Validity of Room-temperature Calibration for On-wafer Measurements up to 220 GHz, 125 °C, and 48 h

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***Abstract* — At-temperature calibration is not only inconvenient, but also complicated by the temperature dependence of impedance standards. This paper examines the validity of a room-temperature calibration for on-wafer measurements from 70 kHz to 220 GHz, from 25 °C to 125 °C, and up to 48 h. The results indicate that the room-temperature calibration is applicable up to 125 °C provided errors up to 0.5 dB in magnitude and 5° in phase are tolerable. Consistent with previous reports up to 110 GHz, the present errors are mainly caused by the time-dependent system drift instead of the temperature dependence of impedance standards. For unknown reasons, the system proven to be stable at room temperature drifts significantly at elevated temperatures. This makes elevated-temperature measurements challenging because presently it takes approximately three hours for the system to stabilize at a new temperature. Therefore, in the near future, efforts should be concentrated on stabilizing the system faster rather than correcting for the temperature dependence of impedance standards.**

***Index Terms* — Calibration, impedance measurement, measurement errors, metrology, microwave technology, millimeter wave technology, scattering parameters**

I. Introduction

The operating frequency of semiconductor devices is being pushed above 110 GHz by 6G wireless communications, low-orbital satellite communications, next-generation automobile radars, etc. It is therefore critical to characterize these devices at not only sub-terahertz (sub-THz) frequencies, but also elevated temperatures to evaluate their robustness under different environments and operating conditions.

For accurate sub-THz characterization, impedance standards are used to extract the error-correction matrix and to transform the measured scattering (*S*) parameters from the vector network analyzer (VNA) to the device under test. Typically, the impedance standards are designed to match the 50-Ω system impedance at room temperature, but their impedance will deviate from 50 Ω at elevated temperatures. Although non-50-Ω calibration techniques have been developed [1], the temperature coefficients of sub-THz impedance standards are not yet well characterized. This presents a dilemma because the temperature coefficients of impedance standards cannot be accurately characterized without accurate measurements at elevated temperatures.

To date, the calibration of elevated-temperature measurements has been sporadically reported [2]–[5]. In [2], a line-reflect-match (LRM) [6], [7] calibration was performed by measuring the match standard at room temperature before other standards were measured at an elevated temperature. The approach limited the phase error of the E_{TF} term of the error-correction matrix to 5° up to 50 GHz and 160 °C with negligible magnitude error. In [3], a multiline thru-reflect-line (MTRL) [8], [9] calibration was performed at room temperature, then applied to a 17-mm coplanar transmission line at 360 °C after correcting for the temperature-induced changes in the cables, probes, and lines. The correction resulted in < 1 dB and < 5° changes up to 50 GHz. In [4], it was found that correcting only for the temperature dependence of the match resistance (49.94 Ω at 25 °C vs. 50.55 Ω at 150 °C) reduced the error of an enhanced-line-reflect-reflect-match (eLRRM) [10] calibration from 2.4% to 0.6% up to 50 GHz, with the error defined as the worst-case $|\Delta S_{ij}/S_{ij}|$ [11]. In [5], the frequency was extended to 110 GHz and it was found that at 85 °C, the worst-case error due to the temperature dependence of impedance standards was three times less than the error due to time-dependent system drift. This paper further extends the frequency to 220 GHz and confirms that presently the effect of time-dependent system drift is greater than the effect of temperature-dependent impedance standards.

II. Measurement Setup

Fig. 1 shows that the measurement setup comprises an Anritsu ME7838G 70-kHz-to-220-GHz VNA, an MPI TS2000-IFE automated probe station, two MPI TITAN T220A-GSG050 probes, and an MPI TCS-050-100-W impedance standard

