Broadband Characterization of Optoelectronic Components to 65 GHz Using VNA Techniques

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Abstract

This paper discusses the typical uncertainties associated with characterizing high-speed photodiodes to 65 GHz when using a vector network analyzer (VNA) measurement technique. We analyzed the accuracy of the technique by comparing measurements of two reference standards that had previously been calibrated using electro-optic sampling (EOS) and heterodyne methods. The results of the comparison show very good correlation to the direct characterizations. Typical uncertainties were less than 1.0 dB at frequencies up to 50 GHz and less than 2 dB at 65 GHz. The dominant sources of uncertainty come from the noise floor in the VNA above 50 GHz (depending upon signal level) and the base uncertainty in the reference-standard calibration.

Introduction

We will discuss the broadband characterization of a photodiode (or other "optical to electrical converter") to 65 GHz using a calibrated Vector Network Analyzer (VNA), a $LiNbO_3$ external modulator, a CW 1550 nm distributed feedback (DFB) laser source, and a calibrated reference photodiode (see Fig. 1). The VNA acts as a calibrated microwave source and receiver, accounting for any electrical mismatches between the VNA and the optoelectronic apparatus. The VNA measures the combined S-parameters of the modulator and photodiode, which must be separated into their individual S-parameters [1]. The calibration is accomplished by first measuring a calibrated photodiode (the reference receiver). Once calibrated, the system can be used to characterize other receivers. In this paper, we use the calibrated system to characterize a check standard and verify the check standard measurements against measurements performed at the National Institute of Standards and Technology (NIST).

Previously, the most common metrology-grade calibrations of high-speed photodiodes used an optical heterodyne method [2] to characterize the response magnitude. Although attempts have been made to calibrate the photodiode phase response, none of them are traceable to fundamental physical principles [3, 4, 5]. Recent research at NIST on an electro-optic sampling (EOS) system [6, 7] has made available both magnitude and phase characterization of photodiodes up to 110 GHz. Using a photodiode, calibrated by the EOS system, and the VNA's internal embedding software, measurements of bandwidth, phase linearity, and group delay to 65 GHz can be realized for a large class of optoelectronic devices.

We use a reference standard photodiode (PD#1), calibrated in magnitude and phase using the NIST EOS system, to calibrate the measurement system. To verify the system calibration, we then measure a check-standard photodiode (PD#2) which has also been calibrated using the NIST EOS system. We then compare the results with an uncertainty analysis of the VNA system.

Procedure

In Figure 1, a reference standard photodiode (PD#1), characterized in relative magnitude and phase, is used as the reference standard to calibrate the modulator. We load the S21 of the reference standard into the 12-term error coefficients of the calibration file using internal VNA software and we assume S11 and S12 of the photodiode are zero. The software embeds the standard photodiode into the existing calibration, essentially moving the port 2 calibration plane to the optical input of the photodiode (P2').

