Photodiode Calibration Comparison between Electro-Optic Sampling and Heterodyne Measurements up to 75 GHz

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***Abstract* — We present the comparison of a photodiode's measured frequency response calibrated with an electro-optic sampling system and a heterodyne system up to 75 GHz, along with the systems' respective 95% confidence intervals. A brief description of each system and its known sources of uncertainties are provided. The two systems agree to within their respective uncertainties at most frequencies.**

***Index Terms* — Calibration, comparison, electro-optic sampling, heterodyne, measurement, photodiode.**

I. Introduction

The electro-optic sampling (EOS) system at NIST [1, 2] is the United States' primary standard for high-speed waveform calibration and is traceable to the SI through fundamental physics. A photodiode calibrated using this system serves as a time- and frequency-domain transfer standard and allows for subsequent calibrations of high-speed oscilloscopes, electronic comb generators, and high-speed modulated signals [3]. Check-standard photodiodes are frequently measured to verify self-consistent operation of the EOS system, however an external comparison to an independently traceable measurement can help verify the measurement.

At NIST, an independently traceable heterodyne measurement system has been used to measure the magnitude response of photodiodes up to 50 GHz [4, 5]. The beat between two single-frequency lasers defines the excitation of the photodiode. While the EOS system is capable of measuring frequencies up to 110 GHz, the low frequency response is limited below 600 MHz, whereas the heterodyne system provides measurements approaching DC.

Each measurement system has its own set of challenges transforming measured quantities to a calibrated response. The EOS measurement requires that (1) the photodiode operate in the linear regime for excitation with pulsed light; (2) the on-wafer coplanar resistor structures be well characterized; (3) the laboratory environment be stable during measurements; and (4) the probe be de-embedded from the measurement. The heterodyne system relies on a set of calibrated, low-power, diode-based RF power meters to cover the measurement frequency range. For both measurements, calibrated scattering-parameters of the photodiode and connecting devices must be measured and propagated through the photodiode calibration [3].

A previous comparison was presented in [4, 5] but was limited to 50 GHz and didn't include measurement uncertainty. To validate the EOS closer to the frequency of 110 GHz, here we present the comparison of a photodiode calibrated with the EOS and heterodyne measurements up to 75 GHz [6], the highest frequency to date performed at NIST, along with their respective uncertainty estimates. A similar comparison was performed at NPL [7]. In the following sections, we provide a brief description of each system and its major sources of uncertainties, and results of the measurement comparison.

II. Electro-Optic Sampling System

NIST's EOS system is comprised of a 1550 nm mode-locked, erbium-doped fiber laser that emits a series of short optical pulses on the order of 100 fs in duration [1, 2, 3] with a 10 MHz repetition rate. The linearly-polarized output is split into optical excitation and sampling beams. The excitation beam excites the 1.0 mm coaxially-connectorized photodiode, which generates an electrical pulse. This electrical pulse is coupled by the wafer probe onto a coplanar waveguide (CPW) fabricated on an electro-optic LiTaO3 substrate. The optical sampling beam reconstructs the repetitive electrical waveform generated by the photodiode at the on-wafer reference plane in the CPW. This is accomplished by passing the sampling beam through a variable optical delay, polarizing it, and passing it through one of the gaps of the terminated CPW. Since the substrate is electro-optic, the electric field between the CPW conductors changes the birefringence of the crystal, altering the polarization of the optical sampling beam passing through it. A polarizing beam splitter and balanced photoreceiver detects this change, which is proportional to the electric field in the CPW at the instant the optical pulse arrives. This process does not perturb the electrical signal on the CPW. Sweeping the relative delay of the sampling beam allows us to map the voltage at the reference plane in the CPW as a function of time.

To calculate the electrical waveform at the photodiode's coaxial connector from the voltage measured in the CPW by the EOS system, a change in reference plane is required. This requires a VNA to characterize the reflection coefficients of the photodiode and an on-wafer resistor as well as the scattering-parameters (*S*-parameters) of the probe head. The *S*-parameters are then used to determine the impedance levels in the measurement system and determine the frequency-domain voltage the photodiode would generate across a 50 Ω load. The frequency-domain results can then be Fourier-transformed to traceably characterize temporal- and frequency-domain instruments up to 110 GHz, the single-mode limit of the 1.0 mm coaxial connectors of the system.

