Time-domain measurement of the frequency response of high-speed photoreceivers to 50 GHz*

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Abstract

We determine the frequency response of high-speed photoreceivers from time-domain measurements collected with a 50 GHz sampling oscilloscope. In order to obtain accurate results, it is important to correct the signals for time-base distortion in the oscilloscope, electrical mismatch, oscilloscope jitter, laser pulse width, oscilloscope frequency response, and nonlinear response of the detector. Results are compared to the response obtained from a calibrated heterodyne system, and they differ by less than ±0.1 dB up to 25 GHz, and by less than ±1.0 dB at 50 GHz.

Introduction

Accurate measurement of the response of high-speed photoreceivers is necessary for applications in high-speed optoelectronic systems such as Gigabit Ethernet and Fibre Channel. We have developed a method for measuring the response of high-speed photoreceivers at frequencies up to 50 GHz by use of a sampling oscilloscope. Historically, both impulse and CW excitation have been widely used to characterize high-speed photoreceivers. Because of the extreme differences in peak powers used in these two families of measurement methods, it has been suggested that the measurement method should depend on the intended application of the photoreceiver[1]. Heterodyne methods have been shown to be extremely accurate[2], but can be very slow and give only the magnitude of the response. Time-domain measurements can be performed very quickly and can give both the magnitude and phase of the response. Work has been done previously by Hawkins et al. to compare heterodyne measurements and oscilloscope-based impulse-response measurements[3]. In our work we correct the impulse response measurements for the effects of oscilloscope frequency response, jitter, and laser pulse width previously considered by the Hawkins group, and we extend their work by correcting for time-base distortion, electrical mismatch, and measurement nonlinearity.

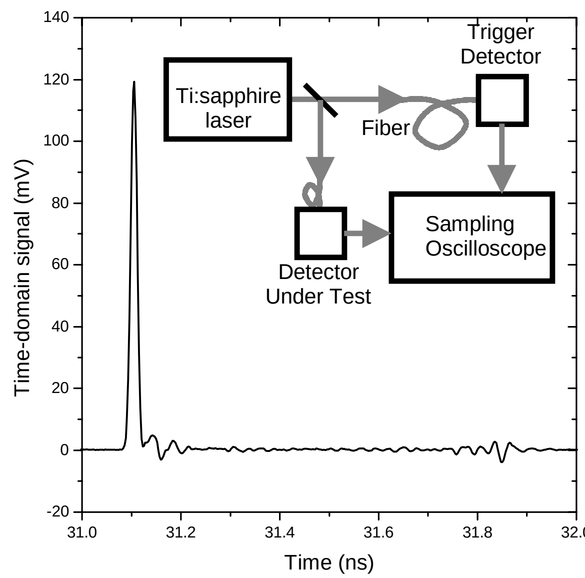

Figure 1. Time-domain photodiode signal. (Inset: schematic of time-domain measurement system.)

Experimental configuration

The inset of figure 1 shows a schematic of the time-domain measurement system. A mode-locked, Ti:sapphire laser provides pulses with a full-width at half-maximum (FWHM) less than 100 fs at 800 nm, with a repetition rate of approximately 80 MHz. The laser beam is split to provide an optical pulse to the detector under test in one arm and a trigger signal for the oscilloscope in the other arm. Reflective neutral-density filters provide attenuation in each arm. The sample arm contains 15 cm of single-mode fiber, which is connected to the detector under test. Dispersion in the optical fiber broadens the optical pulse to $\tau_p \approx 180$ fs FWHM. The optical pulse is convolved with the photoreceiver response in the time domain. We correct for the measured pulse width in the frequency domain (assuming a Gaussian pulse shape),

$$F(\omega) = \frac{F_{observed}(\omega)}{\exp\left\{-\frac{\omega^2 \tau_p^2}{8\ln(2)}\right\}}. \quad (1)$$

We make every effort to ensure that the optical pulse is as short as possible, which results in a very small correction for the convolution with the finite width pulse (3.5×10^{-3} dB at 50 GHz).

The measurements reported here are performed with a commercially available photodiode having a 25 GHz nominal electrical bandwidth. The photodiode is packaged with an internal 50 Ω matching resistor and has an external responsivity of about 0.2 A/W. The photodiode is connected to a 50 GHz sampling oscilloscope, where the response to the ultrashort optical pulses is sampled over a 10 ns time interval, just under the repetition period of the laser. Figure 1 shows a portion of a typical time-domain signal. The pulse duration is 15.7 ps FWHM. An electrical reflection is clearly visible at 750 ps after the peak of the pulse.

In order to improve the signal-to-noise ratio, 100 waveforms are acquired from the oscilloscope in just over two minutes. If the waveforms are averaged internally by the oscilloscope, drift acts to broaden the pulse, and the response in the frequency-domain is reduced by 1.4 dB at 50 GHz. To compensate for the drift, we align the individual waveforms before averaging (using an algorithm based on cross-correlation of all possible pairs of waveforms[4]). Although it is marginally slower to acquire individual waveforms from the oscilloscope, the time-domain technique still has the advantage of increased speed of data acquisition over that of a traditional heterodyne method. For example, it takes less than fifteen minutes to obtain 100 data sets at each of six different laser powers with the time-domain method, while the heterodyne method takes several hours.

