Transmitter for Calibrating Extinction Ratio Measurements of Optical Receivers

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Abstract: We describe a transmitter being developed at the National Institute of Standards and Technology for calibrating extinction ratio measurements of optical receivers. Preliminary measurement results are presented, and major uncertainty components are discussed.

OCIS codes: (060.2330) Fiber optics communications; (120.3940) Metrology.

1. Introduction

Fiber-optic transceivers used in high-speed digital communications systems must comply with a stringent set of performance criteria. One important parameter that is typically measured with an oscilloscope is extinction ratio (ER), which describes how efficiently laser transmitter power is converted to modulation power. ER is defined as the ratio of the average power used to transmit a logic level "1" to the average power used to transmit a logic level "0." ER is an important parameter due to its relationship to bit-error ratio (BER) power penalty [1]-[2]. In order to maintain a constant BER, the average power level of the signal must be increased as the extinction ratio is degraded.

International standards have been developed to set minimum requirements for ER values and to define methods for making such measurements [3]-[7]. Typical minimum values range from 8.2 to 10 dB, depending upon the application, i.e., Gigabit Ethernet, Synchronous Optical Networking (SONET), Synchronous Digital Hierarchy (SDH), or Fibre Channel. Furthermore, ER is usually specified to be computed from the mean of the data located in the central 20 % of the oscilloscope's eye diagram. And typically, measurements require a receiver with a low-pass filter having a fourth-order Bessel-Thomson (BT-4) response whose 3 dB cutoff-frequency is 0.75 times the bit rate. The BT-4 provides advantages over other types of filters, such as striking a balance between providing a good eye opening and suppressing high-frequency energy content, and minimizing jitter with its linear phase response.

Despite the standards that are in place, several manufacturers of test equipment and transceivers have requested NIST traceability in this area. As a first step to providing such a service, we describe a transmitter being developed at NIST for calibrating the extinction ratio of optical receivers. The transmitter makes use of a laser source and two cascaded Mach-Zehnder modulators to achieve a high extinction ratio. In the following sections, we will describe the transmitter in detail, present initial measurement results, and discuss some of the uncertainties involved.

2. Measurement Setup

Fig. 1 illustrates our cascaded-modulator apparatus. The purpose of our dual-stage modulator set-up is to reduce the power of the "0" level signal, which allows for a higher extinction ratio. The laser diode has a peak wavelength of 1553 nm, and is temperature-stabilized. The laser diode is connected via optical fiber to the cascaded 12.5 Gbps, Mach-Zehnder modulators (MZMs), both of which are specified to have an extinction ratio of 15 dB. The modulators are biased with dither-free digital controllers. The fibers from the laser, to and from the first modulator, and to the second modulator are all polarization-maintaining (PM) fibers. The first bias controller also contains a

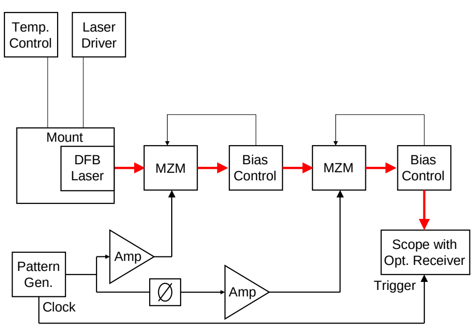

Fig. 1. Block diagram of cascaded modulator setup.

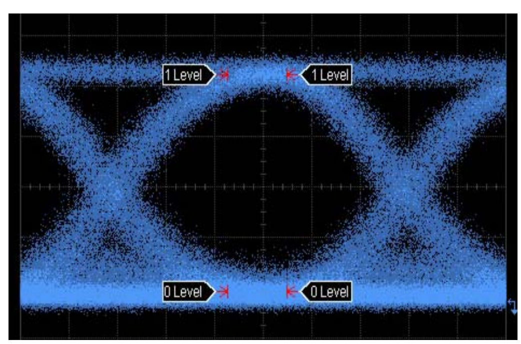

Fig. 2. Measured eye diagram of cascaded modulator setup.