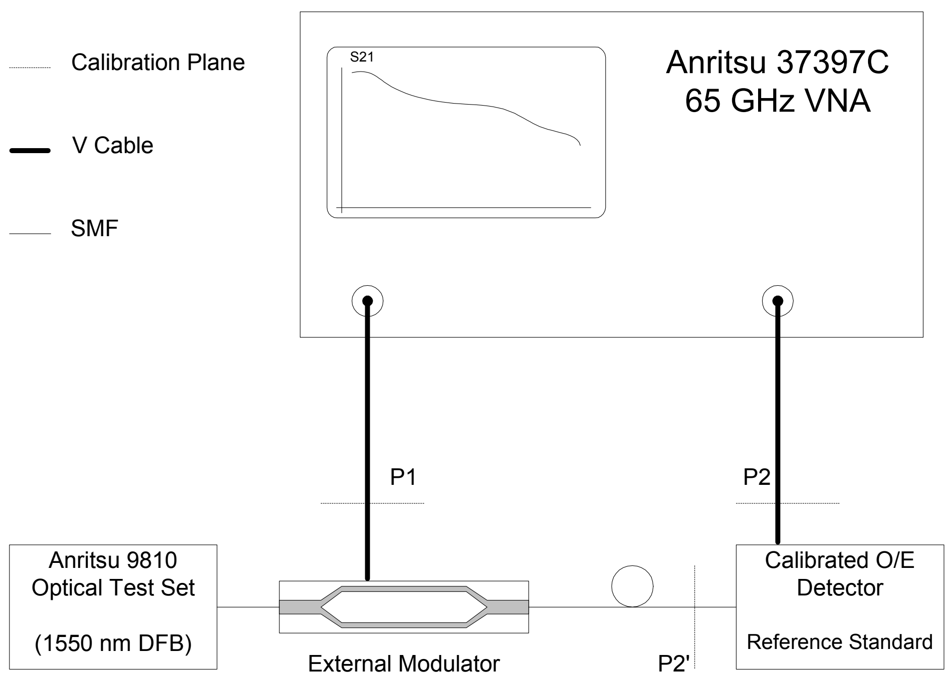


Figure 1: *Optoelectronic calibration using reference-standard photodiode.*

With this modified calibration, the resulting (complex) measurement can be used to generate an S-parameter file describing the modulator. We then use the internal software to embed the modulator's response into the original 12-term calibration coefficients, and replace the reference standard with a photoreceiver we wish to characterize, thus allowing us to characterize the unknown photoreciever. In this case, we insert the check standard, PD#2. Figure 2 is a plot of the |S21| of PD#2 from 0.2 to 65 GHz normalized to 0 dB at 0.6 GHz. The 3 dB bandwidth of this device is near 50 GHz and trace noise is more obvious from 50 to 65 GHz.

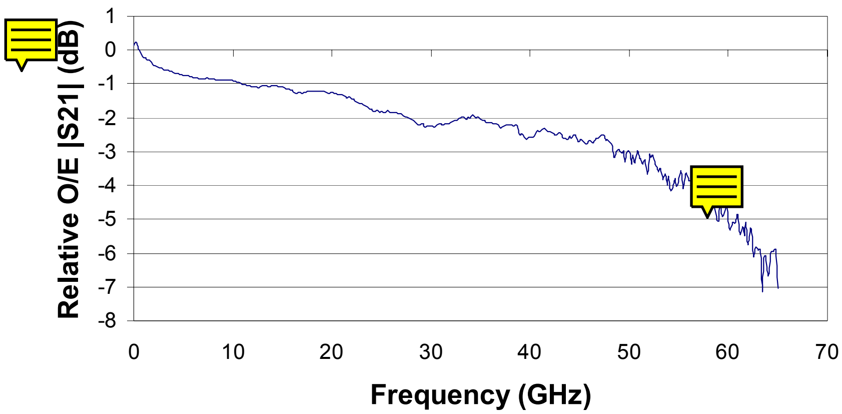
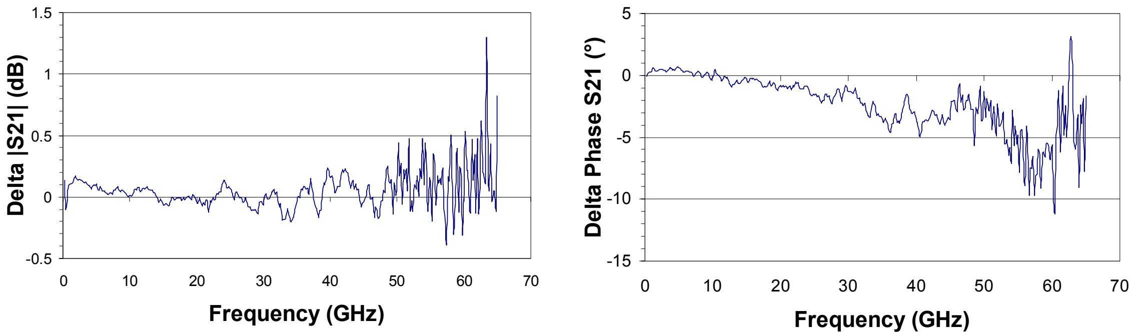


Figure 2: *Response of the check standard PD#2 using the VNA technique.*

Results

In Figure 3 we plot the difference between the S21 of the check standard PD#2 when measured on the VNA and the original measurement obtained using EOS. The two techniques appear to agree within 0.5 dB to 50 GHz and 1.5 dB to 65 GHz. The typical phase deviation shows a linear offset, due mostly to changes in the polarization and different fiber lengths between the reference photodiode and PD#2. Since the EOS measurement does not characterize the absolute delay of the photodiode, this is not unexpected.