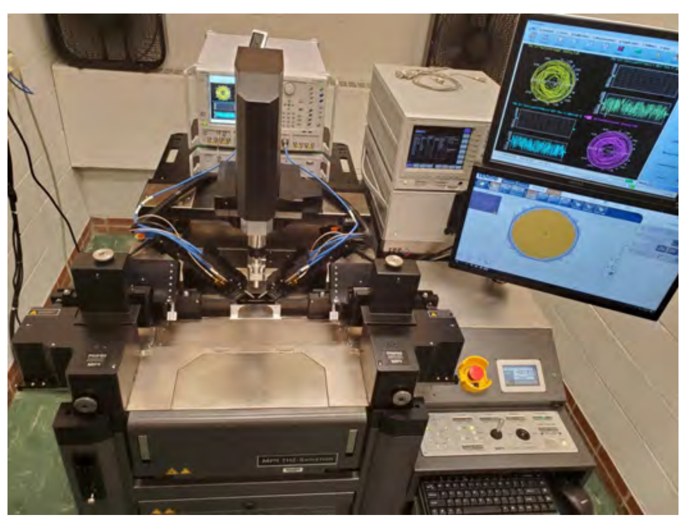
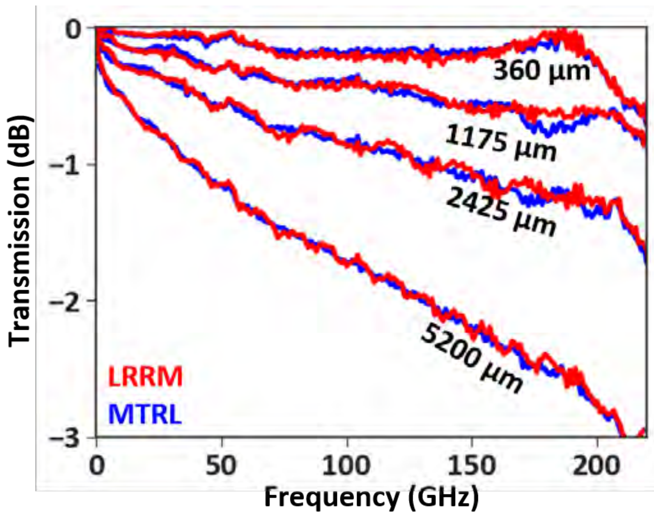


Fig. 1. Measurement setup.



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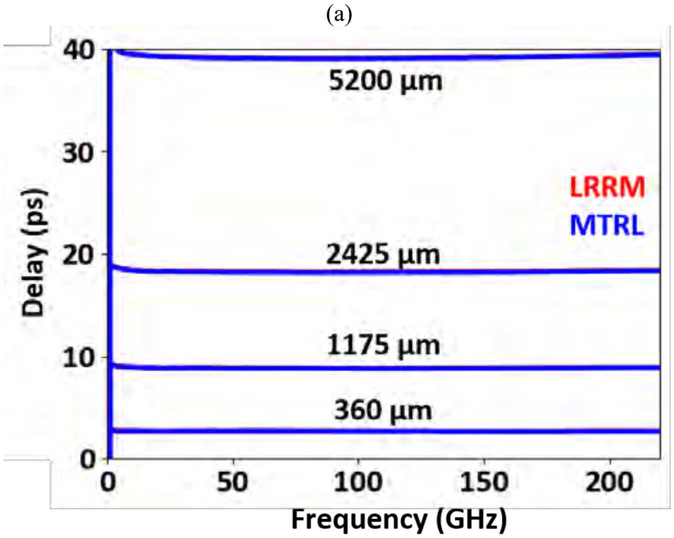

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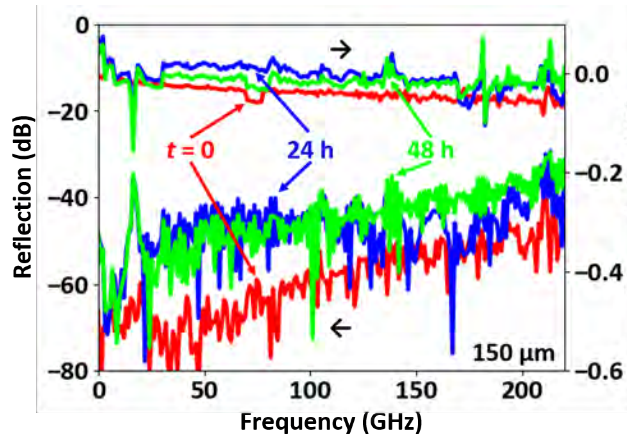
Fig. 2. (a) Loss and (b) delay of coplanar transmission lines of different lengths after LRRM or MTRL calibration. LRRM and MTRL are indistinguishable in (b).

substrate (ISS) [12], [13]. With optical feedback through pattern recognition, the probes automatically land on different impedance standards of the ISS with an error of less than ± 5 µm. This is critical for measurements up to 220 GHz but difficult to achieve manually. Normally, the ISS is placed on an auxiliary chuck made of 20-mm-thick alumina and kept at room temperature. The ISS itself is made of 0.25-mm-thick alumina. To evaluate the temperature dependence of impedance standards, the ISS is moved to the main metal chuck with −60-°C-to-200-°C temperature control, bringing in the ground plane to within 0.25 mm.



