White Paper

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Wideband Optical Modulator and Detector Characterization: Uncertainties and the Impact on Eye Diagrams/Time Domain Modeling

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Abstract: *For subsystem modeling, accurate Electrical-to-Optical (E/O) and Optical-to-Electrical (O/E) characterizations are critical at higher data rates. Careful transfer/calibration processes and a high-stability broadband VNA allow transmission uncertainties <0.5 dB (1550nm/110GHz or 1310nm/70GHz) and model eye height improvements >15%.*

Introduction

Optical modulators and detectors operating to 110 GHz or higher have existed for years [1-3] and characterization/calibration methods have been well-published [4, 5], but less attention has been paid to the optimization of uncertainties of those converter measurements in a practical user context. The frequency dependencies of the various error mechanisms are different, so the wide bandwidths may require procedural changes for optimum results. From a subsystem simulation/modeling/analysis perspective, accuracy in those microwave/millimeter-wave (mmWave) frequency domain characterizations is important but sometimes not studied in terms of how they affect the final eye diagram, bit error rate, or other higher level system operational parameters. This paper will explore the characterization and calibration processes, mainly for >70 GHz bandwidth components in both 1550 and 1310 nm wavelengths, and will look at the net uncertainties and how they propagate to example eye diagram generation.

Characterization/calibration and component-level uncertainties

A basic component measurement setup, based on a broadband network analyzer, is shown in Fig. 1. The optical power used in this analysis was 0 to 6 dBm and the RF power was –10 dBm. Although given the linearity of the measurement system and the components involved, these power levels were not critical. The network analyzer had a bandwidth of 70 kHz to 145 GHz, although only subsets of that frequency range were used here. Data rates of up to 80 Gbps (NRZ and PAM-4) were used in the subsystem models.

The entire measurement process begins with a reference photodiode characterization using an electro-optic sampling process [4]. This process introduces certain uncertainty components, including those related to a network analyzer calibration, photodiode mismatch, drift, optical system limitations, and bandwidth limitations [4, 5]. The initial uncertainties were combined using covariance data on the Type B elements [5], but the subsequent steps used a simpler RSS combination for stochastic terms and a worst-case summation for deterministic terms.

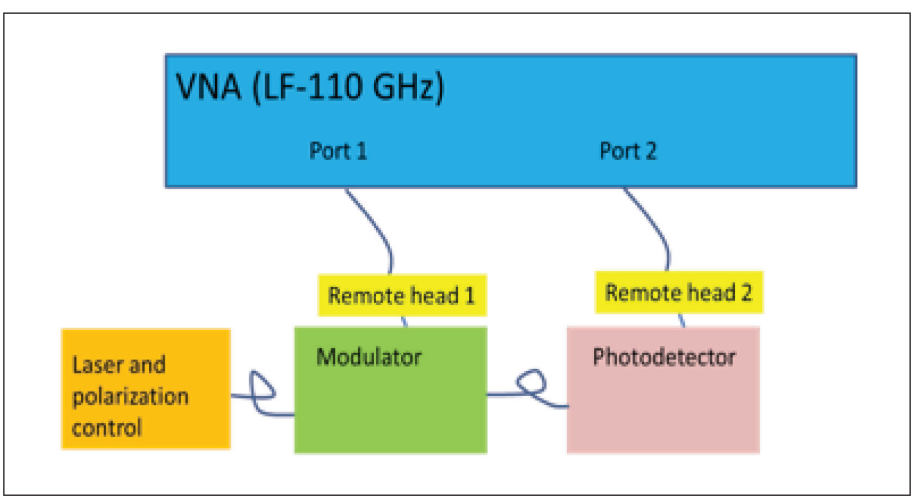

Figure 1. The basic measurement setup. For the extended frequency coverage (>70GHz), remote mmWave heads are often used to minimize loss and improve stability.

The characterization is used to calibrate a reference modulator via de-embedding and then user photodiodes (terms to this point will be lumped under the header “characterization”). Finally, a user modulator can be measured by de-embedding the user photodiode. In each of those follow-on steps, an additional network analyzer measurement is involved that introduces calibration/mismatch and measurement mechanics (including connector repeatability and cable flex) as well as noise floor contributions. Optical power enters into the process via its influence on net noise floor and nonlinear distortion.

A summary of the contributions at two frequencies is shown in Fig. 2 although, in absolute terms, all contributions have increased at 110 GHz compared to those at 20 GHz. Measurement mechanics and noise floor contributions have relatively increased. The former suggests the increasing importance of connector and cable care. The latter is mainly from typically increasing conversion loss and points to the value of higher broadband RF power and reduced IF bandwidth. The user calibration and mismatch relative contribution have not changed but have increased in absolute terms, which emphasizes the importance of the user calibration and the general trend of increasing device mismatch with frequency. The measurement system choice will primarily have an impact on the mechanics and noise floor categories.

For the user RF calibrations, many choices are available over this bandwidth, including both coaxial and on-wafer possibilities. The higher quality variations can lead to a direct transmission uncertainty of ~0.3 to 0.5 dB at 110 GHz, while more modest choices may double that. A non-optimal calibration choice could triple the first category in Fig. 2, while a sub-optimal measurement hardware choice (in terms of drift, noise, and linearity) could increase the 2nd and 3rd category absolute contributions by an order of magnitude.