Time-base distortion and jitter correction

Time-base distortion (TBD) is a deterministic deviation in the sample times of the oscilloscope from ideal, evenly spaced sample times. An estimate of the TBD during the same time window as in the photodiode measurements is determined by acquiring multiple sine waves with the oscilloscope and analyzing the data with an efficient least-squares algorithm[5]. The time axis of the averaged waveform is adjusted by the TBD estimate, and the resulting signal is interpolated onto an evenly spaced time grid using a regression spline model[6]. The signal is then transformed to the frequency domain using a fast-Fourier transform. In figure 2, the black curve shows this frequency-domain response of the photodiode up to 50 GHz. The ripple on the signal comes from multiple reflections between the photodiode and the oscilloscope, and must be corrected to determine the frequency response.

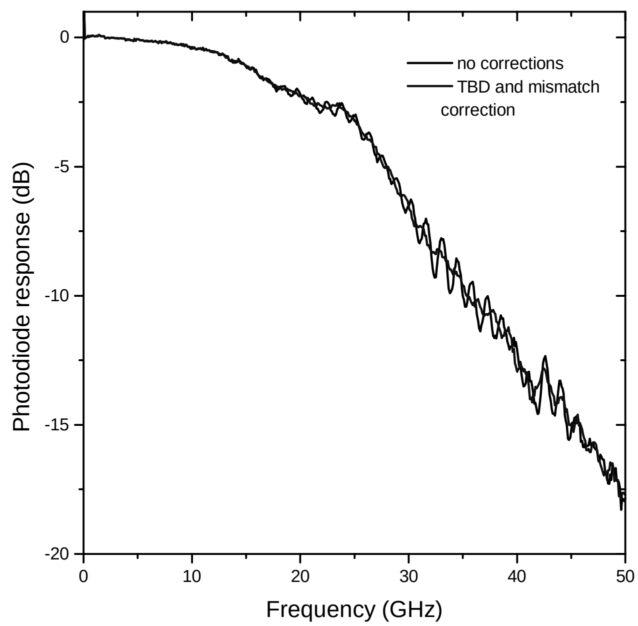

Figure 2. Photodiode frequency response with and without TBD and mismatch corrections

The effect of jitter on an averaged signal is that of a lowpass filter[7]. The variance of the measured signal can be expressed in a Taylor-series expansion as

$$\sigma_{Total}{}^2 \approx \sigma_N{}^2 + \sigma_J{}^2 \left(\frac{dV}{dt}\right)^2 , \qquad (2)$$

where $\sigma_{Total}{}^2$ is the total measured signal variance, $\sigma_N{}^2$ is the additive noise variance, $\sigma_J{}^2$ is the jitter variance, and dV/dt is the derivative of the ideal time-domain waveform. Typically $\sigma_J \approx 1.1$-1.2 ps for our work. $F(\omega)$ is then multiplied by $\exp(\sigma_J{}^2\omega^2/2)$ to deconvolve the jitter effects.

Mismatch and oscilloscope response correction

Electrical mismatch between the photoreceiver and the oscilloscope causes multiple reflections and dispersion of the time-domain signal as seen in figure 1. Reflection coefficients for both the photoreceiver and the oscilloscope are measured from 100 MHz to 50 GHz with a vector network analyzer. The measured signal in the frequency-domain, $F(\omega)$, can be corrected for mismatch to give the actual signal, $F(\omega)_{pd}$, generated by the photodiode,

$$F(\omega)_{\mathrm{pd}} = F(\omega) \times (1 - \Gamma_{\mathrm{s}} \Gamma_{\mathrm{pd}}) \,, \qquad (3)$$

where Γ_s is the electrical reflection coefficient of the oscilloscope, and Γ_{pd} is the electrical reflection coefficient of the photodiode.

We choose not to window the data in the time-domain[3] to remove the reflections because the initial impulse response and its reflections overlap. Thus, windowing would remove an unknown portion of the pulse and introduce an unknown amount of error in the frequency response. Inserting a delay line between the photodiode and the oscilloscope could reduce the overlap of the signal with the reflection, but the effects of the delay line would also need to be measured and accounted for. In addition, windowing the data can introduce incorrect information at low frequencies.

The gray curve in figure 2 shows the frequency-domain response of the photodiode after mismatch and TBD correction. The magnitude of the ripples is greatly reduced by the mismatch correction, although there is still some small effect remaining, especially above 30 GHz. The importance of the TBD correction is especially apparent when combined with the mismatch correction. Without TBD correction, the ripples due to electrical mismatch are only partially reduced because the spacing of the electrical reflections is distorted by the TBD.

