Comparison on the Sensitivity of Fiber-Optic SONET OC-48 PIN-TIA Receivers Measured by using Synchronous Modulation Inter-Mixing Technique and Bit-Error-Rate Tester

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ABSTRACT

The sensitivity of SONET p-i-n photodiode receivers with transimpedance amplifier (PIN-TIA) from OC-3 to OC-48 data rates measured by using a standard bit-error-rate tester (BERT) and a novel synchronous-modulation inter-mixing (SMIM) technique are compared. A threshold inter-mixed voltage of below 15.8 mV obtained by SMIM method corresponding to the sensitivity of 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 inter-mixed voltage for improving the PIN-TIA receiver sensitivity from -31 dBm to -33 dBm has to be increased from 12.5 mV to 20.4 mV. As compared to the BERT, the SMIM is a relatively simplified and low-cost technique for on-line mass-production diagnostics for measuring the sensitivity and evaluating the BER performances of PIN-TIA receivers.

Keywords: Synchronous modulation; inter-mixing; SONET OC-48; PIN-TIA receiver; bit-error-rate; sensitivity

1. INTRODUCTION

The rapid growth of optical communication industry accelerates continual improvement in the performance of optical data link modules. In particular, this further leads to the low-cost consumption issue for measuring these optical data link modules. In any receiving device, one of the most important parametric analyses is its sensitivity that decides the error performance. The traditional method for measuring the sensitivity [1] of a synchronous optical network (SONET) or synchronous digital hierarchy (SDH) transceiver is to characterize the transmission, receiving, and error detection of the pseudo random binary sequence (PRBS) pattern using a commercial bit-error-rate tester (BERT). Such issue was defined by the American National Standards Institute (ANSI) [1] or by the Telecommunication Standardization Sector of International Telecommunication Union (ITU-T) [2, 3], as shown in Fig. 1(a). In more detail, the standards describe that the transmitter module is first keying by a simple binary signal with non-return-zero (NRZ) format, which electro-optically transfers the 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 by the p-i-n photodiode receiver with trans-impedance amplifier (PIN-TIA) is then calculated. Subsequently, an optical attenuator is employed to adjust the minimum output power for required BER (usually under 10^{-10}), such an optical power in front of the PIN-TIA is then defined as its sensitivity.[1-3]

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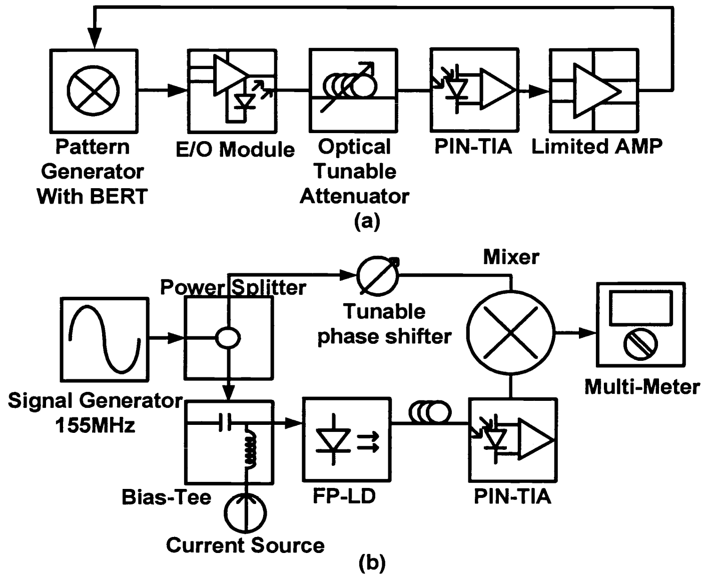

Fig. 1. (a) the schematic diagrams of the BERT-based sensitivity measurement. (b) the experiment setup of a synchronous modulation and inter-mixing technique based sensitivity and BER analyzer.

