Comparison on the Sensitivity of Fiber-Optic SONET OC-48 PIN-TIAs Measured by Using Synchronous Modulation Intermixing Technique and Bit Error Rate Tester

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***Abstract*—A novel synchronous modulation and intermixing (SMIM) technique is presented to measure the sensitivity and evaluate the bit error rate (BER) of p-i-n photodiode receivers with transimpedance amplifiers (PIN-TIAs) without using any BER tester (BERT). When using the SMIM technique, the premier receiving measurement performance from the data rates of the synchronous optical network OC-3 to OC-48 was demonstrated. For general TO-46 packaged PIN-TIAs, a minimum intermixed voltage of 12.5 mV obtained by the SMIM method is equivalent to a sensitivity of −31 dBm at a requested BER of $< 10^{-10}$ determined by BERT. The relationship between the monitoring voltage and the BER of the optical pattern received by the PIN-TIA and limited amplifier is estimated. The error of the measured voltage is 0.28 mV, which corresponds to the error sensitivity of 0.09 dB. This would show the accuracy of the simplified and low-cost SMIM technique for *in situ* diagnostics on a mass-production line.**

***Index Terms*—Bit error rate (BER), intermixing, p-i-n photodiode receiver with transimpedance amplifier (PIN-TIA), sensitivity, synchronous modulation, synchronous optical network (SONET) OC-48.**

I. Introduction

RECENTLY, many investigations of optical receivers meet the demand of rapidly increased capacity in data or metropolitan communication systems based on the Ethernet, synchronous optical network (SONET), and synchronous transport module protocol, in which a large number of high-speed front-end transmitters and receivers are employed. That is, the low-cost and high-performance manufacturing of these qualitatively used optical receivers is essential to the survival of such cost-sensitive medium-short and short-reach fiber-optic communication systems. In any receiving device, one of the most important parametric analyses is its sensitivity, which decides the error performance of receivers. The traditional method for measuring the sensitivity [1]–[3] of a SONET/synchronous digital hierarchy (SDH) transceiver is the transmission, reception, and error detection of the pseudorandom binary sequence (PRBS, $2^7 - 1$) pattern generated by a commercial bit error rate tester (BERT). Current bit error rate (BER) estimation in SONET/SDH or Q factor measurement depends on the reception of the PRBS data train. To perform, a transmitter module is initially encoded by a PRBS data stream with nonreturn-to-zero (NRZ) format, which then emits and propagates through fiber networks that are simulated by an optical fiber spool with a tunable optical attenuator [4]. Afterward, the optical attenuator is employed to adjust the minimum output power required for obtaining the error rate under 10^{-10}. The optical power in front of the p-i-n photodiode receiver with transimpedance amplifier (PIN-TIA) is then defined as the sensitivity of the PIN-TIA. BER performance is affected by the input power of the encoded optical data train, the operational bandwidth, and the sensitivity of PIN-TIAs. On the other hand, it is possible to realize from the Fourier transform analysis a linear relationship between the amplitudes of the encoded data train and its frequency components. This could provide an alternative way to evaluate the sensitivity of the PIN-TIAs by sweeping and sampling the featured frequencies of the encoded data train under different optical powers. The transfer function of the monitoring voltage to the BER of the optical pattern received by the PIN-TIA and limited amplifier can be calculated. In this paper, we demonstrate the comparison between such a synchronous analog modulation and intermixing diagnosis and a typical BERT analysis on obtaining sensitivity and BER. The transfer function of the monitoring voltage to the sensitivity of the OC-48 PIN-TIAs is determined.

II. Systematic Configuration

The newly proposed synchronous modulation and intermixing (SMIM) [2] module for sensitivity and BER analysis is shown in Fig. 1, which consists of the RF signal generator as a modulation source, the RF power splitter, the RF mixer, the RF bias tee, a dc multimeter for the voltage measurements, a Fabry–Pérot laser diode (FPLD) with the optical output power of −6 dBm, and the OC-48 PIN-TIAs with the fiber pigtail package as the testing samples in our SMIM evaluation. In contrast to the digital encoding processes, the proposed method involves a sinusoidal-wave optical modulation of the client signal by using the RF sweep-frequency generator with

