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Frequency response metrology for high-speed optical receivers

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Abstract: We use "standard" optical sources along with microwave calibration methods to accurately calibrate optical receivers to 50 GHz and beyond. The calibrated receivers can be used to characterize sources and receivers using common electrical instrumentation.

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There are two types of optical sources whose modulation can be measured or calculated from fundamental principles: the heterodyne beat between two single-frequency lasers (frequency-domain) and the short pulse from a mode-locked laser (time-domain). While these sources are essential for receiver characterization, good sources are not all that is required. Since typical optical systems must be characterized over a bandwidth as much as 10 times larger than the bit rate, calibrating the electrical instrumentation is extremely challenging. We will discuss the construction of standard optical sources and the importance of electrical calibrations in both the heterodyne and short-pulse measurement methods for receiver characterization below 50 GHz, and propose measurement strategies for going beyond 50 GHz.

Heterodyne measurements

Heterodyne measurement gives the most accurate estimate of the magnitude of an optical receiver's frequency response. Our implementation of heterodyne measurements uses two tunable single-frequency lasers operating at 1319 nm [1]; an external cavity semiconductor laser (ECL) and a Nd:YAG laser (YAG2), to generate a beat frequency, tunable from < 1 MHz to several hundred gigahertz. We pass free-space beams from each of the lasers through variable attenuators and combine them in a beam splitter. The combined beam passes through a polarizer and is coupled through a single-mode fiber to the receiver specimen. Polarizing and combining the beams in a single-mode fiber is critical, as this allows us to exactly match the polarization and spatial-mode of the two beams incident on the receiver, and achieve a precisely calculable modulation depth. With matched received photocurrent from each laser, the optical and electrical signals have 100 % modulation depth.

When the modulation depth is 100 %, the normalized frequency response $\Re^2(f)$ of a photodiode is [2]

$$\Re^2(f) = \frac{P_{\mathrm{rf}}}{\frac{1}{2} i_{\mathrm{dc}}^2 Z_{\mathrm{r}}}, \tag{1}$$

where P_{rf} is the microwave power the photodiode would deliver when connected to a load $Z_{\mathrm{r}} = 50\ \Omega$ at frequency f, and i_{dc} is the total dc photocurrent the photodiode draws from the bias supply. Determining $\Re^2(f)$ from the power P_{m} measured by a microwave power meter requires accurate microwave calibration. To perform this calibration, we must first measure the scattering parameters S_{ij} of any network between the photodiode and the microwave power sensor, and the electrical reflection coefficients Γ_{p} and Γ_{s} of the photodiode and power sensor. Then P_{rf} is related to P_{m} by

$$P_{\mathrm{rf}} = \frac{P_{\mathrm{m}}}{k(f)} \cdot \frac{1}{|r_{\mathrm{sp}}|^2}, \tag{2}$$

where $k(f)$ is the sensor's calibration factor at frequency f and [3]

$$r_{\mathrm{sp}} = \frac{S_{21}}{1 - S_{11}\Gamma_{\mathrm{p}} - S_{22}\Gamma_{\mathrm{s}} - \Gamma_{\mathrm{s}}\Gamma_{\mathrm{p}}(S_{21}S_{12} - S_{11}S_{22})} \ . \tag{3}$$

The last term in (2) corrects for impedance mismatch and loss in the interconnecting network and reduces to $|1 - \Gamma_{\mathrm{p}}\Gamma_{\mathrm{s}}|^2$ if the power sensor is connected directly to the photodiode. We illustrate the importance of the corrections in Fig. 1, where the symbols correspond to uncorrected measurements of a photodiode's response using two different interconnecting networks. Using the bias T gives high mismatch, and using the attenuator gives high loss. The curves show the corrected response, which has the effects of network loss and mismatch (ripple) removed by application of (2).

