Sensitivity evaluation of fiber optic OC-48 p-i-n transimpedance amplifier receivers using sweep-frequency modulation and intermixing diagnostics

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Abstract. The sensitivity of SONET p-i-n photodiode receivers with transimpedance amplifiers (PIN-TIA) from OC-3 to OC-48 data rates, measured by using a standard bit-error-rate tester (BERT) and a novel sweep-frequency-modulation/intermixing (SMIM) technique, are compared. A threshold intermixed voltage below 15.8 mV obtained by the SMIM method corresponding to the sensitivity of the PIN-TIA receiver beyond −32 dBm determined by BERT for the SONET OC-48 PIN-TIA receivers with a required BER of better than 10^{-10} is reported. The analysis interprets that the intermixed voltage for improving the PIN-TIA receiver sensitivity from −31 to −33 dBm has to be increased from 12.5 to 20.4 mV. As compared to the BERT, the SMIM is a relatively simplified, fast, and low-cost technique for on-line mass-production diagnostics for measuring the sensitivity and evaluating the BER performances of PIN-TIA receivers.
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Subject terms: sweep-frequency modulation; intermixing; SONET OC-48; p-i-n transimpedance amplifier receiver; bit error rate; sensitivity.

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1 Introduction

The rapid growth of the fiber optic communication industry accelerates continual progress of optical data link modules. In particular, this leads to low-cost consumption for measuring these optical data link modules. In the receiver part, the most important parametric analysis is its sensitivity that decides the error performance. The traditional method for determining the sensitivity[1] of a sweep-frequency optical network (SONET) or sweep-frequency digital hierarchy (SDH) transceiver is to characterize the transmission, receiving, and error detection of the pseudorandom binary sequence (PRBS) pattern using a commercial bit-error-rate tester (BERT). Such issues were defined by the American National Standards Institute (ANSI)[1] or by the Telecommunication Standardization Sector of the International Telecommunication Union (ITU-T),[2,3] as shown in Fig. 1(a). The BER describes the ratio of the error number to the transmitted bit number in a digital communication system. In more detail, the standards describe that the transmitter module is first keying a simple binary signal with a nonreturn-zero (NRZ) format, which electro-optically transfers the PRBS pattern into an optical fiber through an optical attenuator. The transfer function of the BER to the input power of the optical pattern after receiving the p-i-n photodiode receiver with transimpedance amplifier (PIN-TIA) is then calculated. Subsequently, an optical attenuator after the transmitter is adjusted to obtain the minimum output power that generates the required BER (usually better than 10^{-10}) for the receiver being tested. This minimum output power is then defined as its sensitivity.[1–3]

The BERT measurement is generally based on the strong correlation between the input power of the encoded optical data train and the operational bandwidth of PIN-TIA receivers. A linear relationship between the amplitudes of the encoded data train and its frequency components can also be realized from the Fourier transform analysis. The Fourier frequency spectrum of the PRBS data stream varies temporally to characterize the frequency response of the PIN-TIA receiver at different frequency bands. Therefore, a sweep-frequency modulation, and featured frequency sampling of the signal converted by a PIN-TIA receiver at different optical powers, would also be an alternative way to evaluate the sensitivity of the PIN-TIA receiver. In this work, we demonstrate a sweep-frequency modulation and intermixing (SMIM) technique to evaluate the sensitivity of PIN-TIA receivers. Such a diagnostic scheme makes the on-line sensitivity measurement simplified and more cost effective by first sweep-frequency modulating the transmitter and then sampling the featured frequency signals converted from the PIN-TIA receiver under test. The featured frequency signal from the modulation frequency source and the optoelectronic converted signal after the PIN-TIA receiver are intermixed to obtain the corresponding voltage. The output voltage from the mixer with attenuated input power correlates well with the sensitivity of the PIN-TIA receiver. In experiments, the transfer functions of the monitoring voltage to the sensitivity of PIN-TIA receivers for SONET at different data rates from OC-3 to OC-48 are determined. The *in-situ* determined threshold intermixed