PM coupler. All of the fiber connectors, except for the input to the optical receiver of the oscilloscope, have Ferrule Angled Physical Contact (FC/APC) connectors. The electrical, pseudorandom-binary-sequence (PRBS) signal originates from the pattern generator, which also supplies a trigger to the oscilloscope. The PRBS signal is fed into a power splitter, and the two resulting signals are amplified before being modulated. A manually adjustable phase-shifter is used to align the resulting eye diagrams between the two modulators to an integer multiple of bit periods. Fig. 2 illustrates an eye diagram displayed on an oscilloscope generated by the cascaded-modulator setup.

3. Initial Measurements

We made use of our high-ER transmitter, described in the previous section, to characterize the ER of three separate optical receivers from two different manufacturers, implementing the method of Andersson and Akermark [8]. The calibration factor *CF* for a given receiver at a specified bit rate is determined from its measured ER when it is connected to a transmitter with an infinite extinction ratio. Then, one can measure the ER of a device at any level, denoted by ER_M, and correct for what it would read if the receiver had an ideal BT-4 response, denoted by ER_C:

$$ER_C\,(\%) = ER_M\,(\%) - CF\,(\%)\,. \tag{1}$$

Note that the terms in the equation are calculated in percentages, as opposed to decibels, where *ER*(%) = 100/{10^[*ER*(dB)/10]}, or in other words, the percentage is equal to 100 times the inverse of the linear ratio [9].

Prior to the ER calibrations, each optical receiver was allowed to reach thermal equilibrium and then underwent a “dark calibration” to compensate for residual offset when no light is present. This was done with the vertical and horizontal scales set so that a complete eye diagram could be viewed on the oscilloscope display, as recommended by the manufacturers [9]-[12]. We used a bit rate of 9.953 Gbps and chose a PRBS pattern length of 2^{15}-1 bits.

We made 30 repeated measurements of each optical receiver with our high-ER transmitter, and used the calculated mean value as the calibration factor. Then, to emulate another transmitter and compare calibrated measurements, we detuned our high-ER transmitter to a lower level of ER, and then measured each receiver an additional 30 times. For each measurement, we also calculated the calibrated ER value. Table 1 lists the means and standard deviations for the calibration factors, and measured and calibrated values of ER for the three receivers. The range of the averages of the measured receivers is 0.45 dB, while the range of the calibrated averages is only 0.07 dB. While this does not verify the accuracy of our calibrations, it does demonstrate consistency. The 30 measurements show that the calibration system has a short-term repeatability of approximately ± 0.25 dB, or equivalently ± 0.59 % at an ER of 10 dB.

Table 1. Comparing calibration factors, and measured and calibrated ER values for three receivers.

	Receiver #1	Receiver #2	Receiver #3
Calibration Factor (dB)	13.99 ± 0.23	15.90 ± 0.38	14.97 ± 0.24
Measured ER (dB)	8.54 ± 0.21	8.98 ± 0.26	8.83 ± 0.24
Calibrated ER (dB)	10.00 ± 0.22	9.97 ± 0.25	10.04 ± 0.25

4. Measurement Uncertainties

Since most optical receivers cannot reliably measure values of ER much past 15 dB, due mainly to their finite impulse response, it is difficult to directly ascertain how high the actual ER is of our transmitter. For the calibrations we performed in the previous section, we assumed it was “high enough.” Thus, performing a detailed uncertainty analysis is a necessity in order to determine the error bounds of this technique.

As a first step, we used a commercial optical communications system simulator to explore the effects of non-ideal frequency response, signal bandwidth, and PRBS length on the values of ER. For each simulation, we used components that closely matched our actual set-up and specifications, although we used only one Mach-Zehnder modulator with a variable ER setting.

