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Reduction of the Power Penalty Induced by Low-Frequency Tone Using Variable Decision Threshold Technique

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We propose 'variable decision threshold technique' to decrease the power penalty induced by low-frequency tones. The proposed scheme uses a simple low-speed receiver to change the decision threshold of the optical receiver according to the low-frequency tones. We demonstrate the proposed method at 2.5 Gb/s.

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I. INTRODUCTION

In many optical communication systems, low-frequency (LF) tones - usually called pilot tones - are used for performance monitoring: wavelength and optical power monitoring [1], crosstalk monitoring [2], optical path monitoring [3], remote supervisory system in submarine system [4], packet switched networks [5], and so on. In addition, unwanted LF tones are imposed on the data signal by some optical devices driven with LF - e.g., acousto-optic tunable filter [6]. Since LF tones modulate the amplitude of the data signal, there exists a power penalty at the optical receiver [5]. Therefore, to have an acceptable power penalty, we have to control the LF modulation index, LF-tone frequency, and the number of LF tones. Thus there exists a limitation in the application of a pilot tone and in the optical devices that generate LF modulation.

To reduce the power penalty induced by LF tones, a LF-blocking technique (i.e., high-pass filter) can be used in the optical receiver. However, it also cuts off the low frequency spectrum of the data signal. Consequently, there exists the power penalty due to cutting off the low-frequency part of the data signal spectrum. Thus application of this technique is very limited.

In this paper, we propose and demonstrate a 'variable decision threshold technique' to relieve the power penalty induced by LF tones. This technique is simple and has no harmful side effects.

II. PRINCIPLE OF VARIABLE DECISION THRESHOLD TECHNIQUE

Fig. 1 shows the waveforms of a normal optical signal and an optical signal with LF modulation. In the normal optical signal shown in Fig. 1(a), the optimum decision threshold on Gaussian noise assumption is well known and given by [7]

$$D_{fix} = \frac{\sigma_0 I_1 + \sigma_1 I_0}{\sigma_0 + \sigma_1} \quad (1)$$

where I_0 and I_1 are the current level of '0' and '1', and σ_0 and σ_1 are the standard deviation of the noise imposed on the signal levels of I_0 and I_1, respectively. The decision threshold is a constant although the standard deviations of the noise is a function of the signal level. It is the geometric center of the signal level when the noise is independent of the signal level. However, it shifts to level '0' if the standard deviation of the noise is proportional to the signal level. For the optical signal modulated by LF tones, the signal level

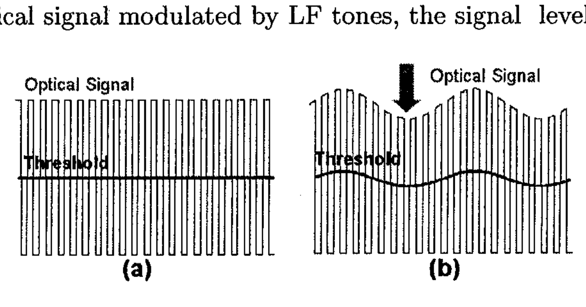

FIG. 1. Optical signals and corresponding optimum decision threshold (a) Normal optical signal (b) Optical signal modulated by a LF tone.

is no longer a constant. Then, the optimum decision threshold is time-variant and given by

$$D_{var} = \frac{\sigma_0(I_1 + F(t)) + \sigma_1 I_0}{\sigma_0 + \sigma_1} = \frac{\sigma_0}{\sigma_0 + \sigma_1}F(t) + D_{fix} \quad (2)$$

where F(t) is the LF tone signal passing through the decision circuit. Here, we assume that the extinction ratio is high enough to ignore the LF modulation on level '0'. And, we also neglect the modulation of the standard deviation of the noise caused by signal dependent noise. From Eq. (2), we can see that the optimum decision threshold of the optical signal modulated by LF tones is a function of time.

For the optical signal modulated by LF tones, we can minimize the bit error rate (BER) or the power penalty by changing the decision threshold as a function of time according to Eq. (2). This is the main idea of the variable decision threshold technique. To implement the proposed technique, we modified the optical receiver, which will be shown in the experimental setup.

However, even if we use the 'variable decision threshold technique', the power penalty cannot be removed totally because eye opening becomes small at the point marked in Fig. 1(b). At the point, power penalty occurs inevitably since eye opening decreases due to the LF tones.

III. EXPERIMENTAL SETUP

Fig. 2 shows the experimental setup for the variable decision threshold technique. We modulate the $LiNbO_3$ external modulator at 2.5 Gb/s with $2^{23} - 1$ pseudo-random binary signal (PRBS). The addition of LF modulation is made by modulating the second $LiNbO_3$ external modulator. The LF signal of the second modulator is a 3 MHz sine wave.

In the receiving part of our experiment, we separate the optical signal by 3-dB coupler and send one part to the optical receiver based on an avalanche photo detector (APD). The other part is coupled to a low-speed receiver based on the low-speed PD whose bandwidth is adjusted to 4 MHz.