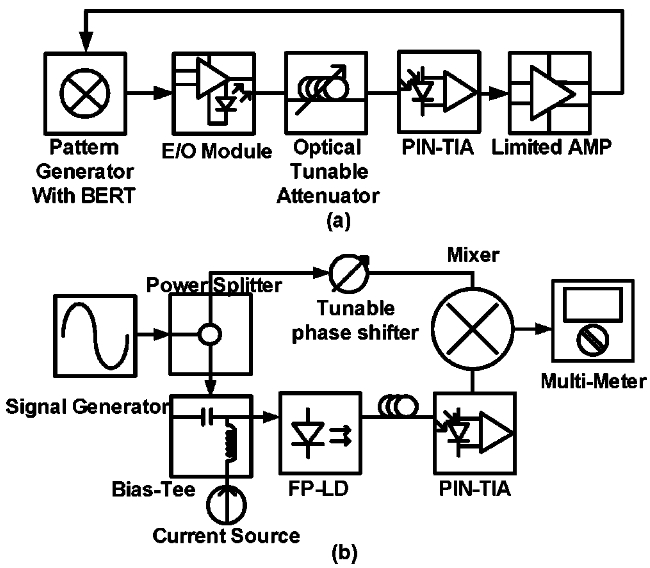

Fig. 1 (a) The schematic diagrams of the BERT-based sensitivity measurement. (b) The experiment setup of a sweep-frequency modulation and intermixing technique based sensitivity and BER analyzer.

voltage to the sensitivity is relatively comparable with the measured sensitivity using BERT analysis under ANSI specifications during a mass-production process.

2 Systematic Configuration

In contrast to a digital encoding process, the proposed method is performed by sinusoidal-wave optical modulating the client optical signal by a rf sweep-frequency generator. After fiber transmission, the PIN-TIA receives and optoelectronically converts the sweep-frequency modulated signal, which is mixed with the original signal from the rf sweep-frequency generator and generates a dc output voltage. The voltage measured at a minimum optical input power corresponding to a BER of 10^{-10} correlates well with the sensitivity of the PIN-TIA receiver. The proposed sweep-frequency modulation and intermixing[4] module for sensitivity estimation of PIN-TIA receivers is shown in Fig. 1(b), which consists of a rf signal generator with operation frequency and level of 155 MHz to 2.488 GHz and +3 dBm, respectively. A microwave power splitter is used to split the electronic signal into two signals with equivalent levels. A microwave mixer is employed to frequency translate the electronic signals from the rf generator and the PIN-TIA receiver. The bias-tee circuit is used to combine the featured rf signal and dc current for driving the transmitter or to split the intermixed dc signal. The most important issue in such a system is the phase synchronization between the electronic signals from the rf generator and the PIN-TIA receiver before intermixing. To implement, we control the distance of electronic and optical routes via a phase shifter and slightly detune the featured frequency to meet the complete phase-match condition. In a transmitter, an auto-power-control (APC) circuit is used to drive a Fabry-Perot laser diode (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 intermixed voltage is

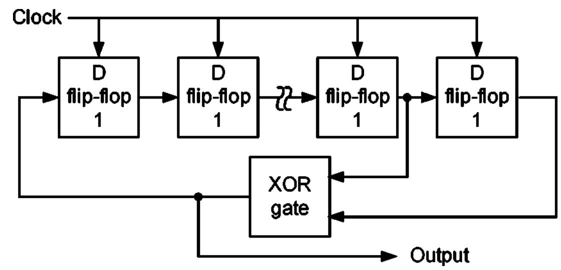

Fig. 2 (a) The monitoring voltage of different PIN-TIA receivers and (b) the sensitivity of different PIN-TIA receivers.

monitored by a dc multimeter, as shown in Fig. 1(b). The sensitivity of PIN-TIA at BER of 10^{-10} measured by BERT, and the intermixed dc voltage of the same device measured by our proposed system, are compared to obtain a transfer function of $V\,(\mathrm{mV}) = C1 \cdot S\,(\mathrm{dBm}) - C2$ between the sensitivity (S) and the intermixed dc voltage (V).