Our first experiment was to examine the effects of non-ideal receiver frequency response on ER. In addition to the standard fourth-order Bessel-Thomson response, we generated four modified BT-4 filters that fell within tolerances specified in the standards, as shown in Fig. 3. One had a faster roll-off near the lower tolerance level, one had a slower roll-off near the upper tolerance, and two had cyclical responses centered on the ideal BT-4 response. For this simulation, the bandwidths of the RF amplifier and the MZM were set to 10 GHz. Fig. 4 illustrates how the various filters affect the “measured” ER as a function of the modulator’s “actual” ER. Obviously, filters that deviate from the ideal BT-4 response can have a drastic influence on the “measured” ER, even if they remain within the tolerance levels. It should be noted that the ideal BT-4 deviates from the infinite-bandwidth receiver by 0.06 dB at an ER of 5 dB, 0.23 dB at an ER of 10 dB, and 0.71 dB at an ER of 15 dB. This is to be expected, as the ideal BT-4 receiver (as well as the other receivers) does not respond in an infinitesimal time.

Next we examined the effects of signal bandwidth (or rise-time) on ER. In this experiment we simultaneously varied the bandwidths of the RF amplifier and MZM while making use of an ideal BT-4 filter. Fig. 5 illustrates how the various bandwidth settings affect the "measured" ER as a function of the modulator's ER. As the bandwidth increases, the "measured" ER approaches that of an infinite-bandwidth (or zero rise-time) transmitter, where the "measured" ER matches the modulator ER. We also examined the effects of PRBS length on ER, but they were negligible compared to the previous contributions.

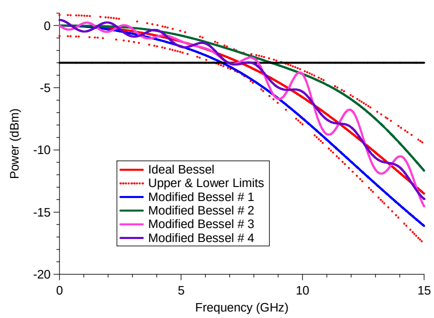

Fig. 3. Frequency response of non-ideal filters.

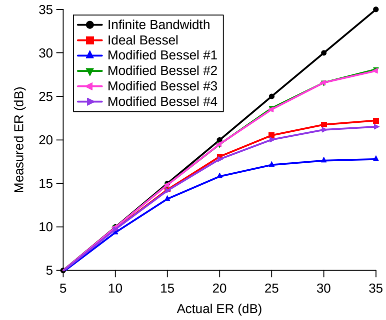

Fig. 4. Simulated ERs for non-ideal filters.

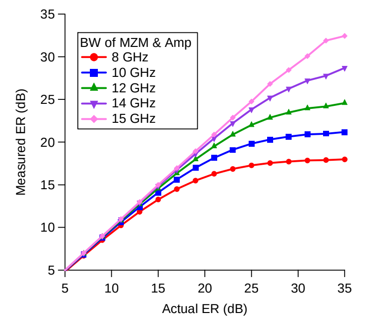

Fig. 5. Simulated ERs for varying BWs.

4. Discussion and Conclusions

Although the simulations we performed in the previous section diverge significantly at high values of ER when the frequency response of the receiver is varied, these effects are much less pronounced at lower values of ER, where measurements are typically performed. For example, from Table 1, Receiver # 2 had a calibrated ER of 9.97 dB. If the *CF* for this receiver had an uncertainty of 1 dB, this would translate to an ER uncertainty of only 0.29 dB.

In contrast to the simulations, where the "actual" ER is known, it is difficult to directly ascertain how high the actual ER is of our transmitter. However, even large uncertainties in the actual ER value have a limited effect on the calibrated measurements. For example, referring to Fig. 4 for the ideal BT-4 response, if the "actual" ER were 25 dB rather than 30 dB as presumed, then the measured ER would correspond to 20.53 dB on the graph rather than 21.75 dB. If the wrongly calibrated receiver were used to characterize a device measuring 12 dB, the calibrated value would be mistakenly computed as 12.66 dB, rather than the correct value of 12.49 dB. Thus, in this example, a mistake of 5 dB in the "actual" transmitter ER affects the calibrated value by only 0.17 dB.

From the plots in Fig. 5, we conclude that the *CF* of the receiver should be calibrated with a source that approximates the bandwidth of the intended device under test (DUT). However, it appears that in instances where the bandwidths of the source and the DUT differ, a correction may be possible.

5. Acknowledgement

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