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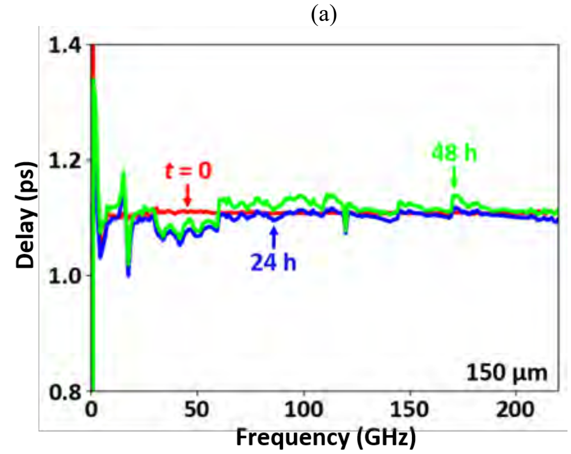


(b)

Fig. 3. Temporal stability of (a) reflection/transmission coefficients and (b) delay of a 150-µm line after LRRM calibration.

III. Results and Discussion

A. Room-temperature Measurements

At room temperature, the system is stable and LRRM and MTRL calibrations are in agreement, except it is impractical to extend the MTRL calibration much below 1 GHz. Fig. 2 shows that the insertion loss and delay of coplanar transmission lines of different lengths after LRRM or MTRL calibration with the ISS on the alumina chuck. The difference between LRRM and MTRL is on the order of 0.1 dB in magnitude and 0.1° in phase. Fig. 3 shows that the insertion loss and delay of a 150-µm line obtained by using the same LRRM calibration at $t = 0$ varied by less than 0.1 dB in magnitude and 2° in phase over 48 h. During this period, the room temperature was kept at 24.5 ± 0.5 °C. The excellent repeatability and stability across the bandwidth of more than six decades is consistent with that of previous reports [14], [15].

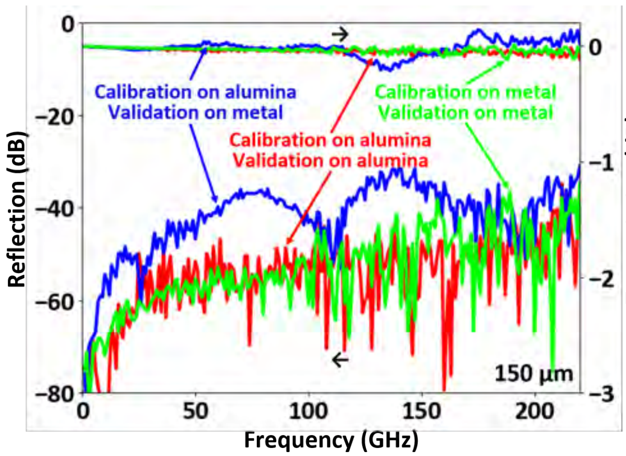


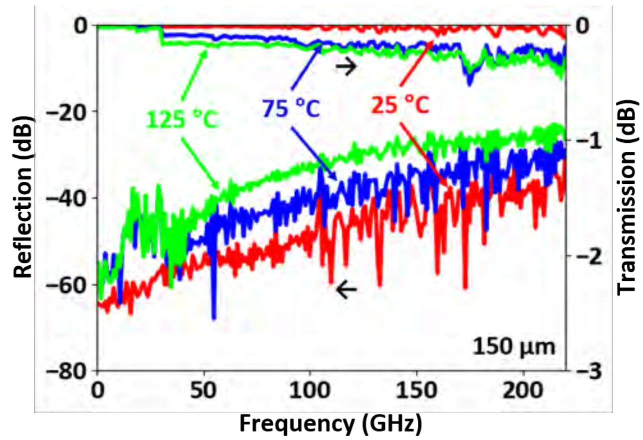
Fig. 4. Effect of metal vs. alumina chuck on reflection/transmission coefficients of the 150-µm line after LRRM calibration.

To evaluate the effect of metal vs. alumina chuck (0.25-mm vs. 20-mm ground plane), the LRRM calibration and the 150-µm-line validation were performed in three different combinations: 1) calibration and validation both on alumina, 2) calibration on alumina; validation on metal, and 3) calibration and validation both on metal. Fig. 4 shows that there is no significant difference between the three combinations. Therefore, all elevated-temperature measurements were performed with the ISS on the metal chuck. It has been reported that the MTRL calibration is significantly affected by placing the ISS on metal, absorber, or thick alumina [16]. However, the present lumped impedance standards used in the LRRM calibration may be less sensitive to a closely-spaced ground plane, and the 50-µm narrow pitch of the present probes may help suppress parasitic modes.

B. Elevated-temperature Measurements

LRRM calibration was performed at 25 °C with the ISS on the main (metal) chuck after turning on its temperature control for more than 3 h in order to stabilize the system. Immediately after calibration, the impedance standards on the ISS were measured. Then, to evaluate the temperature and temporal stability of the calibration, the chuck was elevated to 75 °C or 125 °C and the impedance standards were remeasured after three or more hours at each temperature. Fig. 5 shows that by applying the room-temperature LRRM calibration to the 150-µm line at 75 °C or 125 °C, its transmission coefficient can change by as much as 0.5 dB in magnitude and 5° in phase. However, because the elevated-temperature measurements were made 3 h after calibration, time-dependent system drift could contribute to the changes.