3 Theoretical Model

The basic principle for the sweep-frequency modulation and intermixing technique can be explained by deducing the mixed output of the demodulated optical signal and the reference clock. The corresponding function of a reference clock can be written as $V_a + V_c \sin(\omega t)$, where V_a is the mean voltage of the reference clock and V_c is the amplitude. The corresponding function of the demodulation signal from the PIN-TIA (signal under test) is $V_b + V_d \sin(\omega t)$, where V_b is the dc voltage of the PIN-TIA and V_d is the amplitude of the modulation signal. The $\Delta\theta$ denotes the phase difference between two signals. After mixing, the output signal is written as Eq. (1),

$$\begin{aligned} V_{\mathrm{out}} &= [V_a + V_c \cdot \sin(\omega t)] \cdot [V_b + V_d \cdot \sin(\omega t + \Delta\theta)] \\ &= V_a V_b + V_b V_c \cdot \sin(\omega t) + V_a V_d \cdot \sin(\omega t + \Delta\theta) \\ &\quad + V_c V_d \cdot \sin(\omega t) \cdot \sin(\omega t + \Delta\theta) \\ &= \left[V_a V_b + \frac{1}{2} V_c V_d \cos(\Delta\theta) \right] \\ &\quad + V_b V_c \cdot \sin(\omega t) + V_a V_d \cdot \sin(\omega t + \Delta\theta) \\ &\quad + \frac{1}{2} V_c V_d \cdot \cos(2\omega t + \Delta\theta), \end{aligned} \tag{1}$$

where V_{out} is the demodulation signal that is mixed by the reference clock and the signal under test. If we set $V_a = 0$ and extract the dc component from the aforementioned formula with a filtering function, the output voltage from the mixer can thus be written as $V_{\mathrm{out}} = [V_c V_d \cos(\Delta\theta)]/2$, which is exactly the monitoring voltage on a dc meter. Since the signal passing through the FPLD and the PIN-TIA will exhibit different phase $\Delta\theta$ as compared to others passing through only a transmission line, such a phase shift thus influences the measured voltage. A tunable phase shifter is employed to adjust the phase difference $(\Delta\theta)$ between the demodulated signal and reference clock. The monitored dc voltage will be maximized as the $\Delta\theta$ adjusts to zero. Then the output signal is written as Eq. (2),

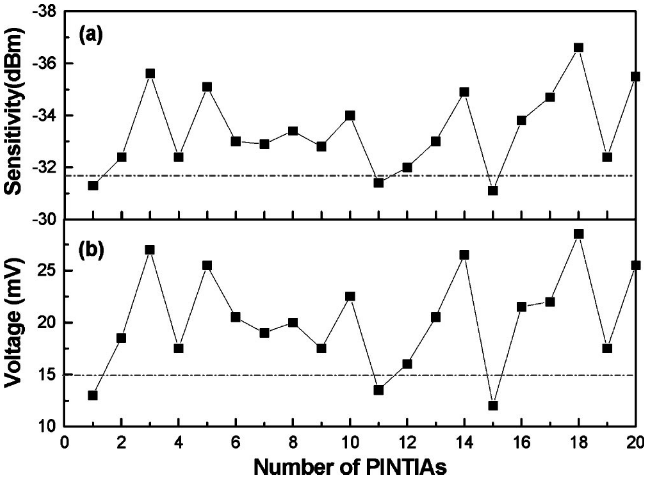

Fig. 3 The block circuit diagram for generating a 2^7-1 PRBS pattern by using train of shift registers with feedback.

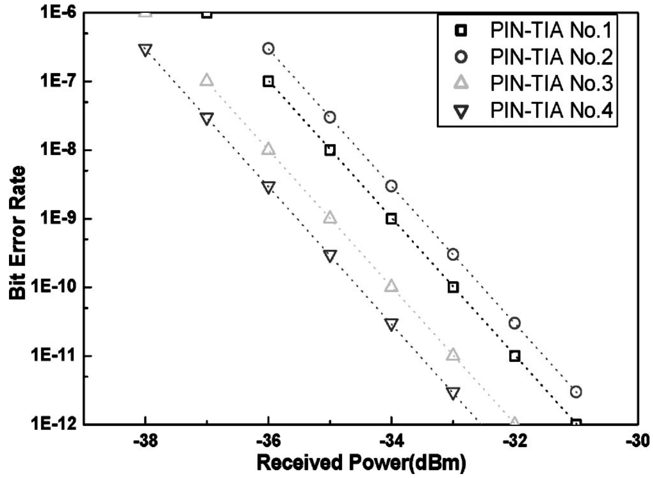

Fig. 4 The BER of the PIN-TIA receivers with different received power.

$$V_{\text{out}}=\left[V_aV_b+\frac{1}{2}V_cV_d\right]+V_bV_c\cdot\sin(\omega t)+V_aV_d\cdot\sin(\omega t)$$
$$+\frac{1}{2}V_cV_d\cdot\cos(2\omega t), \qquad (2)$$

where the $V_aV_b+1/2V_cV_d$ term is pure dc voltage. Finally, a dc meter can detect V_d (the PIN-TIA amplitude of the modulation signal) by monitoring V_{out}.