The frequency-domain photodiode response must be corrected for the response of the 50 GHz oscilloscope. The magnitude response of the oscilloscope is measured by direct comparison to a calibrated power meter, and the phase response of the sampling oscilloscope is determined with a "nose-to-nose" measurement[8].

Laser power dependence

Although the average power incident on the photodiode is relatively low, the peak power during the femtosecond laser pulse can reach tens of kilowatts, producing very high instantaneous carrier densities and peak currents. At very high currents, space-charge effects and carrier-recombination nonlinearities may significantly degrade the photoreceiver performance[1,9]. In addition, nonlinearity in the vertical response of the oscilloscope may cause changes in the photodiode response.

We take data at many different input powers ranging from 5 to 100 μW. Figure 3 graphs the frequency response of the photodiode at some representative input powers. (We actually take data at more powers on the lower end, but they become hard to distinguish in such a graph.) The response decreases as a function of increasing power. For the lowest powers, this decrease can be approximated as a linear function of increasing power and increasing frequency. At higher powers (above ~30 μW), significant nonlinear effects are also evident.

In order to correct for the power-dependent effects, we observe the response as a function of power at many frequencies. Assuming that the effect is linear at low powers, we obtain a correction factor in dB/(μW*GHz), and use this to effectively extrapolate the data back to zero average power. After this correction, the responses for all of the relatively low-power inputs (below ~30 μW average power) agree within the noise of the measurement.

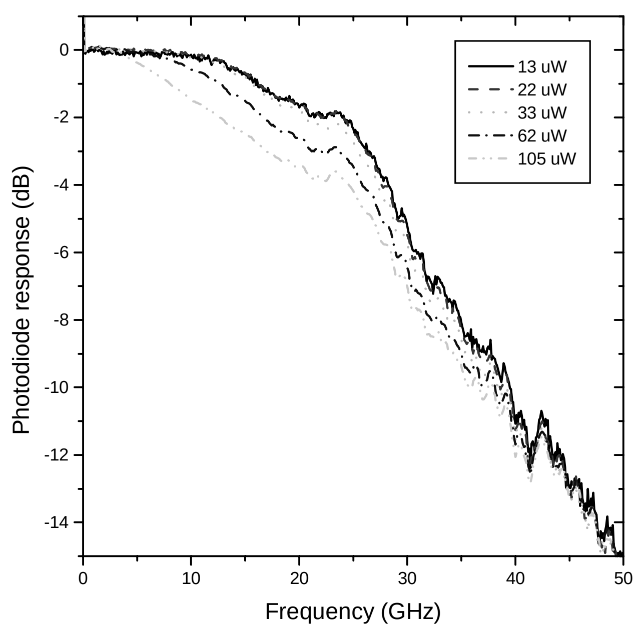

Figure 3. Frequency response for various input powers

Comparison to heterodyne experiment

We have measured the frequency response of the same photodiode with a heterodyne technique[10]. Figure 4 shows the difference between a time-domain measurement with all of the above corrections applied and the measured heterodyne data. The disagreement is less than 0.1 dB from 100 MHz to 25 GHz. At higher frequencies (inset) the difference increases to an average value of ~0.6 dB at 50 GHz, with excursions of about ±0.5 dB, probably due to mismatch that is not corrected in the time-domain measurement. We have also used the time-domain technique described here to obtain the frequency response of several other photoreceivers, and comparisons with heterodyne measurements show similar agreement. Although we have not focused on it in this paper, the time-domain technique determines the phase as well as the magnitude of the frequency response of a photoreceiver, while the heterodyne method can determine only the magnitude.

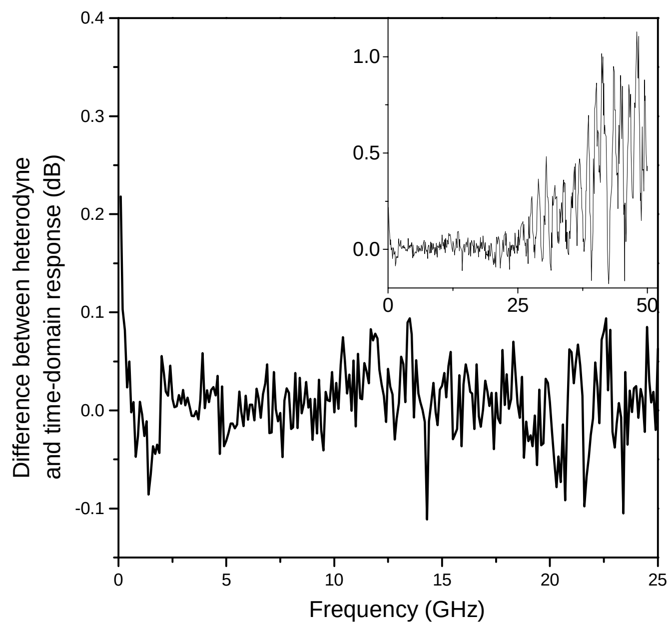

Figure 4. Difference between heterodyne and time-domain response.

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