The output of the low-speed PD is proportional to the LF modulation signal F(t) in Eq. (2). We introduce an optical delay to match the phase of the LF signals from both receivers at the input of the decision circuit. We also adjust the amplitude of the LF signal using a variable electrical attenuator to have the optimum value derived in Eq. (2) - i.e. $(\sigma_0/(\sigma_0 + \sigma_1)) \times F(t)$. Then, the BER is measured as a function of modulation index *with* and *without* the decision threshold control.

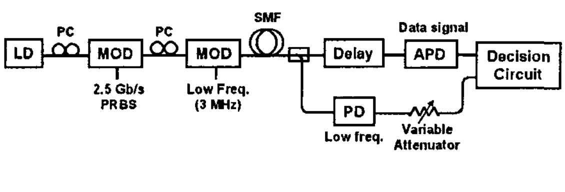

FIG. 2. Experimental setup for variable decision threshold technique.

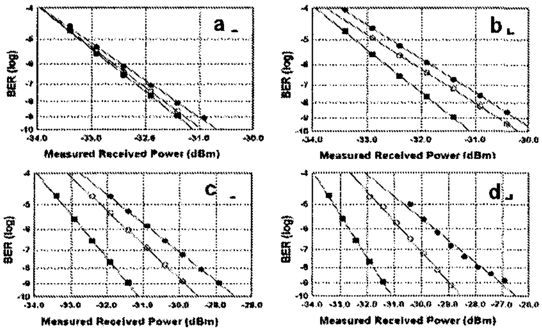

FIG. 3. Experimental result of improving BER using variable decision threshold technique at LF modulation index (a) 10%, (b) 16%, (c) 22%, and (d) 29% (□ no LF tone, ○ : *with* our technique, • : *without* our technique).

IV. RESULT AND DISCUSSION

Fig. 3 shows the measured BER curves *with* and *without* the decision threshold control. We show the measured BER curves at different LF modulation indices - (a) 10%, (b) 16%, (c) 22%, and (d) 29%. Using our technique, we can reduce the power penalties induced by LF modulation. The experimental results are compared with the simulation results in Fig. 4. In the simulation, we assume that all noises including *shot noise, thermal noise and beating noise* are approximately Gaussian so that we can use the simple BER-calculation method [7,8].

Without the decision threshold control (solid circles

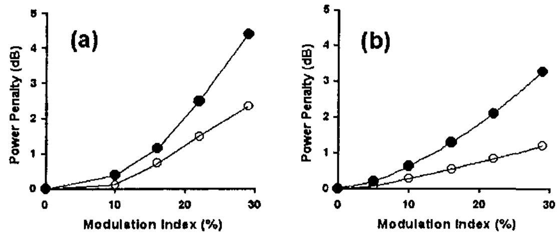

FIG. 4. Power penalty for 10^{-9} BER versus LF modulation index *with* (○) and *without* (•) the variable decision threshold technique respectively by (a) experiment and (b) simulation.

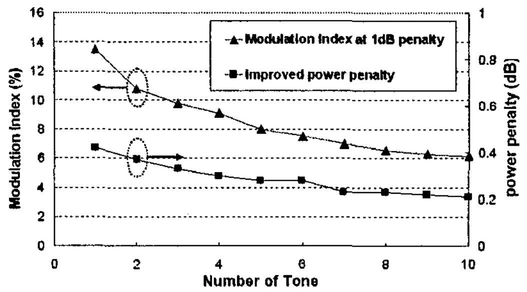

FIG. 5. Effective modulation indices causing 1 dB power penalty and the improved power penalties with our technique in multiple tone case.

in Fig. 4), the experimental results give a larger power penalty than the simulation results. This feature would be caused by the additional noise in the LF signal when inserting the LF signals. After using the variable decision threshold technique, the experimental results show less reduction of the penalty than for the simulation results. This discrepancy is caused by the low frequency spectrum component of the PRBS signal. Since the bandwidth of the low-speed receiver is 4 MHz, the PRBS spectral components below 4 MHz pass through the low-speed receiver. These components act on the decision threshold control signal as a noise. As a result, the simulation results give better performance since we neglected these effects in the simulation. However, the discrepancy would decrease if we increase the LF modulation index, since the carrier-to-noise ratio of the decision threshold control signal increases. As a proof of that, the amount of the power penalty reduction in the experiment and simulation becomes almost same to 2 dB at modulation index 29%.

In the experiment, we investigated the performance of our technique with single tone. However, since several LF tones are commonly used or generated in the practical system, we investigated the performance of our technique when several tones exist. For the multiple tone case, we define the modulation index below

$$m = \sqrt{m_1^2 + m_2^2 + \cdots} \qquad (3)$$

where m is the effective modulation index of multiple tone, m_i is the modulation index of the i_{th} LF tone. Fig. 5 is the simulation result that shows the effective modulation indices at 1 dB power penalty and the improved power penalties with our technique. As the number of LF tones increases, the modulation index at 1 dB power penalty and the improved power penalty decrease. In other words, the 'variable decision threshold technique' performs better in the system corrupted with multiple tones.

V. CONCLUSION

We proposed and demonstrated the 'variable decision threshold technique' to reduce the power penalty induced by LF tones. The proposed method can be implemented simply since it does not require any high speed circuits or complex optical devices. Our result shows that our technique performs better in the practical system where multiple tones exist.

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