port and probe tip of the probes, respectively. Fig. 8 shows the extracted S-parameters of the crosstalk network \( S_{CT} \) using the above-mentioned calibration procedure. As shown in this figure, the transmission coefficients (i.e., \( |S_{21}| \) and \( |S_{12}| \)) are approximately –30 dB at 140 GHz, increasing to close to –10 dB when the frequency reaches 220 GHz. Port reflections (i.e., \( |S_{11}| \) and \( |S_{22}| \)) are greater than 0 dB. This may result from probe launch differences between calibration and measurement [25]–[27].

Fig. 9 shows S-parameters of the 10-dB attenuator, corrected using the COF method, 16-term error model based on the SVD method [6], and SOLT (conventional 12-term error model), along with the simulated results. It is clear that the magnitudes of \( S_{21} \) and \( S_{12} \) corrected by the COF method show better agreement with the simulation results compared with the results corrected using the SOLT method, particularly at the higher frequencies in the band (i.e., above 180 GHz) where the presence of crosstalk is more likely to be a problem. The main reason for this is that the conventional 12-term error-based SOLT calibration technique does not correct for the effect of crosstalk properly; therefore, the crosstalk contributes to the total observed transmission between the probes.

It is also observed that the S-parameters corrected using the COF method are free of ripples compared with those corrected using the 16-term error model. In the authors’ opinion, the ripples shown in the 16-term error model are likely due to two reasons: one is that the 16-term error model treats the probe-to-probe crosstalk as a constant, but in fact, it varies with the length and impedance of the DUT, as described in Section II and the other is that the 16-term error model requires five standards whose S-parameters are fully known, but in practice, four standards along with SVD method are used which leads to approximation.

In addition, one may notice that the inconsistent return loss shown in Fig. 9. In the authors’ opinion, the difference in reflection may be caused by the inconsistent broadband matched standards between the chip and the rectangular waveguide. The reflection is heavily dependent on the load standard in SOLT calibration. However, it is difficult to manufacture broadband matched loads very accurately for rectangular waveguides or on-chip.

V. CONCLUSION

In this article, we have presented a new error model for a two-port on-wafer measurement system. The new model truly reflects the variable probe-to-probe crosstalk that is subject
to change during the calibration/measurement process. The new error model separates the probe errors from the system errors and treats the probe-to-probe crosstalk as an error network in parallel with the DUT. Thus, the crosstalk can be corrected while measuring the DUT. Based on the new error model, a novel COF calibration and measurement method has been presented. To implement this method, an open–open pair standard fabricated on the same substrate as the DUT was used for crosstalk correction. A load–load pair standard can also be used but not a short–short pair standard as it leads to a singularity when solving the equations. To test the method, a 10-dB attenuator was measured using a G-band on-wafer probe system. The results showed that the correction using the new error model provides improvement by almost 1-dB (i.e., 10%) compared with the conventional SOLT method.

ACKNOWLEDGMENT

The authors would like to thank Dr. X. Shang from the National Physical Laboratory, Teddington, U.K., for providing access to the wafer test equipment used in this article.

REFERENCES


Faguo Liang was born in Liaocheng, Shandong, China, in 1965. He received the B.Eng. degree in microelectronics from Shandong University, Jinan, China, in 1984, and the M.Eng. degree in microelectronics from the Hebei Semiconductor Research Institute, Shijiazhuang, China, in 1989.

From 1984 to 1986, he was a Research Assistant with the Jinan Semiconductor Research Institute, where he has been an Engineer since 1989 and currently a Professor. His research interests include microwave instrumentation metrology and on-wafer microwave parameter measurements.

Xuefeng Zou was born in Shuangyashan, China, in 1977. He received the B.Eng. degree in automation from the China University of Mining and Technology, Xuzhou, China, in 2000.

