Verification of Commercial Probe-Tip Calibrations*

Roger B. Marks & Dylan F. Williams
National Institute of Standards and Technology
Mail Code 813.06, 325 Broadway
Boulder, CO 80303

Abstract

We present results of a verification procedure useful in evaluating the accuracy of probe-tip scattering parameter measurements. The procedure was applied to calibrations and measurements performed in industrial laboratories. Actual measurement discrepancies, due primarily to calibration errors, are directly compared to bounds determined by the comparison method. The results demonstrate the utility of the verification technique as well as serious flaws, particularly at high frequencies, in some conventional calibrations.

Introduction

For this paper, we applied a verification procedure to evaluate the accuracy of probe-tip scattering parameter measurements performed in several industrial laboratories. In each case, we compared a commercial "off-wafer" calibration to an accurate on-wafer calibration, using calibration standards built on the same wafer as the device under test (DUT) so as to replicate the DUT's electromagnetic environment. We computed bounds on the difference between the scattering parameters as measured using the two different calibrations and then confirmed the validity of those bounds using measurements of a number of devices performed using both calibrations. The results demonstrate that the computed bounds are indeed representative of the actual measurement discrepancies. They also show that some commercial calibrations differ significantly from the on-wafer calibration.

Calibration verification is vital due to the proliferation of calibration methods used for probe-tip scattering parameter and impedance parameter measurement. Certain methods provide high accuracy, while others are more convenient, are less time consuming, or make use of simple standard artifacts demanding little wafer space. Commercial users, who often prefer to trade accuracy for low cost, may require an assessment of their measurement accuracy. Sometimes they wish to know only that they are "in the ballpark" but cannot ensure even this limited requirement. Other requirements, such as product specification, demand detailed error bounds.

Until recently, it has been difficult to assess the effect of calibration variations. This has changed, however, with the introduction of the calibration comparison procedure [1] developed at the National Institute of Standards and Technology (NIST). This procedure directly compares two different calibrations of the same probe station and offers bounds that effectively limit the magnitude of the difference

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between the scattering parameters as measured using the two different calibrations. The procedure provides a practical and easily understood alternative to exhaustive studies comparing measurements of a multitude of devices.

Methodology

The experiment employed probe-tip calibrations, the principles of which are discussed in [2]. Essentially, each calibration had a nominal reference impedance of 50 Ω and a reference plane nominally located just ahead of the probe tips. Thus, each calibration was nominally identical, although they used different structures on different substrates, including GaAs, vitreous silica (which we here call quartz), and alumina. Furthermore, a variety of methods and algorithms were used, including LRM (line-reflect-match) [3], LRRM (line-reflect-reflect-match) [4], and OSLT (open-short-load-through).

In the NIST calibration comparison procedure [1], the calibration under test is followed by an accurate multiline TRL (through-reflect-line) calibration [5] with reference impedance correction [6]. This requires that multiline TRL standards be measured with respect to the initial calibration. The subsequent second-tier calibration identifies the "error boxes" which relate the two calibrations. Analysis of these error boxes provides upper bounds on the difference in measurements as obtained using the two calibrations.

We used eighteen passive structures in coplanar waveguide (CPW), half on a GaAs substrate and half on quartz, as test devices. Both the GaAs and quartz device wafers included on-wafer multiline TRL calibration sets using CPW that was identical to that in which the devices were embedded. This allowed us to perform an accurate on-wafer probe-tip calibration using multiline TRL with impedance correction. In both GaAs and quartz cases, we used these calibrations to accurately measure the device scattering parameters. In order to quantify the repeatability errors, we repeated the on-wafer calibration and used the NIST calibration comparison process to quantify the difference between the two nominally identical calibrations. This result provides a rough estimate of the measurement uncertainty due to random repeatability errors and instrument drift.

We carried out the entire on-wafer calibration, measurement, and uncertainty assessment process once, at NIST, to develop a baseline for the assessment of various commercial calibrations and measurements. At each site, the DUTs were remeasured using the commercial calibration. If this calibration were accurate, the resulting measured scattering parameters would differ from the NIST on-wafer measurements by little more than the measured uncertainty.