In principle, such a measurement is based on the strong correlation between the input power of the encoded optical data-train, the operational bandwidth and the sensitivity of PIN-TIA receivers. A linear relationship between the amplitudes of encoded data-train and its frequency components can also be realized from the Fourier transform analysis. Therefore, a sweep-frequency, the electronic measurement and the featured frequency sampling of the encoded data-train under different optical powers would also be an alternative way to evaluate the sensitivity of the PIN-TIA receivers. In this paper, we demonstrate a synchronously synchronous modulation and inter-mixing (SMIM) technique to evaluate the sensitivity. Such a diagnostic scheme makes the current measurement greatly simplified and more cost-effective, which is done by first sweep-frequency modulating the transmitter and then sampling featured frequency signals with the PIN-TIA receiver under test. An inter-mixing between the featured frequency signal and the opto-electronic converted signal after the PIN-TIA receiver is implemented for obtaining the corresponding voltage. The output voltage from the mixer under the attenuated input condition correlates well with the sensitivity of PIN-TIA receiver. In experiment, 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 determination of threshold inter-mixed voltage to the sensitivity exactly meets the demands of measuring sensitivity under ANSI specification during mass-production process.

2. EXPERIMENTAL SETUP

In contrast to a digital encoding process, the proposed method involves a sinusoidal-wave optical modulation of the client optical signal by a RF sweep-frequency generator with featured frequencies from 1.55MHz to 2.488GHz. After passing through the connecting fiber, the PIN-TIA receives and opto-electronically converts the modulated signal, which then inter-mixes with the original signal and generates a DC output voltage. The voltage correlates well with the sensitivity of the PIN-TIA receiver. The proposed synchronous modulation and inter-mixing [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 from 155 MHz to 2.488 GHz and +3 dBm, respectively. A microwave power-splitter is used to split electronic signal into two signals with equivalent levels. A microwave mixer is employed to frequency multiply 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 inter-mixed DC signal. The most important issue in such system is the phase synchronization between the electronic signals from the RF generator and the PIN-TIA receiver before inter-mixing. To obtain the synchrony, we control the distance of electronic and optical routes, and then slightly detune the featured frequency to meet the phase-match condition. In transmitter, an auto-power-control (APC) circuit is used to drive a Fabry-Perot laser diode (FPLD) at -6 dBm with extinction ratio of 15.2 dB for better power stability as shown in Fig. 2(a), Fig. 2(b). The frequency responses of all components in the system are well beyond the OC-48 criterion. The inter-mixed voltage is monitored by a DC multimeter. To evaluate the sensitivity at desired BER, the PIN-TIA receives the optical signal encoded by PRBS pattern generator (PPG), and the minimum optical power in front of the PIN-TIA required for obtaining the error rate under BER of 10^{-10} is then defined as the sensitivity. The sensitivity of PINTIA using BERT, and the intermixed DC-voltage of the same device measured by our proposed system are compared to obtain a transfer function of V (mV) $= C_1 \cdot S$ (dBm) $- C_2$ between the sensitivity (S) and the inter-mixed DC-voltage (V).

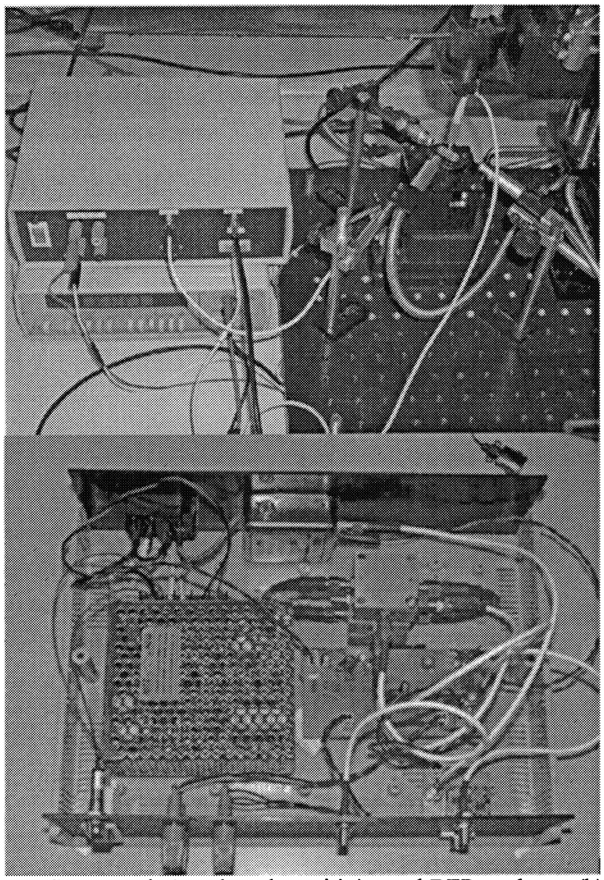

Fig. 2. (a) The detail picture of a SMIM technique based sensitivity and BER analyzer. (b) the system picture of a SMIM technique based sensitivity and BER analyze