In applications where the photodiode is to be used only to measure the modulation depth of a source, a transfer standard [2] consisting of a photodiode and a power sensor can be calibrated as a single unit with lower uncertainty than a calibration using (1). The combined response $\mathbb{R}^2(f)$ of the transfer standard is found using (1) with P_m substituted for P_rf . The second and last terms in (2) are not required for the calibration, eliminating the need for calibrations of microwave power and measurements of scattering parameters. The transfer standard can be used to determine the fractional modulation depth $M_O = (P_\mathrm{max} - P_\mathrm{min})/(P_\mathrm{max} + P_\mathrm{min})$ of a source as [2]

$$M_O^2 = \frac{P_\mathrm{m}}{\frac{1}{2} i_\mathrm{dc}^2 Z_\mathrm{r}} \frac{1}{\mathbb{R}^2(f)}, \tag{4}$$

where P_max and P_min are the maximum and minimum optical powers of the modulated source.

Heterodyne measurements above 50 GHz

Below 50 GHz, we can easily measure the beat frequency with an electrical spectrum analyzer and harmonic mixers, and the microwave power with a coaxial diode power sensor. Making measurements above 50 GHz is much more difficult, due partly to the lack of commercially available equipment.

The frequency-measurement portion of the system is complicated by the lack of readily available photodiodes with bandwidths larger than 50 GHz and the high conversion loss of harmonic mixers, required to down convert the signal into the frequency range of a spectrum analyzer. The combined conversion loss gives a poor signal-to-noise ratio. Our solution to the frequency-measurement problem is to use a high-power single-frequency Nd:YAG laser (YAG3) with a frequency (wavelength) between YAG2 and ECL. We measure the YAG2/YAG3 beat frequency with a counter and the YAG3/ECL beat frequency with a microwave spectrum analyzer. The frequency stability of the ECL in a heterodyne system is adequate to give sub-megahertz resolution [4], but will not accurately trigger our counter. We send the beat signal between YAG2 and ECL, whose frequency is the sum of the YAG3/ECL and YAG2/YAG3 beat frequencies, to the receiver specimen.

Measurements of microwave power above 50 GHz are also complex. Calibrated coaxial diode power sensors capable of measuring powers of 1 nW to 1 μW are not available. Waveguide power sensors that

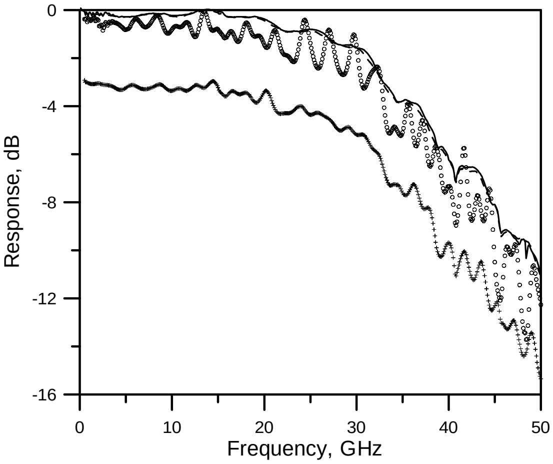

Figure 1. Raw measured response using 3 dB attenuator (+) and bias T (o) as connecting network. Overlapping curves show corrected response.

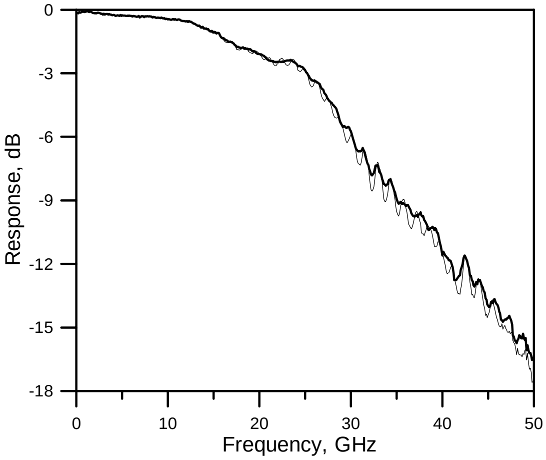

Figure 2. Effect of time-base distortion correction on mismatch correction. Thick and thin lines show mismatch-corrected response with and without time-base distortion correction.

have adequate sensitivity in the 50 to 75 GHz (WR-15) and 75 to 110 GHz (WR-10) frequency ranges are available, but must be connected to the receiver through an adapter. Furthermore, the VSWR of these sensors can be as high as 2.5:1, possibly giving 8 dB (peak-peak) ripple in the measurement of a high-impedance photodiode. By including a 10 dB attenuator as part of the sensor the ripple can be reduced to about 0.8 dB, small enough that it can be adequately corrected using (2). This gives a sensor that is robust, but at the expense of sensitivity. The resulting microwave sensor is nevertheless a good candidate for part of a combined transfer standard.