He joined the Hebei Semiconductor Research Institute, Shijiazhuang, China, as a Research Engineer in 2000, where he is currently a Senior Research Engineer with the Department of Technology. His current research interests include FET devices and circuits, GaAs monolithic microwave integrated circuit (MMIC), GaN-based FETs, and measurement techniques.

Yibang Wang was born in Jining, China, in 1987. He received the B.Sc. degree in communication engineering from the Nanjing University of Aeronautics and Astronautics, Nanjing, China, in 2009, and the M.Sc. degree in instrument design from the Handan Purified Equipment Research Institute, Handan, China, in 2012.

He joined the Department of Metrology and Maintenance, Hebei Semiconductor Research Institute, Shijiazhuang, China. His current research interests include microwave metrology, particularly on-wafer terahertz S-parameters measurements, and the fabrication of on-wafer calibration kits and research of calibration algorithm.

Peng Luan was born in Liaoning, China, in 1978. He received the B.Eng. degree from Northeastern University, Shenyang, China, in 2002, and the M.Sc. degree from the University of Electronic Science and Technology of China, Chengdu, China, in 2011.

In 2002, he joined the Department of Metrology and Maintenance, Hebei Semiconductor Research Institute, Shijiazhuang, China, as a Research Engineer. His current research interests include the design and characterizing of on-wafer thru-reflect-line (TRL) S-parameters calibration kits, the development of accurate on-wafer S-parameters and load–pull system measurement techniques, and the verification of on-wafer S-parameters and load–pull system using active and passive devices.

Chong Li (Senior Member, IEEE) was born in Liaoning, China, in 1979. He received the B.Eng. degree from Donghua University, Shanghai, China, in 2002, the M.Sc. degree (Hons.) from The University of Manchester, Manchester, U.K., in 2007, and the Ph.D. degree in electronics and electrical engineering from the University of Glasgow, Glasgow, U.K., in 2011.

In 2011, he became a Post-Doctoral Research Assistant and later a Post-Doctoral Research Associate with the University of Glasgow, working on the development of millimeter-wave signal sources and terahertz imaging systems. In January 2014, he joined the National Physical Laboratory (NPL), Teddington, U.K., as a Higher Research Scientist, where he contributed to and led several commercial projects and U.K. national and European research projects. He was the Measurement Service Provider (MSP) of the ultrafast waveform metrology service at NPL. He also led work on microwave and millimeter-wave on-wafer measurements. In August 2017, he became a Lecturer with the University of Glasgow, where he is currently leading the Microwave and Terahertz Electronics Research Group. He held a Visiting Position at the Advanced Technology Institute (ATI), University of Surrey, Guildford, U.K., in 2017. He has published more than 60 journal and conference papers. His current research interests include microwave and terahertz components, systems and metrology, and next-generation wireless communications.

Dr. Li received the Best Non-Student Paper Prize at the Loughborough Antennas and Propagation Conference (LAPC) in 2015. He is also an Associate Editor of the Royal Society Open Science.

Nick Ridler (Fellow, IEEE) received the B.Sc. degree from the King’s College London, University of London, London, U.K., in 1981.

He is currently the Head of Science with the Department of Electromagnetic and Electrochemical Technologies, National Physical Laboratory, Teddington, U.K. He is also the Non-Executive Director of La Techniques Ltd., Surbiton, U.K., and a Visiting Professor with the Pollard Institute, University of Leeds, Leeds, U.K.; the Department of Electrical Engineering and Electronics, University of Liverpool, Liverpool, U.K.; and the Faculty of Engineering and Physical Sciences, University of Surrey, Guildford, U.K. He has more than 35 years’ experience working in industrial, government, and academic research establishments. His research interest includes precision high-frequency electromagnetic measurement (1 kHz–1 THz).

Mr. Ridler is a Fellow of the Institution of Engineering and Technology (IET) and the Institute of Physics (IOP). He is also the Past Chair of the IEEE MTT Society’s “Microwave Measurements” Technical Committee and the Past President of the Automatic RF Techniques Group (ARFTG).