While the true on-wafer calibration provides a good benchmark, it is not part of a realistic plan for verifying commercial calibrations, for users may have no access to accurate on-wafer standards appropriate to their DUT. Therefore, instead of comparing the commercial and on-wafer calibrations directly, we compared each to a 50 Ω multiline TRL probe-tip calibration based on NIST's GaAs coplanar waveguide standards (the "NIST calibration"). Since the calibration comparison method is based on a linearization, we are justified in simply adding the bounds arising from the on-wafer vs. NIST comparison (performed once at NIST) to the NIST vs. commercial comparison (performed at the commercial laboratory) in order to obtain bounds valid for the on-wafer vs. commercial comparison. Since we intend the result to be a reflection of the inaccuracies in the commercial calibration, we decided to include the experimental uncertainty associated with the on-wafer calibration itself into the overall bound. This was easily accomplished; we simply added the uncertainty determined earlier during the on-wafer calibration.

While this procedure is somewhat complicated, most of the work is done at NIST. The only measurements required at the commercial facility are of the DUTs and the NIST standards, using the commercial calibration. Custom NIST software handles all of the data processing.

Experimental Results

We analyzed several calibrations from various commercial laboratories, each using coplanar waveguide standards. For each DUT in each calibration, we computed the four quantities $|S_{ij} - S_{ij}'|$, where S_{ij} and S_{ij}' are the scattering parameters measured with the commercial and NIST calibrations, respectively, and where $ij \in \{12, 21, 12, 22\}$. Although the four scattering parameters could be considered separately, we have chosen to simplify the data presentation by displaying only the largest of the four values, plotted as solid curves in the figures.

In each figure, we also include plots representing upper bounds on $|S_{ij} - S_{ij}'|$, as established by the calibration comparison procedure. The verification software computed this result using only the calibration data. The plotted bounds indicate the largest possible difference in any of the four scattering parameters for any passive device. The bound for the commercial calibration vs. on-wafer calibration, marked with solid circles, is the sum of the three individual bounds, plotted with broken curves.

Figure 1 compares an OSLT calibration using off-wafer GaAs standards to the benchmark calibration using standards on the GaAs DUT wafer. The computed bound does indeed bound the actual measurement discrepancies, without radically overestimating them. This demonstrates the utility of the verification technique. However, the discrepancies shown in Figure 1 are large. Errors of magnitude 0.5 are generally unacceptable in measurements of scattering parameters with magnitude less than 1. The problem does not arise from operator error but apparently from inappropriate calibration parameter definitions, calculated by the laboratory from physical models of the standards. A TRL calibration, using the same standard substrate but not requiring standard models, was much closer to the benchmark, with bounds less than 0.16 in the 2-40 GHz band.

Figure 2 presents results of another laboratory's OSLT calibration using alumina standards. The discrepancies are much smaller than those of Fig. 1 but remain well above the uncertainty level.

A different laboratory at the same company, using alumina LRM standards, performed the calibration illustrated in Fig. 3. The results were significantly better than the OSLT calibrations studied.

The LRRM results, as shown in Fig. 4., were even closer to the on-wafer calibration. However, an analysis of the verification results suggested a calibration problem, particularly at the low frequencies. By repeating the experiment using uniform frequency internals, rather than the nonuniform frequencies at which we conducted the original verification, we determined that the LRRM software did not properly account for unequal frequency spacing. This is illustrated in Fig. 5, which compares the bound of Fig. 4 to similar bounds in experiments conducted by various operators using uniformly-spaced frequencies. The software problem turned out to be a minor one that has since been corrected.

All of the results presented to this point have concerned the devices on the GaAs wafer. For contrast, Fig. 6 presents results for the 9 DUTs built on quartz using the same LRM calibration illustrated in Fig. 3. The discrepancies are much larger than for the GaAs devices because the transition from the probe to the quartz transmission line is electrically unlike the transition to the alumina standards.

Conclusions

The experiments confirm the validity of the verification procedure, demonstrating that the actual measurements discrepancies are indeed smaller than the computed bounds. They also confirm the utility of the method by showing that the computed bounds do not vastly overestimate typical errors.

In addition, we demonstrated that the calibration comparison procedure is useful in the diagnosis of calibration error, identifying mistakes that had previously gone unnoticed. Without independent verification, it is difficult to confirm that a calibration is correct or even "in the ballpark." Self-consistency checks do not suffice.

Furthermore, we demonstrated that common calibration methods can result in significant errors. Although some methods are much more effective than others, each resulted in discrepancies much larger than the experimental repeatability and large enough to be easily measured.