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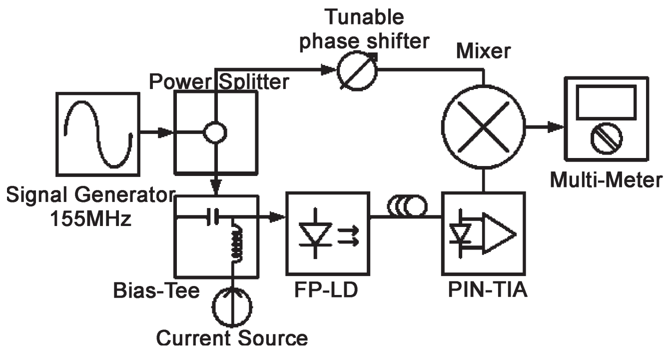

Fig. 1. Experimental setup of a SMIM-technique-based sensitivity and BER analyzer.

the featured frequencies and the RF level from 155 MHz to 2.488 GHz and $+3$ dBm, respectively. In the optical transmitter, an auto-power-control (APC) circuit is used to drive an FPLD at -6 dBm with an extinction ratio of 15.2 dB for better power stability. The frequency responses of all components in the system are well beyond the OC-48 criterion. The bias-tee circuit is used to combine the featured RF signal and dc current for driving the transmitter or for splitting the intermixed dc signal. In this circuit, an optical sinusoidal modulated signal stream was generated in the featured frequency. After the modulated signal passes through the connecting fiber path, the PIN-TIA optoelectronically converts the modulated signal. The microwave mixer in our SMIM system is employed to frequency-multiply the electronic signals from the RF generator and the converted signals from the PIN-TIA. The intermixed voltage is monitored by a dc multimeter only. To evaluate the sensitivity at the desired BER, the PIN-TIA receives the optical signal encoded by PRBS pattern generator, and the minimum optical power in front of the PIN-TIA required for obtaining the error rate under a BER of 10^{-10} is then defined as the sensitivity. The temporal waveform of the InGaAs MM-PIN-PD was monitored on a digital sampling oscilloscope (Agilent/HP $86100A + 86116A$, $f_{3\,\mathrm{dB}} > 63$ GHz and $t_{\mathrm{FWHM}} = 7.5$ ps). In addition, the p-i-n receivers in this experiment were assembled with transimpedance amplifiers into a TO-46 can, and a ball lens was used to focus the light from a single-mode fiber onto every InGaAs p-i-n photodetector with a coupling loss of 4 dB. Sensitivity and BER analyses were carried out under the illumination of a tunable laser, which is encoded with a PRBS data stream from a BER analyzer (Agilent, 71612B) at a bit rate up to 2.5 Gb/s. The sensitivities of PIN-TIA, which were measured by a BERT, and the intermixed dc voltage of the same device measured by our proposed system are compared to obtain a transfer function of $V_{\mathrm{SMIM}} = C_1 \times S_{\mathrm{sen}} + C_2$ between the sensitivity (S_{sen}) and the intermixed dc voltage (V_{SMIM}). C_1 and C_2 are the fitting constants, and their values are -3.033 and -81.052, respectively.

III. Results and Discussion

In traditional BER measurements, the BERT consists of a pattern generator and an error detector. The pattern generator creates the test pattern together with a separate clock signal at the selected data rate. In general, the exact time delay through the system under test is unknown. Therefore, the error detector must have some a provision for synchronizing its internally generated pattern to the incoming data. The commonly used test pattern for out-of-service BER testing is the PRBS, and this is a repetitive pattern whose pattern length is of the form $2^N - 1$, where N is an integer. Within the pattern, the bit sequence is designed to approximate the characteristics of truly random data. For example, a $2^7 - 1$ PRBS pattern adopted in international standards is generated by using a train of shift registers with feedback. Each different NRZ signal stream exhibits a different Fourier-transformed frequency spectrum. The challenge of frequency is the highest frequency of test, although the PRBS pattern contains all spectrum components from the frequency of the data rate to almost zero frequency. Therefore, the worst condition among all patterns with the highest frequency component is selected as the clock signal for characterization in our intermixing system.