4 Results and Discussions

First of all, the relationship of PIN-TIA sensitivity and intermixed voltage after measuring more than 100 different sets of PIN-TIA receivers is determined. These PIN-TIAs are from the same wafer and have almost the same broadband rf characteristics, conversion gain, and noise performances. For comparison, these PIN-TIAs are also characterized by BERT analysis for obtain their corresponding sensitivities. The commonly used test pattern in BERT testing is PRBS, which is a repetitive sequence with a pattern length of 2^N-1, where N is an integer (typical values of N are 7, 10, 15, 20, 23, and 31). Within the pattern, the bit sequence is arbitrarily designed to approximate the characteristics of truly random data. For example, a 2^7-1 PRBS pattern adopted in ITU-T standards is generated by using a train of shift registers with feedback, as shown in Fig. 2. Under the same injection power and the same modulation frequency, the sensitivities of different PIN-TIA receivers are shown in Fig. 3(a), and the intermixed dc voltage of the same devices can be seen in Fig. 3(b). In the experiment, each different NRZ signal stream exhibits a different Fourier-transformed frequency spectrum. The worst condition among all patterns with the highest frequency component is selected as the clock signal for characterization in our intermixing system. At a requested BER of 10^{-10}, the measured voltage of 12.5 mV is equivalent to a sensitivity −31 dBm, measured by BERT, while 20.4 mV corresponds to a sensitivity of −33 dBm. We conclude that if the monitoring voltage is larger than 12.5 mV, the sensitivity can be better than −31 dBm for any PIN-TIA receivers.

Figure 4 shows the BER of the PIN-TIA receivers under different receiving power. The reduction in received power in front of the PIN-TIA receivers inevitably leads to a rising BER of PIN-TIA receivers. The minimum acceptable BER for most telecommunication communication applications is often considered as 10^{-9}, and the sensitivity of the PIN-TIA receiver at a BER of 10^{-10} is usually denoted as the error floor during on-line error performance tests. For performance monitoring, the measured sensitivity of the PIN-TIA receivers with their corresponding BERs are characterized. Figure 5 shows the relationship between the measured voltage of 20 sets of PIN-TIA receivers and its minimum received power at BER of 10^{-10}. A linear transfer function for the sensitivity to the intermixed voltage of $V=-3.033S$ to 81.052 is obtained, where V is the monitoring voltage in units of mV, and S is the sensitivity in units of dBm at a desired $\text{BER}=10^{-10}$. For any monitoring voltage, we can use this equation to calculate the corresponding sensitivity of the PIN-TIA receiver.

It is seen that the larger intermixed voltage, the better sensitivity performance of the PIN-TIA receiver. The

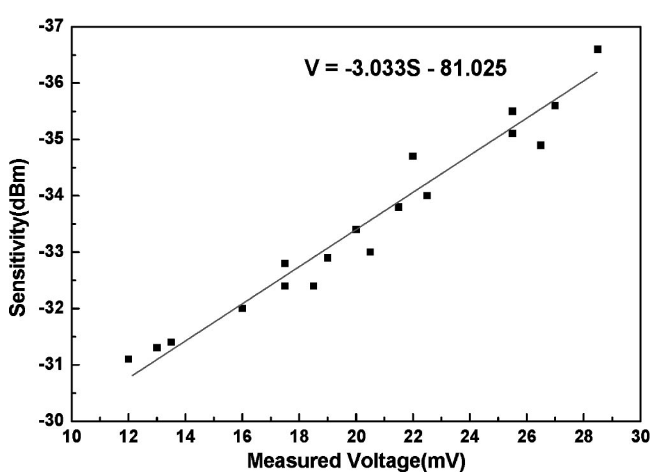

Fig. 5 The measured sensitivity against the measured voltage of dc meter.