[2] Trade names and product numbers are included to completely describe the experiment. Use of these trade names and product numbers does not constitute and endorsement by NIST. Similar instruments by other vendors may perform just as well for this experiment.



(a) (b)

Figure 3: *Difference between metrology EOS and VNA measurements of PD#2 magnitude (a) and phase (b).*

Uncertainty Analysis

To ensure the accuracy of the EOS method, the measurements were compared (up to 50 GHz) with data obtained from a more well known characterization technique, the swept optical heterodyne method [2, 8]. The difference between the EOS and heterodyne |S21| proved to be well within the combined uncertainty of the two characterization methods [9]. Figure 4 plots the difference between the heterodyne data and EOS data for our reference-standard.

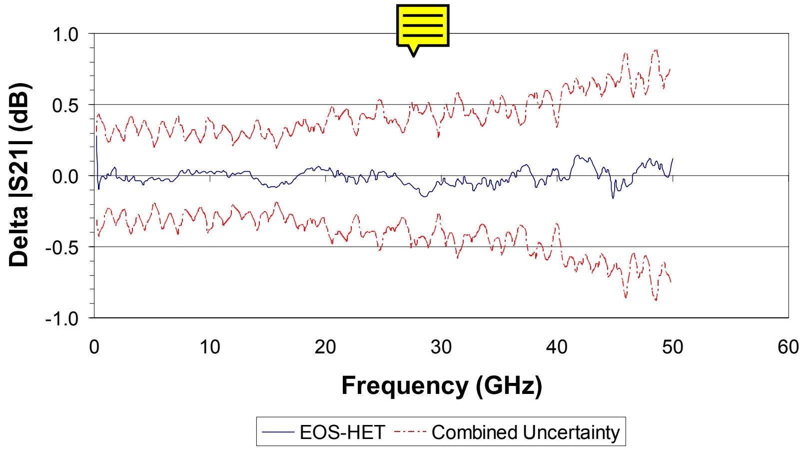


Figure 4: *Difference between EOS measurement and heterodyne measurement of the reference-standard photodiode (PD#1) used in this experiment.*

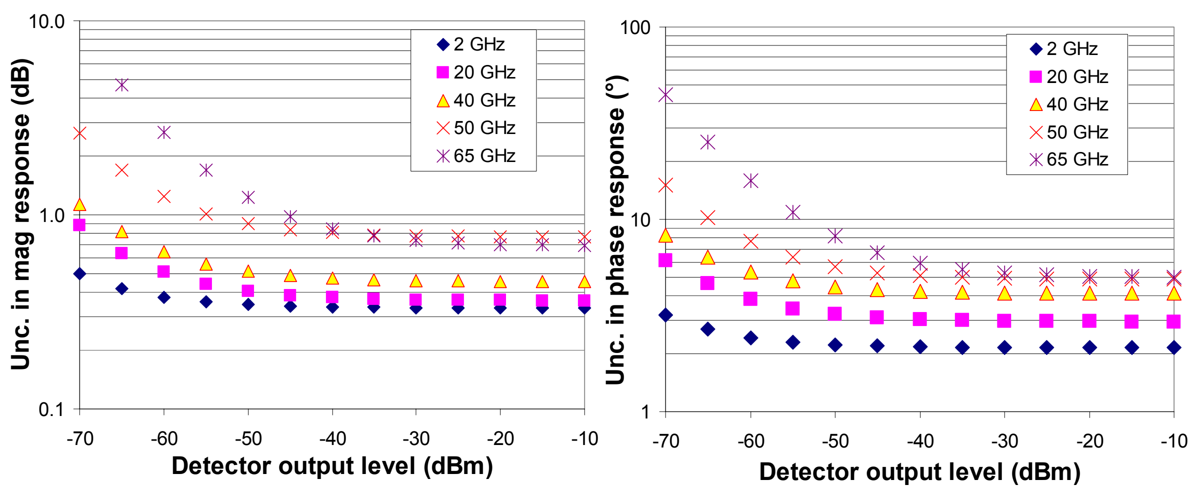
We performed a type B uncertainty analysis on the optoelectronic calibration process. In the measurements just described, the source of error can be broken into two categories

1) Uncertainty associated with the characterization of the transfer standards
2) Uncertainty in the measurement with the device under test (DUT).