Finally, we have shown that the applicability of any probe-tip calibration is limited to a class of test devices. For example, an LRM probe-tip calibration based on alumina artifacts may give good measurements of GaAs devices and yet be unsatisfactory for the measurement of devices built on quartz.

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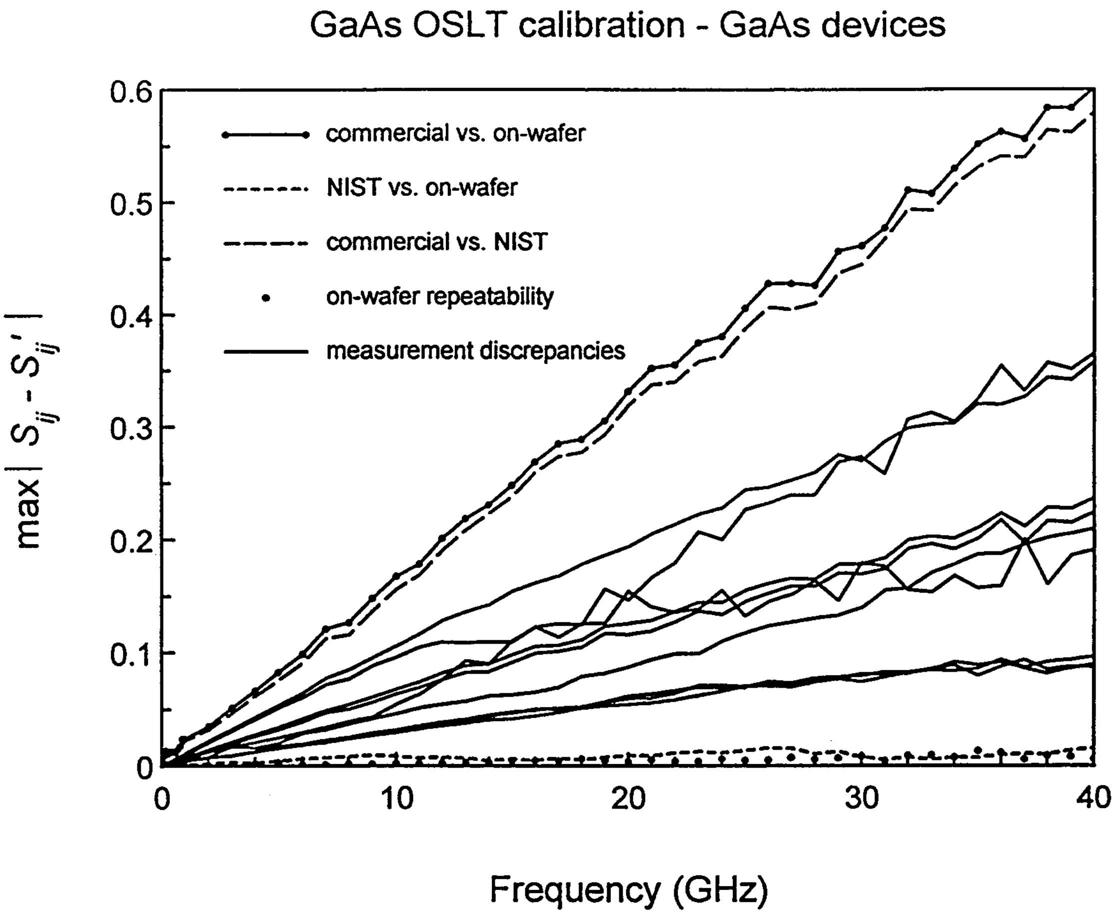
GaAs OSLT calibration - GaAs devices