The SMIM technique can be expressed by deducing from the mixed signals of the demodulated optical signal and the reference clock. The function of this reference clock can be expressed as an offset voltage V_{a} and a sinusoidal signal $V_{\mathrm{c}} \sin(\omega t)$. The mean voltage V_{a} and the amplitude of the sinusoidal signals V_{c} can be controlled as constants. The demodulation signal from the PIN-TIA (signal under test) was written as $V_{\mathrm{b}} + V_{\mathrm{d}} \sin(\omega t)$, where V_{b} is the dc voltage of the PIN-TIA, and V_{d} is the amplitude of the modulation signal. The mixed signal V_{out} is the demodulation signal that was mixed by the reference clock and the signal under test, which was frequency-multiplied by using the RF mixer. The output signal can, thus, be written as $V_{\mathrm{out}} = [V_{\mathrm{c}} V_{\mathrm{d}} \cos(\Delta\theta)]/2$, which is exactly the monitoring voltage on a dc multimeter. When setting the $V_{\mathrm{a}} = 0$, the V_{out} can be extracted as the dc component from the aforementioned formula with a filtering function. There is a phase difference $(\Delta\theta)$ between the reference clock and the demodulation signal from the PIN-TIA, and the phase difference can be canceled by fine-tuning the modulated frequency of the FPLD and PIN-TIA. As the principle of our SMIM, the different phase $\Delta\theta$ decreases the output dc voltage and ac amplitude. Even with the decadence caused by the different phase $\Delta\theta$, the good linearity between the dc voltage and synchronous SMIM signal is still well obtained. However, the higher output voltage generated by reducing $\Delta\theta$ can effectively benefit the accuracy of the measured signal. For our SMIM measurements, the output signal can be seen as a dc function as $V_{\mathrm{a}} V_{\mathrm{b}} + 0.5 V_{\mathrm{c}} V_{\mathrm{d}}$ in the situation of zero $\Delta\theta$. The monitored dc voltage can be maximized by adjusting the $\Delta\theta$ to zero. Finally, a dc multimeter can detect the PIN-TIA amplitude V_{d} of the modulation signal by monitoring V_{out}.

After analyzing more than 300 different sets of PIN-TIAs, the relationship of sensitivities and intermixed voltages is determined. Later on, the eye diagram analysis at 2.488 Gb/s is also performed to characterize the data-receiving performance of the PIN-TIAs in a simulated SONET OC-48 fiber-optic network. This is done with an electronic time-division multiplexing (ETDM) experiment using a 2.5-Gb/s optical PRBS data stream (with NRZ pattern length of $2^7 - 1$ and optical input power of -6 dBm). For most digital communications, the 10^{-10} BER is

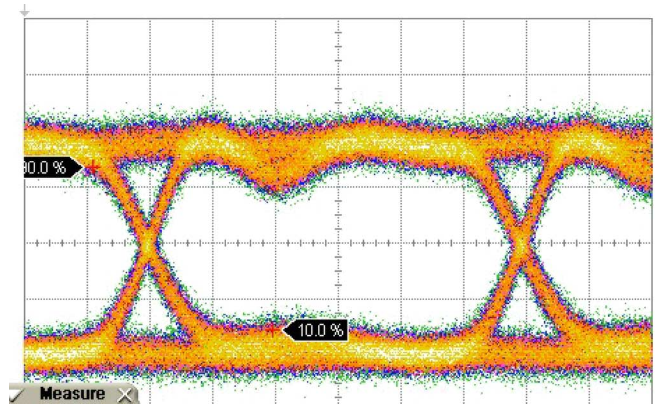

Fig. 2. Eye pattern at 2.5 Gb/s received by the InGaAs PIN-PD with transimpedance amplifier at −6 dBm. (Color version available online at http://ieeexplore.ieee.org.)

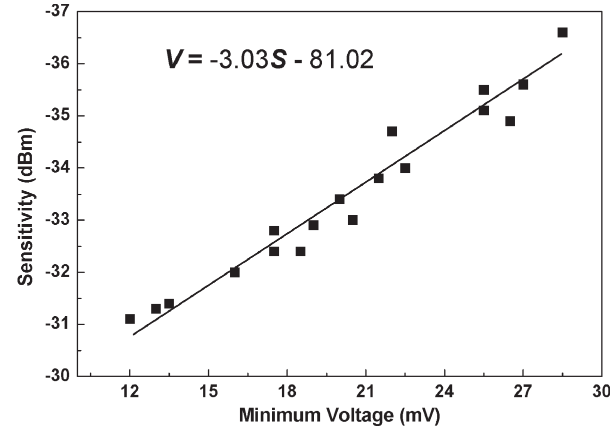

Fig. 4. Measured sensitivity against the measured voltage of a dc meter.