3. THEORETICAL MODEL

The basic principle for the synchronous modulation and inter-mixing 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 $\Delta\theta$ denote the phase difference between two signals. After mixing, the output signal is written as

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

where V_{out} is the demodulation signal which be 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 $V_{out} = [V_c V_d \cos(\Delta\theta)]/2$ which is exactly the monitoring voltage on a DC-meter. Since the signal passing through a LD and a PIN-TIA will exhibit different phase $\Delta\theta$ as compared to that passing through only a transmission line. The phase shifts thus influence the measured voltage. A tunable phase shifter is required to adjust the $\Delta\theta$ value 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),

$$
V_{out} = \left[V_a V_b + \frac{1}{2} V_c V_d\right] + V_b V_c \cdot \sin(\omega t) + V_a V_d \cdot \sin(\omega t) + \frac{1}{2} V_c V_d \cdot \cos(2\omega t), \qquad (2)
$$

, where the $VaVb+1/2VcVd$ term is pure DC voltage. Finally, a DC-meter can detect Vd (the PIN-TIA amplitude of the modulation signal) by monitoring Vout.

4. RESULTS AND DISCUSSIONS

The commonly used test-pattern for out-of service BER testing is the PRBS. This is a repetitive pattern whose pattern length is of the form 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 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, as shown in Fig. 3. Each different NRZ signal stream exhibits different Fourier-transformed frequency spectrum. The worst condition among all patterns with highest frequency component is selected as the clock signal for characterization in our inter-mixing system.

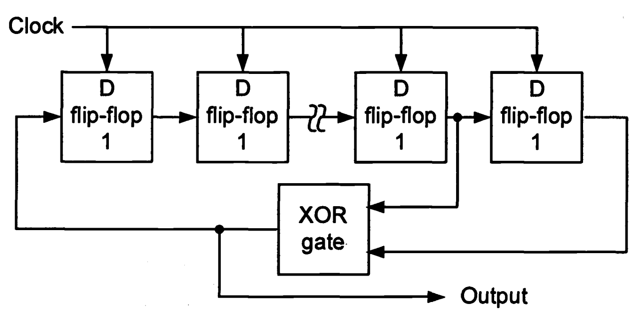

Fig. 3. The block circuit diagram for generating 27-1 PRBS pattern by using a train of shift registers with feedback.

First of all, the relationship of PIN-TIA sensitivity and inter-mixed 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. Under the same injection power and the same modulation frequency, the sensitivities of different PIN-TIA receivers are shown in Fig. 4(a), and the inter-mixed DC voltage of the same devices can be seen in Fig. 4(b). At a requested BER of 10^{-10}, that measured voltage of 12.5 mV is equivalent to a sensitivity -31 dBm, measured by BERT, while 20.4 mV corresponding to a sensitivity of -33 dBm. We conclude that if the monitoring voltage is under 12.5 mV, the sensitivity can be better than -31 dBm for any PIN-TIA receivers.

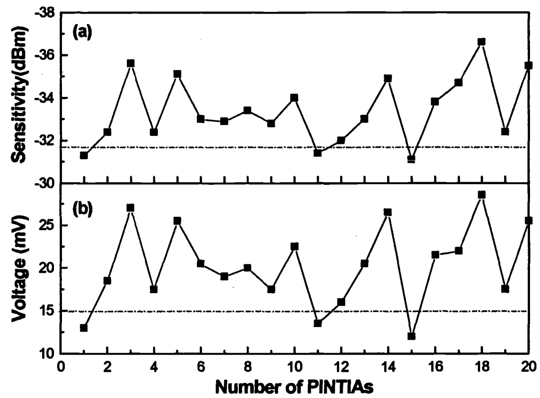

Fig. 4. (a) the monitoring voltage of different PIN-TIA receivers and (b) the sensitivity of different PIN-TIA receivers.

Figure 5 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. For most digital communications, the BER of 10^{-10} is denoted the error floor, and the sensitivity of PIN-TIA receiver becomes the criteria during on-line error performance test. For performance monitoring, the measured sensitivity of the PIN-TIA receivers with their corresponding BERs are characterized. Figure 6 shows the relationship between the measured voltage of 20 sets PIN-TIA receivers and its minimum received power at BER of 10^{-10}. A linear transfer function for the sensitivity to the inter-mixed voltage of $V = -3.033S - 81.052$ is obtained, where V is the monitoring voltage in unit of mV, and S is the sensitivity in unit of dBm at a desired BER = 10^{-10}. For any monitoring voltage, we can use this equation to calculate the corresponding sensitivity of the PIN-TIA receiver.