Figure 1

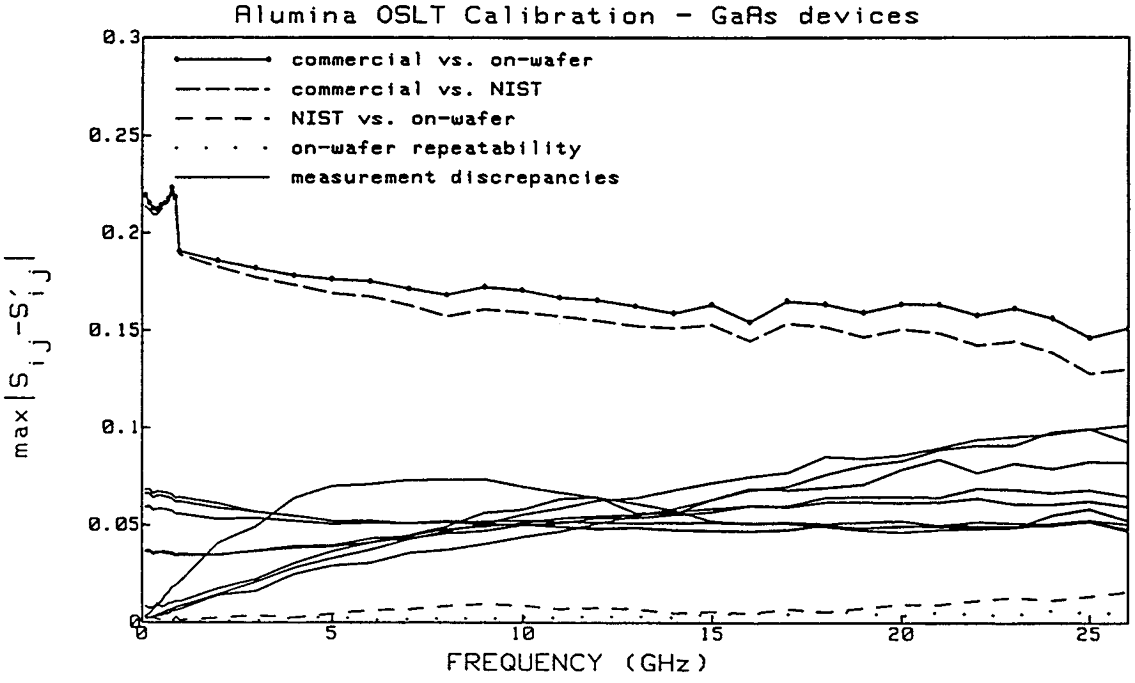
Alumina OSLT Calibration - GaAs devices

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Figure 2