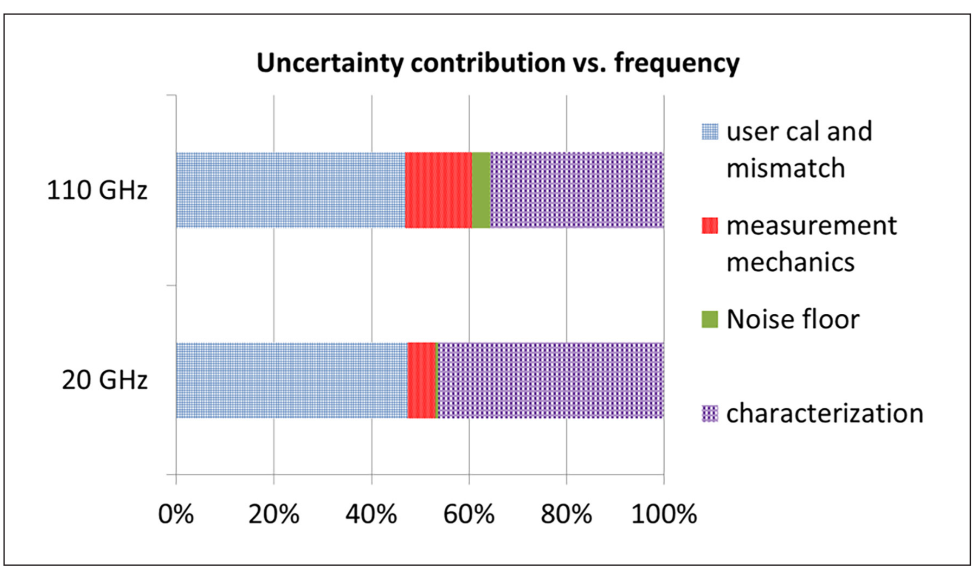

Figure 2. Relative uncertainty component weightings are shown here for an E/O measurement at two frequencies.

Propagation to eye diagrams and other metrics

To see the effect of characterization/calibration issues on modeled bit stream parameters, consider the calculation process. In the analog-like portions of the system, the frequency domain data sets are often cascaded (pre-filtering of data, modulator, detection, post-detection gain, etc.) and an impulse response is generated from the net frequency domain data with a Chirp-Z or similar transform (e.g., [6]). That broadly integrates the data over the frequency sweep, prior to convolution with the data stream. Thus, any highly oscillatory defects (from a mismatch problem, for example) are likely to have small impact while a frequency-sloped defect (from a calibration tracking issue, drift, or sometimes repeatability) may have an amplified effect [6]. In the frequency domain, these two classes of effects are shown in Fig 3. The oscillatory defect may occur from a calibration issue on the network analyzer (at either characterization or user calibration steps) or a reference plane problem from a mischaracterized adapter. The slope problem could occur from drift on the measurement hardware, repeatability, or a reference plane problem from an un-characterized adapter. The values chosen in the Fig. 3 are equivalent to common calibration problems.

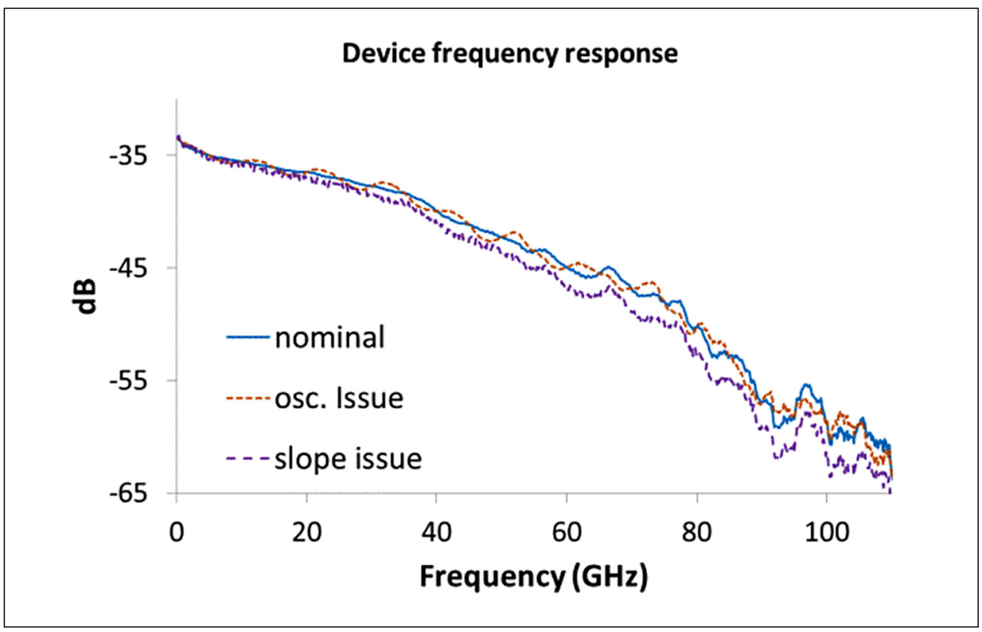

Figure 3. The frequency response of an example broadband component along with possible distortions.