There are numerous sources of uncertainty in the EOS system beyond the impedance corrections, including optical reflections from the surfaces of the LiTaO3 wafer, field penetration into the LiTaO3 wafer, the radius of the optical sampling beam, finite temporal widths of the optical sampling and excitation pulses, and measurement repeatability. Correlated uncertainty is propagated through the chain of calibrations using the NIST Microwave Uncertainty Framework [8].

III. Heterodyne System

The NIST heterodyne system for measuring the magnitude of the frequency response of photodiodes operates at frequencies up to 75 GHz. Two single-mode fiber lasers having up to 1 nm of continuous wavelength tuning and a linewidth specification of <1 kHz are combined with free-space optics. The use of free-space optics rather than fiber components reduces the wavelength and polarization dependence of the coupled beams.

After passing through polarizing isolators, fiber-pigtailed collimators are used to collect and deliver the polarized light to the fiber-coupled photodiode under test and the photoreceiver used for frequency measurement. Polarizing and mode-matching the beams in a single-mode fiber is critical to ensuring that the modulation of the light incident on the photodiode is precisely calculable. Adjustable rotary attenuators are used to equalize the power delivered by each laser, as monitored by the photodiode bias current. Tuning of the heterodyne beat frequency between the lasers is performed by controlling the operating temperature of the lasers [4].

The frequency of the heterodyne signal up to 50 GHz is detected by use of an amplified photoreceiver and electrical spectrum analyzer. Above 50 GHz the operating wavelength of each laser is monitored with interferometer-based wavelength meters and the difference frequency is determined.

Aside from impedance corrections, the major sources of uncertainty in the heterodyne system include power meter range scaling, bias current measurement, power sensor noise, and measurement repeatability.

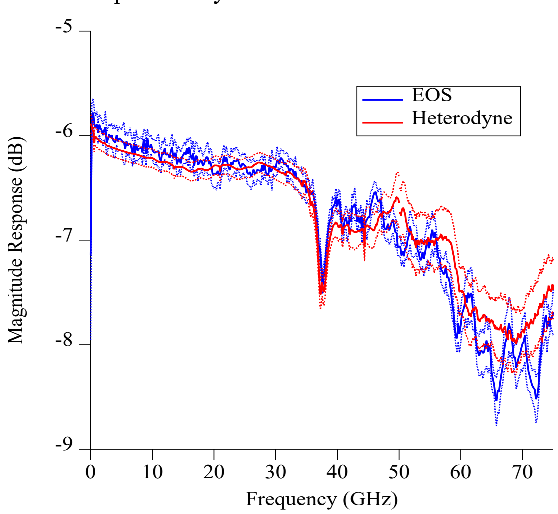

Fig. 1. Comparison of EOS and heterodyne measurements.

IV. Measurement Comparison

The magnitude of the frequency response of a 110 GHz photodiode as measured by the EOS and heterodyne techniques is presented in Fig. 1. The two methods correspond closely in defining the roll-off of the response, with most points agreeing to within their uncertainties. The points that do not agree could be attributed to repeatability of the on-wafer and coaxial connections and calibrations. The EOS measurement indicates more structure despite having a much coarser frequency resolution (200 MHz) relative to the heterodyne measurement (30 MHz). We chose not to connect the two heterodyne curves at 50 GHz, which resulted from the two methods of measuring the beat frequency and different RF power sensors.

The results presented is our best comparison of the methods so far and suggests areas for making meaningful improvements. For the EOS method, improving the frequency resolution from increased range and precision of the delay sweep could reduce distortions in the measured response. The EOS method relies on impedance corrections for the wafer, probe, and photodiode which introduce additional components of uncertainty. The value of the heterodyne method comes from its simplicity and known modulation but relies heavily on the calibrated RF power sensor efficiencies as well as the impedance corrections to isolate the response of the photodiode. The maximum frequency of the heterodyne measurement is limited by the sensitivity of available power sensors to 75 GHz.

V. Conclusion

We presented a comparison of a photodiode's frequency response measured with both EOS and heterodyne methods up to 75 GHz, along with their estimated uncertainties. The results compare favorably while indicating areas for improvement which could result in better agreement.

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