Dynamic Birefringence of the Linear Optical Amplifier and Application in Optical Regeneration

Mingshan Zhao, Jan De Merlier, Geert Morthier, *Senior Member, IEEE*, and Roel G. Baets, *Senior Member, IEEE*

***Abstract*—Dynamic birefringence of the linear optical amplifier (LOA) is theoretically and experimentally investigated. Significant nonlinear variations of the state of polarization with the input power and bias current of the LOA have been found. Based on this nonlinear change of the state of polarization, an all-optical 2R regenerator is demonstrated. Under static operation, an extinction ratio (ER) improvement of 15 dB has been obtained for an input ER of 5 dB. With a degraded input signal, a receiver sensitivity improvement of over 3 dB at a bit-error rate (BER) of 10^{-9} has been found for 2.5 Gb/s. For 10 Gb/s, zero power penalty is observed. Significant improvements of ER for both 2.5 and 10 Gb/s are obtained.**

***Index Terms*—All-optical regeneration, birefringence, optical communication, polarization, semiconductor optical amplifiers.**

I. INTRODUCTION

RECENTLY, the linear optical amplifier (LOA) with an integrated vertical laser has been demonstrated as a new type of semiconductor optical amplifier (SOA) [1]. Due to its unique properties for linear amplification, the LOA has been getting much attention in the past two years. In addition to its excellent operating performance for linear amplification [2], the LOA has been shown to have potential applications in optical signal processing [3], [4]. The polarization properties of the LOA are of prime interest in most of its applications, especially for LOA-based interferometric structures used in optical signal processing. Besides the polarization-insensitive gain which is valuable in most applications, the nonlinear effect on the state of polarization of the output optical signal, which has been found in conventional SOAs as well [5], is also of importance. In a practical LOA, a small difference between the TE and TM effective indices exists owing to the guiding properties of the amplifier waveguides. Even though this effective birefringence is very small, and does not affect the polarization independent gain, a significant polarization direction variation at the output of the LOA can be induced. It is therefore interesting to investigate in detail the polarization variation induced by the effective birefringence. In this paper, we present the theoretical analysis and experimental demonstration of the evolutions of the state of polarization at the output of the LOA with input power level and bias current to the LOA. Significant nonlinear variations of the state of polarization have been found. The nonlinear behavior of the polarization due to the effective birefringence is insignificant for optical amplification and optical signal processing applications that are based on the gain and phase nonlinearities. On the other hand, optically controlled effective birefringence in the LOA can also be used as a new form of nonlinear operation for optical signal processing. As an example, an all-optical 2R regenerator based on the nonlinear effective birefringence in the LOA is demonstrated in this paper.

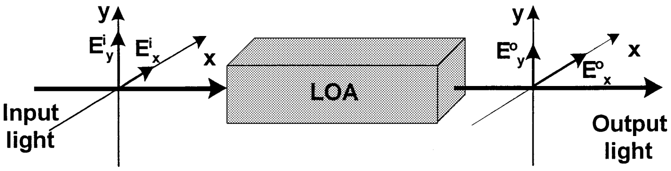

Fig. 1. The state of polarization of the input and output lights of the SOA.

II. THEORETICAL ANALYSIS

The LOA is an amplifier with an integrated vertical-cavity surface-emitting laser (VCSEL). The VCSEL and the amplifier share the same active region. The VCSEL operates along the entire length of the amplifier and the lasing action is perpendicular to the propagation of the amplified light. The circulating optical power of the VCSEL overlaps with the amplifier waveguide and acts as an optical feedback to maintain a constant local gain in the amplifier. The aim of this section is to derive the relative variations of the state of polarization of the output light with the input optical power level and bias current for a given input linear polarization. The effect of the LOA on the incident light can be described by the 2×2 Jones matrix, which relates the state of polarization of the light at the output to the state of polarization at the input. Given the definition of two orthogonal reference axes (e.g., x and y), perpendicular to the direction of propagation, as shown in Fig. 1, the complex amplitudes (E_x^o and E_y^o) of the Jones vector of the output light are related to the input complex amplitudes (E_x^i and E_y^i) by [6]

$$\begin{bmatrix} E_x^o \\ E_y^o \end{bmatrix} = Ce^{j\beta} \begin{bmatrix} B_{11}e^{j\delta_{11}} & B_{12}e^{j\delta_{12}} \\ B_{21}e^{j\delta_{21}} & 1 \end{bmatrix} \begin{bmatrix} E_x^i \\ E_y^i \end{bmatrix} \qquad (1)$$

where C and B_{11} are real numbers and are determined by the gain of the device. δ_{11} is determined by the phase shift between the outputs along the x and y axes. δ_{mn} and B_{mn} $(m, n = 1, 2, m \neq n)$ are determined by the conversion between the linear vibrations along x and y axes. For simplicity, we only

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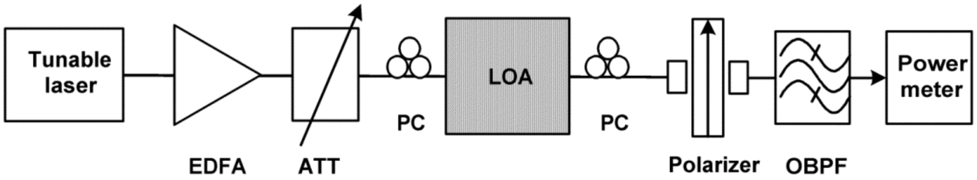