As an example, a 110 GHz system was characterized using the procedure of Section 2 with a highly stable VNA and quasi-optimized calibration steps, and run using a 50 Gbps NRZ signal. The resulting eye diagram is shown in Fig. 4. If an oscillatory defect (of 1 dB peak at high frequencies; matching the maximum likely variance) is introduced, the eye diagram was indistinguishable from that in Fig. 4. If, instead, a slope error was introduced of 1.5 dB at the high end (resulting from an adapter not characterized or high system drift), the eye height was reduced by ~10% and the width by ~4%. This size of defect is not difficult to generate in the multi-phase process required.

For a more physical experiment, the same 110 GHz system was characterized with a simplified process where a heterodyne characterization and phase-modeled process was used (resulting in an increased characterization error on the order of 0.5 dB at 110 GHz). The final user calibration was only a transmission normalization and a 1.85-1mm coaxial adapter used in the measurement was not de-embedded (resulting in both magnitude and phase deviations approaching 0.5 dB and 5 deg). The resulting eye diagram, to be compared against that in Fig. 4, is shown in Fig. 5. Here the eye height was reduced by ~15% and there were additional baseline distortions, partially from the phase distortions that were not linear with frequency. This amount of eye reduction may or may not be critical depending on other parts of the system, but the point is the model result was noticeably distorted by common characterization/calibration issues on the converter components.

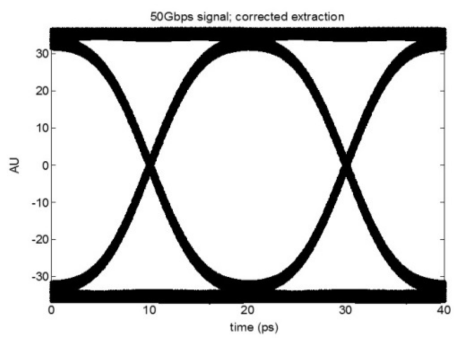

Figure 4. The 50 Gbps eye diagram from the nominal 110 GHz system.

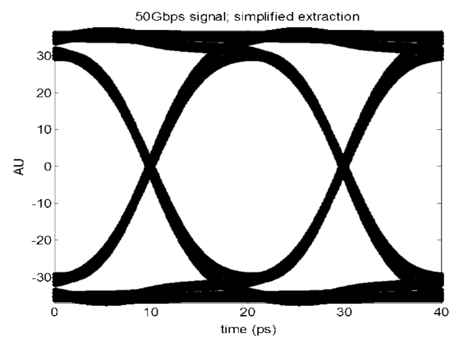

Figure 5. The 110 GHz system, when characterized/calibrated with a simplified approach, produced this result.

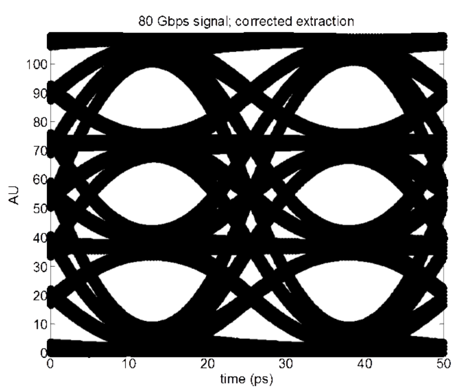

Figure 6. The 1310nm/70 GHz set with full characterization produced this result.

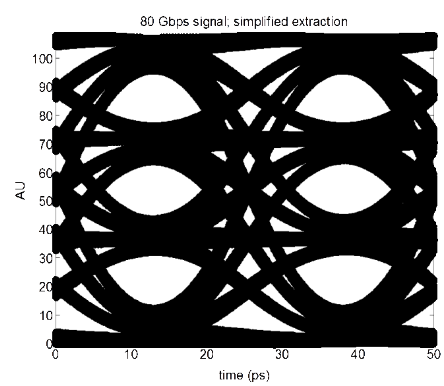

Figure 7. The 1310nm/70 GHz set with the simplified characterization produced this result.

A 1310 nm/70 GHz bandwidth component set was also analyzed, this time with a PAM-4 data stream at 80 Gbps with similar characterization procedures. The size of potential distortions in the frequency domain is smaller (perhaps 1 dB vs. 2 dB and 5 vs. 10 degrees of phase). But since the data rate is higher in this example relative to the device bandwidth, those issues are still relevant. The results with the full and simplified approaches are shown in Figs. 6 and 7, respectively. The simplified approach reduced the modeled eye height by ~15%.

Summary

The characterization and measurement of E/O and O/E components at higher microwave frequencies has a different uncertainty distribution than at lower frequencies. A careful process can help minimize many of those categories. The individual uncertainty components have very different effects on final subsystem modeled time domain results, such as eye diagrams. Understanding that error propagation can be useful. In a practical example, optimizing the critical uncertainty components can lead to noticeably better eye behavior in the final model.

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11410-00939, Rev. B Printed in United States 2018-01