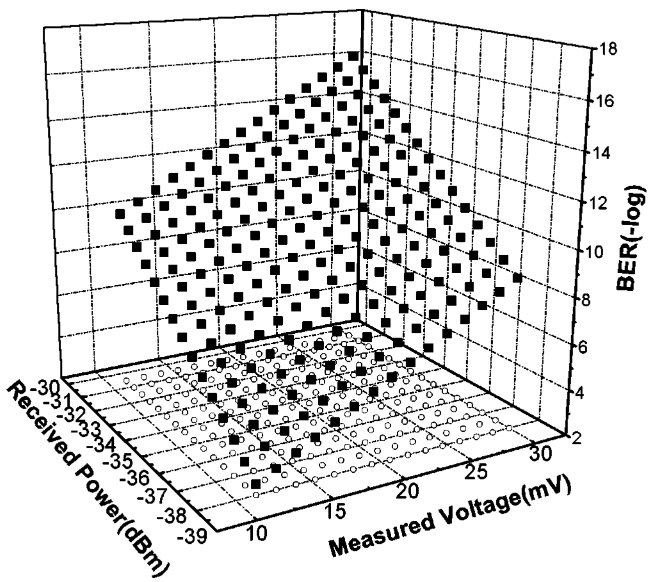

Fig. 6 The relationship among the sensitivity, measured voltage, and BER of PIN-TIA receivers.

shifted error-rate traces for different PIN-TIA receivers (see Fig. 4) all exhibit linear relationships with sensitivity as well as the intermixed voltage (see Fig. 5). According to the equation of sensitivity and measured voltage, the value of the BER from different PIN-TIA can thus be described as

$$P = -(\log_{10} \mathrm{BER} + 0.33 \cdot V + 36.7), \quad (3)$$

where P is the receiving power of a PIN-TIA and V is the intermixed voltage of our system. Equation (3) precisely evaluates the received power under a given BER and intermixed voltage, as shown in Fig. 6. BER is generally determined by using a long-time sequence of PRBS pattern sequences, 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, which is mainly attributed to the different loss of coupling power induced at the interface between fiber connectors of different PIN-TIA receivers. This inaccuracy can be ruled out by extracting the fiber loss or insertion loss of connectors. Another inaccuracy is introduced by the imperfect APC function of the optical transmitter during measurements, since the average power of an optical transmitter is still fluctuated in a tiny scale. The calibration of optical transmitter parameters such as average power, extinction ratio, and fiber cable length is thus mandatory, which helps improve the accuracy of intermixed voltage and the corresponding sensitivity.

Nonetheless, such a sweep-frequency modulation and intermixing technique has shown its capability of measuring the sensitivity at desired BER and evaluating the error rate of a PIN-TIA receiver under a desired receive power, which may be treated as an on-line fast tester as compared to a traditional BERT instrument. In a practical case, a monitor voltage of 12.5-mV output from the proposed diagnostic system that denotes the PIN-TIA sensitivity of -31 dBm corresponding to a BER of less than 10^{-10} is successfully determined. The transfer function of a threshold voltage to the sensitivity that exactly meets the request of BER for SONET/SDH under ANSI/ITU specifications can also be provided. Such a sweep-frequency-based sweep-frequency modulation and intermixing technique is useful for sensitivity and BER estimation of PIN-TIAs on a mass-production line.

5 Conclusion

We demonstrate a sweep-frequency modulation and intermixing technique to measure sensitivity at desired BERs and evaluate the error rate of a PIN-TIA receiver under a desired receive power. Our system replaces the traditional expensive BERT instrument and exhibits comparable performance. A monitor voltage of 12.5-mV output from the proposed diagnostic system that denotes the PIN-TIA sensitivity of -31 dBm corresponding to a BER of less than 10^{-10} is determined. The transfer function of a threshold voltage to the sensitivity that exactly meets the request of BER for SONET/SDH under ANSI/ITU specifications is provided. Using the sweep-frequency-based sweep-frequency modulation and intermixing technique, we confirm that this measurement system is useful for on-line sensitivity and BER estimation of PIN-TIAs during mass-production processes. This system is fast and low-cost, and could be a practical diagnostic scheme for PIN-TIA performance monitoring and on-line testing.

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