Time-domain measurements

Time-domain methods determine not only the magnitude response of a receiver, but also its phase response. However, the uncertainties are not as well understood as those of the heterodyne method. We use a 50 GHz sampling oscilloscope for time-domain measurements. The response measured with an oscilloscope can be broken into the convolution of three effects: (1) the response of the oscilloscope to a matched 50 Ω source, (2) a contribution due to the impedance mismatch and loss in the network connecting the receiver to the oscilloscope, and (3) the effect of the finite duration of the optical impulse stimulus.

Calibration and correction of oscilloscope response is not well understood at high frequencies and includes several non-ideal effects. We use the nose-to-nose procedure to calibrate the oscilloscope phase response [5]. However, we have been unable to verify the accuracy of the nose-to-nose phase calibration, possibly introducing large errors into the measurement. We use swept-sine measurements for calibrating the oscilloscope's magnitude response [5]. Drift and jitter are random variations in the sampling time that occur over long and short time scales relative to one complete sweep of the display. To correct for drift and to achieve a low noise level, we store 500 to 1000 waveforms and then align and average them [6]. Time-base distortion (TBD) is caused by repeatable errors in the oscilloscope delay generator that determines when the oscilloscope takes a sample. We use a nonlinear least-squares fit to sinusoidal input waveforms to estimate the TBD, and then use a regression spline interpolation of the impulse waveform to correct for the TBD [5]. The corrections for drift and TBD are nonlinear processes, so we perform them in the time-domain first. We then multiply by the linear corrections for mismatch [7], oscilloscope response, and jitter [6], in the frequency-domain, as in (2).

Not correcting for the TBD ruins the mismatch correction. Fig. 2 compares mismatch-corrected responses both with and without prior correction for TBD, and illustrates the necessity of the TBD correction.

Commercially available oscilloscopes operate up to only 50 GHz. However, we have found that for accurate measurement of time-domain properties such as rise- and fall-time, the bandwidth of the measurement system should be about 10 times larger than the signal bandwidth. Thus we believe that a 40 Gb/s system should be characterized to at least 200 GHz, and preferably to 400 GHz. Both the heterodyne and oscilloscope approaches presently being implemented fall far short of this frequency requirement. We are currently investigating time- and frequency-domain methods to extend receiver characterization to these high frequencies.

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1. Some high-speed photodiodes use a guided-wave design optimized for 1550 nm and should be characterized at the ultimate application wavelength for the highest accuracy.
2. P. D. Hale, C. M. Wang, R. Park, and W. Y. Lau, "A transfer standard for measuring photoreceiver frequency response," *J. Lightwave Technol.* **14**, 2457-2466 (1996).
3. "S-parameter design," Hewlett Packard Application Note 154, April 1972, 9-13.
4. P. D. Hale and C. M. Wang, "Heterodyne system at 850 nm for measuring photoreceiver frequency response," *Symposium on optical fiber measurements*, (Sept. 2000).
5. P. D. Hale, T. S. Clement, K. C. Coakley, C. M. Wang, D. C. DeGroot, and A. P. Verdoni, "Estimating the magnitude and phase response of a 50 GHz sampling oscilloscope using the 'nose-to-nose' method," *55th ARFTG Digest*, (June 2000).
6. T. S. Clement, P. D. Hale, K. C. Coakley, and C. M. Wang, "Time-domain measurement of the frequency response of high-speed photoreceivers to 50 GHz," *Symposium on optical fiber measurements*, (Sept. 2000).
7. Time windowing of the measured waveform, a common technique for correcting mismatch, can be arbitrary and can be a source of uncontrolled measurement errors.