When characterizing the check standard, there is an uncertainty associated just with the VNA measurement, which is discussed elsewhere (e.g., [10]). Since the characterized photodiode response is then de-embedded, the characterization uncertainty must be combined with the VNA measurement uncertainty to obtain an overall value. In the case of an optoelectronic measurement, there are actually two user measurements involved (one with a modulator and the reference photodiode and one with that modulator and PD#2) so an additional uncertainty must also be added in. Typically these uncertainties are all added on a root-sum-square basis since the measurements are assumed to be uncorrelated.

Specifications for the Anritsu 37397C 65 GHz VNA.[2] and 3654B V calibration kit were used to calculate VNA uncertainties at various frequencies. Optical system drift is included in the error model, but it is observed that all components are mechanically and thermally stable. Connector repeatability is also included in the model, but all connectors are assumed to be in very good condition. The results are shown with an independent variable of photodiode output power and plotted for both magnitude and phase for the two different types of measurements.

The output power of PD#2 during characterization was measured to be -38, -42, -45, -46, and -54 dBm at 2, 20, 40, 50, and 65 GHz respectively. It is evident from Figure 5 that the uncertainty follows an asymptotic response for detector output powers greater than -40 dBm. The dominant uncertainty below -40 dBm comes from an increase in the receiver's noise floor to 65 GHz. Reduction in the VNA dynamic range and increase in the modulator and detector insertion loss result in a typical optoelectronic characterization uncertainty of 1 to 2.5 dB at 65 GHz.



(a) *(b)*

Figure 5: *Magnitude (a) and phase (b) uncertainties for a photodiode characterization are shown here versus signal level and frequency.*

[2] Trade names and product numbers are included to completely describe the experiment. Use of these trade names and product numbers does not constitute an endorsement by NIST. Similar instruments by other vendors may perform just as well for this experiment.

Conclusion

Our investigation remained limited to an upper frequency of 65 GHz in part due to RF response of commercially available modulators. Figure 6 is a plot of the combined response of the modulator and PD#1 with the y-axis in output power from the detector. The sharp increase in uncertainty at -45 dBm is a direct result of optoelectronic insertion loss combined with a decreasing VNA dynamic range above 50 GHz. At a laser output power of 10 dBm, the signal-to-noise ratio at 65 GHz is around 32 dB for this modulator and photodiode combination.

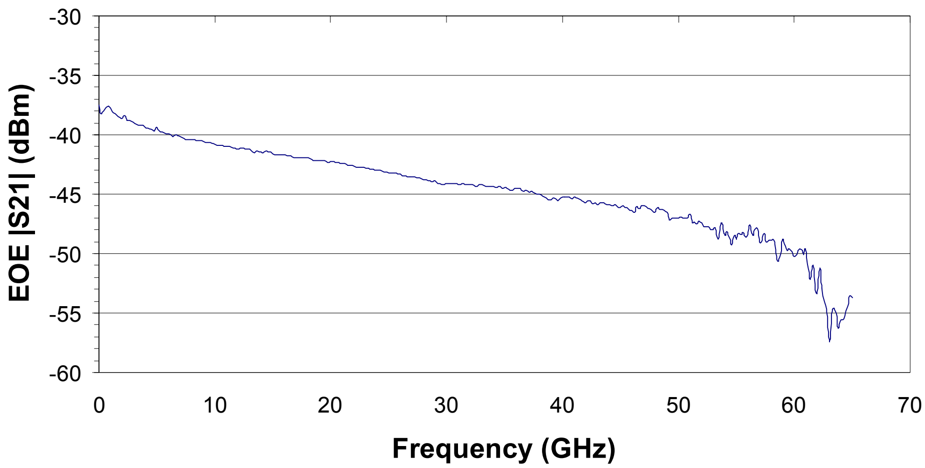


Figure 6: *|S21| response of modulator and reference standard.*

This experiment shows that frequency-domain techniques using VNAs to characterize and measure optoelectronic devices correlate quite well with direct methods like heterodyne and impulse response. VNAs require a very simple optical and electrical set-up, and the uncertainties are acceptable for commercial and laboratory environments. Further investigation should include extending the frequency range of the modulator and detector standards to improve the frequency range and uncertainty in the optoelectronic characterization.

References

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