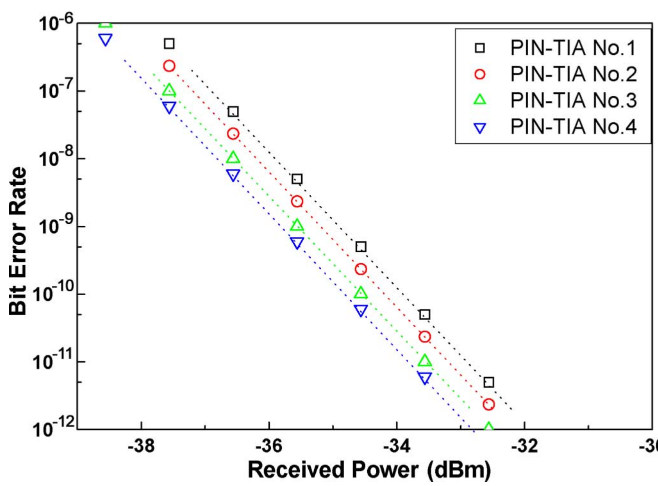

Fig. 3. BER of the PIN-TIAs with different received powers. (Color version available online at http://ieeexplore.ieee.org.)

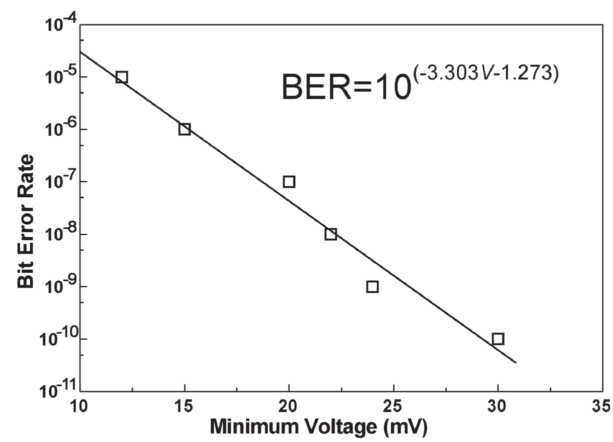

Fig. 5. Relationship between the measured voltage and the BER of PIN-TIAs.

denoted as the error floor, and the sensitivity of the PIN-TIA becomes the criterion during the on-line error performance test. These PIN-TIAs are from the same wafer and have almost the same broadband RF characteristics, conversion gain, and noise performance. In the proposed SMIM measurement, the BERT is necessary to calibrate the measured voltage (multimeter) to the 10^{-10} BER of the receivers from different vendors of TIA or different processes of the p-i-n photodetectors, but it is not necessary to calibrate the measured voltage of receivers from different wafers. We concluded that if the monitoring voltage is above 12.5 mV at a requested BER of 10^{-10}, the sensitivity can be better than −31 dBm for any PIN-TIAs, as shown in Fig. 3. Fig. 2 shows the received eye pattern measured at the PIN-TIA output. It is seen that a well-opened eye pattern can be obtained with a relatively large dynamic range during a measuring time of 15 min. The rising and falling times (defined as the duration between 20% and 80% of on-level amplitude) are 147 and 133 ps, respectively. Fig. 3 shows the BER of the PIN-TIAs under different receiving powers. The reduction in received power in front of the PIN-TIAs inevitably leads to a rising BER of PIN-TIAs. The rms jitter of 14.3 ps was measured by determining the mean and standard deviation of a sampled eye-pattern histogram in the time domain. For performance monitoring, the measured sensitivities of the PIN-TIAs with their corresponding BERs are characterized.

Fig. 4 shows the relationship between the measured voltage of the PIN-TIA and its minimum received power at the 10^{-10} BER. A linear transfer function for the sensitivity to the intermixed voltage of $V_{\mathrm{SMIM}} = -3.033S_{\mathrm{sen}} - 81.052$ is obtained, as shown, in Fig. 4, where V_{SMIM} is the monitoring voltage in units of millivolts, and S_{sen} is the sensitivity in units of decibels below 1 mW at a desired BER $= 10^{-10}$. The shifted error-rate traces for different PIN-TIAs exhibit a linear relationship with sensitivity as well as with the intermixed voltage. The linear transfer function between the BER and intermixing voltage precisely evaluates the received power under a given BER and intermixed voltage, which can be described as BER $= 10^{(-0.303V-1.273)}$, as shown in Fig. 5. The BER is generally determined by using a long time sequence of the PRBS pattern sequence, but our sweep-frequency-based SMIM system uses much less time to evaluate its BER. The sensitivity penalties ranging from 0.1 to 0.5 dB at most intermixed voltages are also addressed during measurements.