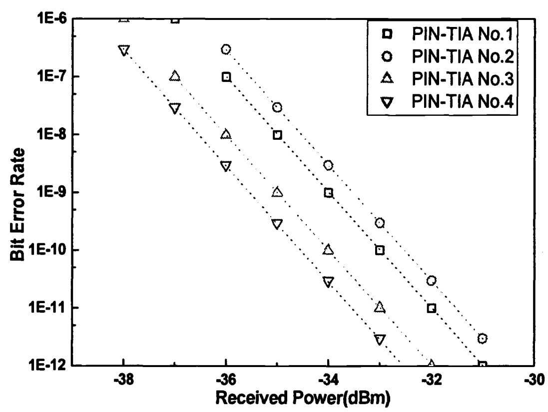

Fig. 5. The BER of the PIN-TIA receivers with different received power.

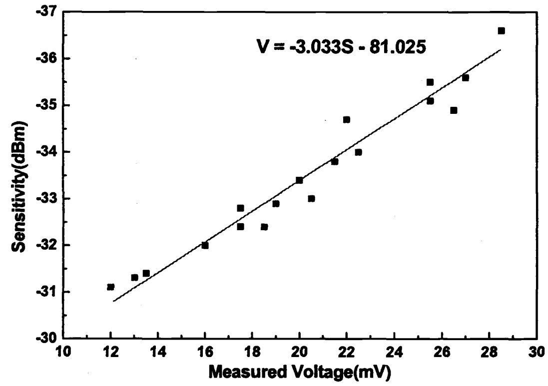

Fig. 6. The measured sensitivity against the measured voltage of DC-meter.

It is seen that the larger inter-mixed voltage, the better sensitivity performance of PIN-TIA receiver. The shifted error-rate traces for different PIN-TIA receivers (see Fig. 5) all exhibit linear relationship with sensitivity as well as the inter-mixed voltage (see Fig. 6). According to the equation of sensitivity and measured voltage, the value of the BER from different PIN-TIA can thus be described as

$$P = -\left(\log_{10} BER + 0.33 \cdot V + 36.7\right), \tag{3}$$

where P is the receiving power of a PIN-TIA, and V is the inter-mixed voltage of our system. The Eq. (3) precisely evaluates the received power under given BER and inter-mixed voltage, as shown in Fig. 7. BER is generally determined by using long time sequence of 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 dB to 0.5 dB at most inter-mixed 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 causes from the imperfect APC function of the optical transmitter during measurements, since the average power of 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 improving the accuracy of inter-mixed voltage and the corresponding sensitivity,

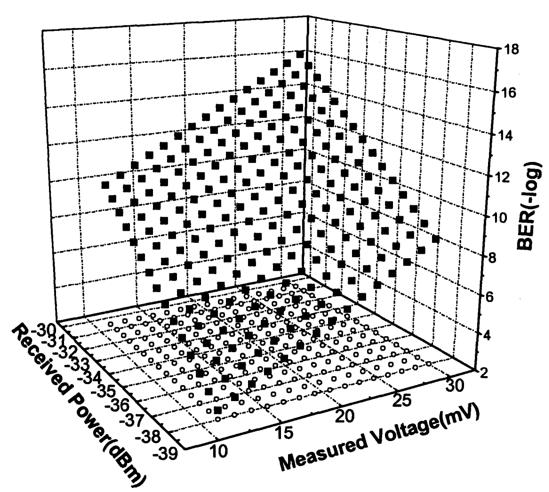

Fig. 7. The relationship among the sensitivity, the measured voltage, and the BER of PIN-TIA receivers.

5. CONCULSION

In conclusion, we demonstrate a synchronous modulation and inter-mixing technique to measure the sensitivity at desired BER and evaluate the error rate of a PIN-TIA receiver under a desired receive power. Our system replaces the traditional expensive BERT instrument and exhibit comparable performance. A monitor voltage of 12.5mV 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 which exactly meets the request of BER for SONET/SDH under ANSI/ITU specification has been provided. Using the sweep-frequency based synchronous modulation and inter-mixing technique, we have confirmed that this measurement system is useful for on-line sensitivity and BER estimation of PIN-TIAs during a mass-production process. 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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