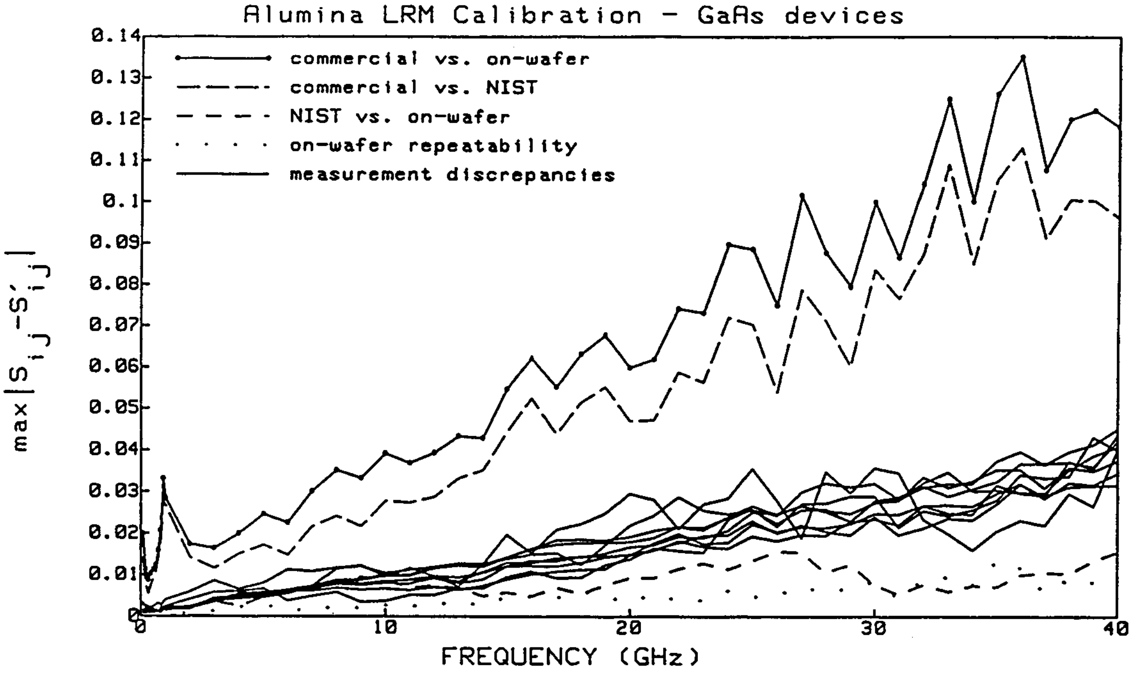

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Figure 3

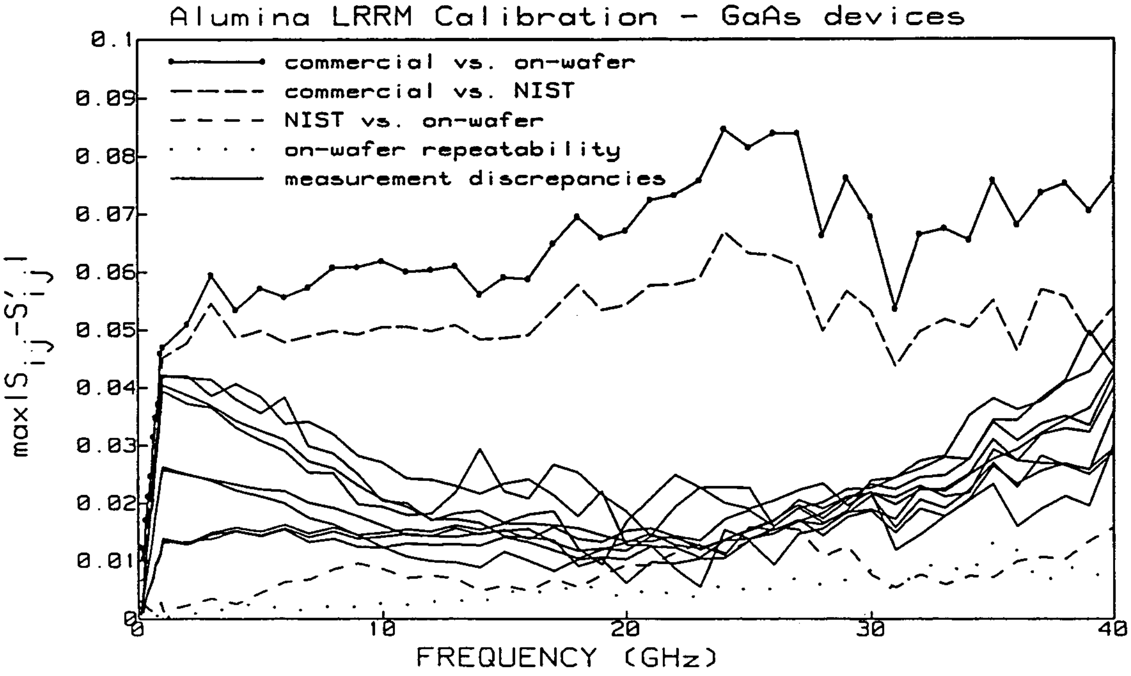

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Figure 4