Previously, Bergano *et al.* have demonstrated a BER evaluation method by measuring the signal-to-noise ratio (or Q factor)

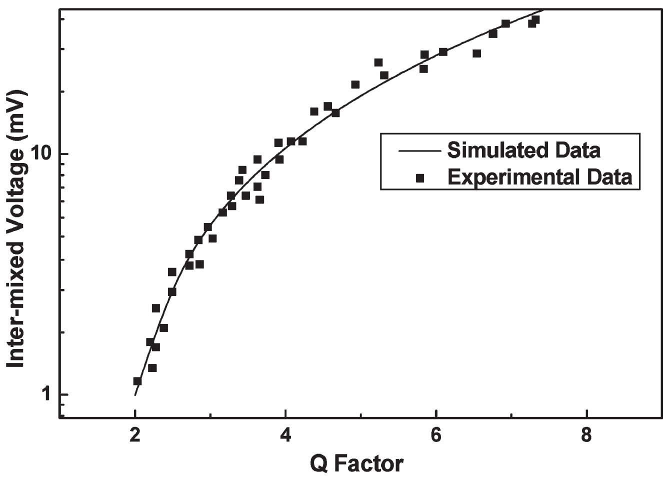

Fig. 6. Relationship between the Q factor and the BER of PIN-TIAs.

at the decision circuit of an optical transmission and receiving system [5], as given by

$$Q = \frac{I_1 - I_0}{\sigma_1 + \sigma_0} \tag{1}$$

$$\mathrm{BER} = \frac{1}{2}\mathrm{erfc}\left(\frac{Q}{\sqrt{2}}\right) \tag{2}$$

where $I_{1,0}$ and $\sigma_{1,0}$ are the mean value and standard deviation of the mark and space data rail, and $\mathrm{erfc}(x)$ is the complementary error function. The measured BER of the data stream received by the InGaAs PIN-PD can be accurately calculated from the recorded Q factor of the received eye pattern at the desired data rate. Fig. 6 shows the relationship between the measured voltage of the PIN-TIAs and the Q factor. The results, using this equation to calculate the corresponding sensitivity of the PIN-TIA, are comparable with the method of the Q factor. The inaccuracy is mainly attributed to the different loss of coupling power induced at the interface between fiber connectors of different PIN-TIAs in the packaged PIN-TIA. In standard BER measurements as 10^{-10}, the 155-Mb/s test expends 640 s and the 2.5-Gb/s test expends 40 s for the appearance of ten errors. At a requested BER of 10^{-12}, the 155-Mb/s test expends 64 000 s, and the 2.5-Gb/s test expends 4000 s for the appearance of ten errors. In our SMIM system, the intermixed voltage is stabilized in less than 4 s for all requested BERs. Comparing the BER and eye diagram analyses of the received PRBS signal corroborates that such a cost-effective intermixing SMIM technique is very promising for test applications in the SONET OC-48 fiber-optic communication receiving devices.

IV. Conclusion

We have compared the sensitivity of fiber-optic SONET OC-48 PIN-TIAs measured by SMIM and BERT. In comparison with the BER and eye diagram analyses of the received PRBS signal, our SMIM system exhibits comparable testing performance but gives the benefit of fast testing. The transfer function of the threshold voltage versus the sensitivity has provided an alternative to the BER parameters for SONET/SDH PIN-TIAs under the American National Standards Institute/International Telecommunications Union specification. At a requested BER of 10^{-10}, the measured voltage of 12.5 mV is equivalent to a sensitivity of -31 dBm. The error of the measured voltage is 0.28 mV, which corresponds to an error sensitivity of 0.09 dB. With the SMIM technique, the fast sensitivity and BER estimations of PIN-TIAs on the mass-production line are performed. Such a diagnostic scheme makes the current measurement, which has been an alternative on-line diagnostic scheme for PIN-TIAs, greatly simplified and more cost effective.

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