Fig. 6 shows that the transmission coefficient of the 150-µm line can drift by as much as 1 dB after heating to 75 °C or 125 °C for up to 20 h, and the drift at 75 °C is more severe than that at 125 °C. In either case, the drift is far more severe than at room temperature as shown in Fig. 3. Presently, it is not clear what causes the drift and why it is far more severe than that at room temperature. It appears that, under heating, beside the wafer chuck and sample, many other parts of the system need to reach a steady-state temperature, which may take a long time, especially for the VNA, cables and probes that are indirectly heated.



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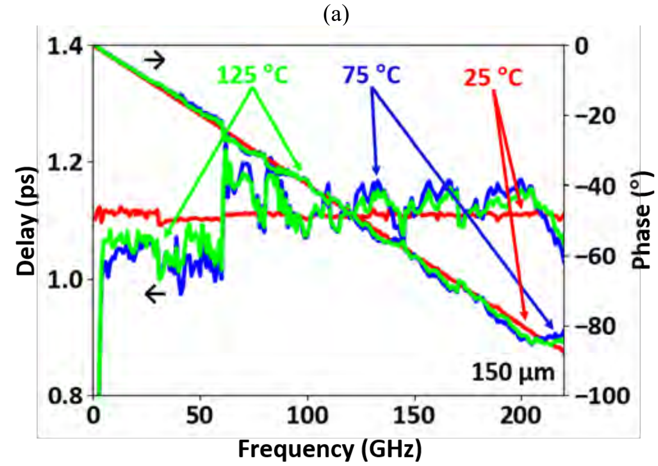

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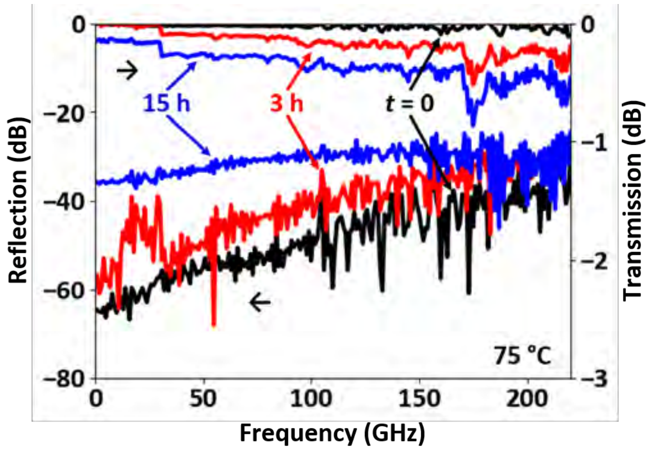
Fig. 5. Temperature effects on (a) reflection/transmission magnitude and (b) transmission delay of the 150-µm line after LRRM calibration.

IV. Conclusion

This study explores the validity of room-temperature calibration for on-wafer measurements up to 220 GHz, 125 °C, and 48 h. The results are consistent with previous reports conducted at lower frequencies. The results confirm that room-temperature calibration is applicable for elevated-temperature measurements up to 125 °C, provided errors up to 0.5 dB in magnitude and 5° in phase are tolerable. The errors appear to be caused by time-dependent system drift instead of the temperature-dependent impedance standards. Therefore, for accurate and efficient measurements at elevated temperatures in the near future, efforts should be concentrated on stabilizing the system faster, rather than correcting for the temperature dependence of impedance standards.



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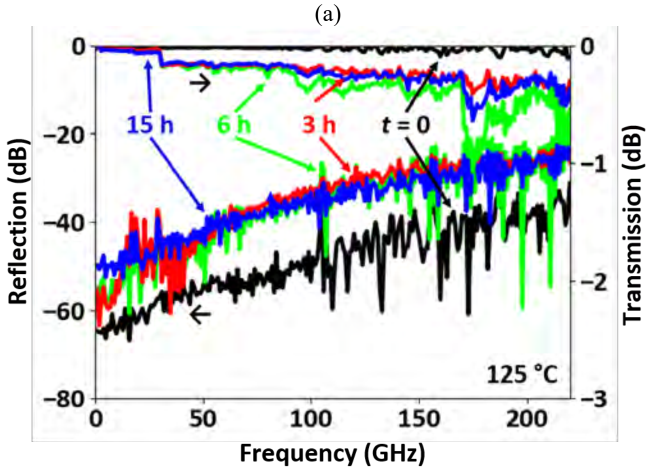

(b)

Fig. 6. Reflection/transmission coefficients of the 150-µm line after LRRM calibration at 25 °C then heated at (a) 75 °C and (b) 125 °C up to 20 h.

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