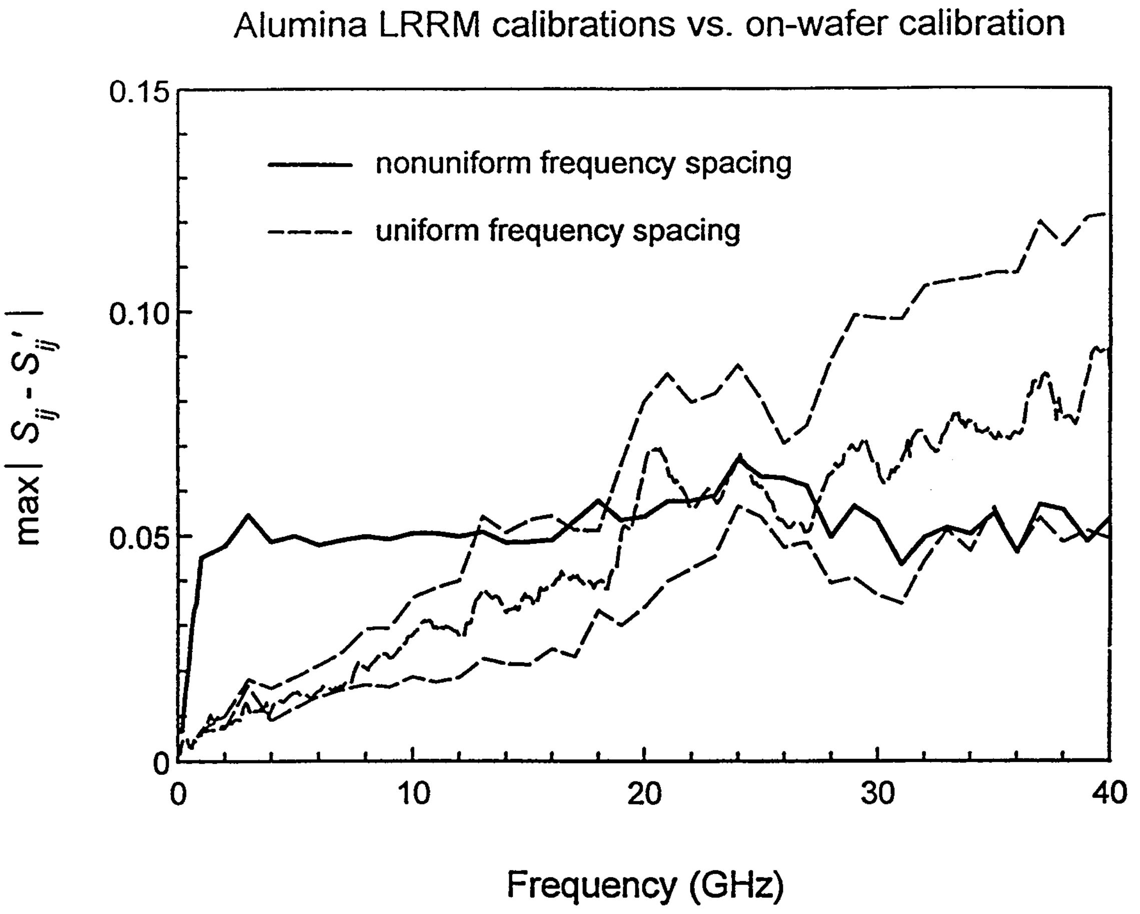

Figure 5

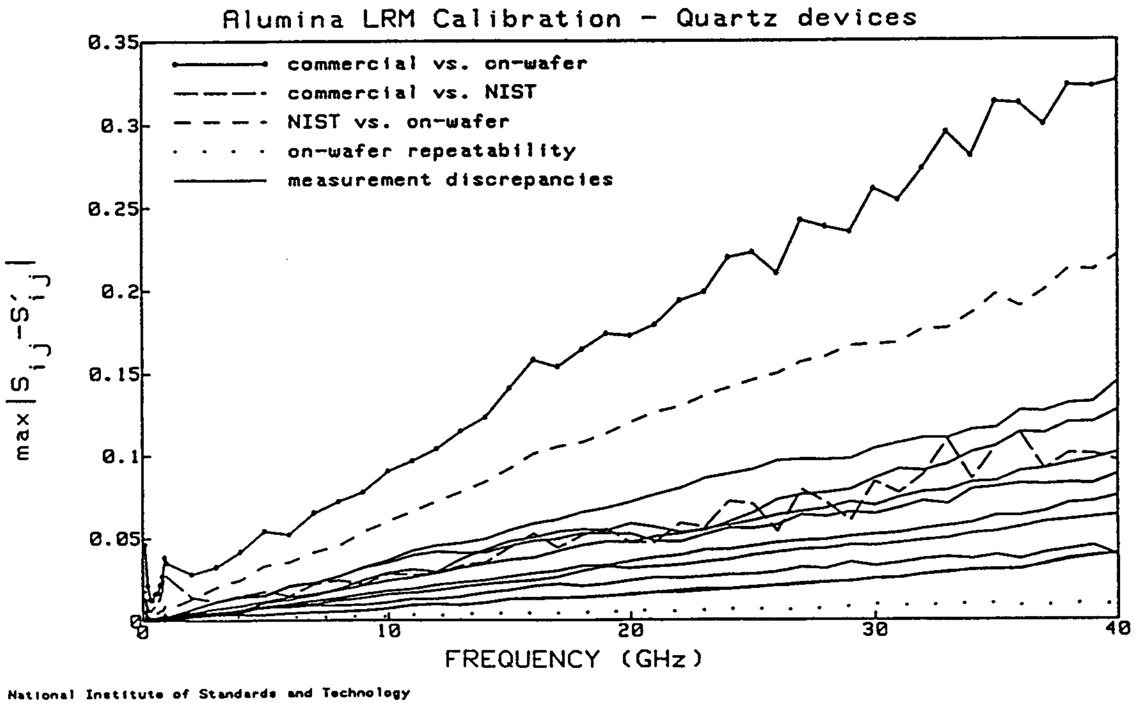

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Figure 6