Fig. 2. Experimental setup for measuring the polarization rotation of the LOA. ATT: variable attenuator; PC: polarization controller; OBPF: optical bandpass filter.The polarizer is rotatable around the light beam axis. Two collimators are used for the in- and out-fiber coupling of the polarizer.

discuss δ_{11}, which represents the influence of the effective birefringence. If the x and y axes are chosen to correspond to the TM and TE polarization directions, respectively, δ_{11} will represent the differential phase shift between the TM and TE mode. For uniform refractive indices along the waveguide, one has

$$\delta_{11} = kL\left(n_{TM}^{a} - n_{TE}^{a}\right) \tag{2}$$

where $k = 2\pi/\lambda$ and n_{TE}^{a} and n_{TM}^{a} are the TE and TM effective indices averaged along the LOA. L is the length of the LOA.

However, because of carrier depletion due to stimulated emission, the LOA waveguide will not be uniform. The local effective refractive indices for TE and TM modes vary linearly with $N(z)$ as

$$n_{TE}(z) = n_{0TE} + \Gamma_{TE} N(z)\left(\frac{\partial n}{\partial N}\right) \tag{3a}$$

$$n_{TM}(z) = n_{0TM} + \Gamma_{TM} N(z)\left(\frac{\partial n}{\partial N}\right) \tag{3b}$$

where n_0 is the effective refractive index of the waveguide for zero free carrier density, Γ is the confinement factor, and ($\partial n/\partial N$) is the rate of change of the active region refractive index with the carrier density $N(z)$.

The local effective index is different for the TE and TM components of the optical signal owing to the TE/TM asymmetry in both the confinement factors and the unperturbed effective refractive indices of the LOA. Thus, the LOA exhibits an effective birefringence that changes with the carrier density.

The total TM/TE differential phase shift δ_{11} is then obtained by the following integration over the length of the LOA:

$$\delta_{11} = k\int_{0}^{L}[n_{TM}(z) - n_{TE}(z)]dz. \tag{4}$$

Clearly, the TM/TE differential phase shift δ_{11} changes with the carrier density due to the effective birefringence in the LOA. Thus, the state of polarization of the output light changes with the carrier density of the LOA.

In the LOA, the gain is clamped and both the free carrier density and the total photon density (photon density of both laser and optical signal) are constant when the input power level varies in the linear regime. Since there is no carrier density change, there will not be an effective birefringence change, and neither a polarization state change at the output. Once the linear power range is exceeded, the gain and thus the carrier density will drop rapidly. A significant change in the effective birefringence and thus in the polarization state of the output will be caused.

For a given input power in the linear regime, both the carrier density and the total photon density in the active region increase with increasing the bias current to keep a constant gain of the LOA. Therefore, the effective birefringence changes with the bias current, and thus the state of polarization at the output of the LOA changes when changing the bias current.

The state of polarization of the output light from the LOA is generally an elliptical polarization (A linear polarization can be seen as a special case of the elliptical polarization). It can be described with a number of elliptic parameters: azimuth θ, ellipticity e, amplitude A, and absolute phase δ. The relation between these parameters and the Jones components is given by [6]

$$\begin{bmatrix} E_x \\ E_y \end{bmatrix} = Ae^{j\delta}\begin{bmatrix} (\cos\theta\cos\varepsilon - j\sin\theta\sin\varepsilon) \\ (\sin\theta\cos\varepsilon + j\cos\theta\sin\varepsilon) \end{bmatrix} \tag{5}$$

where ε is the ellipticity angle, $e = \tan\varepsilon$.

The change of the state of polarization at the output of the LOA will be concisely specified by the changes of the azimuth θ, ellipticity e, and the amplitude A in the following experimental analysis.

III. EXPERIMENTS AND RESULTS

The evolution of the state of polarization at the output of the LOA with input power level and bias current has been experimentally investigated. The experimental setup is shown in Fig. 2. A CW light beam from a tunable laser (Model Tunics-plus, Photonetics) at 1550 nm is amplified by an erbium-doped fiber amplifier (EDFA) and then coupled into the LOA with its input polarization set to be at some angle with respect to the TE axis. The variable attenuator is used to change the input power to the LOA. The polarization controller after the LOA linearizes the polarization of the elliptically polarized output light when the LOA operates with a low input power in the linear regime. The polarizer before the power meter is used as an analyzer to check the evolution of the state of polarization of the output light from the LOA. By rotating the analyzer around the light beam axis, a minimum and a maximum detected power $P_{\min}$ and $P_{\max}$ can be found. At the minimum, the state of polarization at the input of the analyzer must be oriented orthogonal to the transmission axis of the analyzer. The elliptical polarization parameters, azimuth θ, ellipticity e, and amplitude A can be thus determined from the azimuth angle of the analyzer and the measured optical power $P_{\min}$ and $P_{\max}$. In our experiment, only the relative change of the azimuth θ with respect to the value in the linear regime is measured for varying input power and bias current to the LOA. The extinction ratio of the polar-

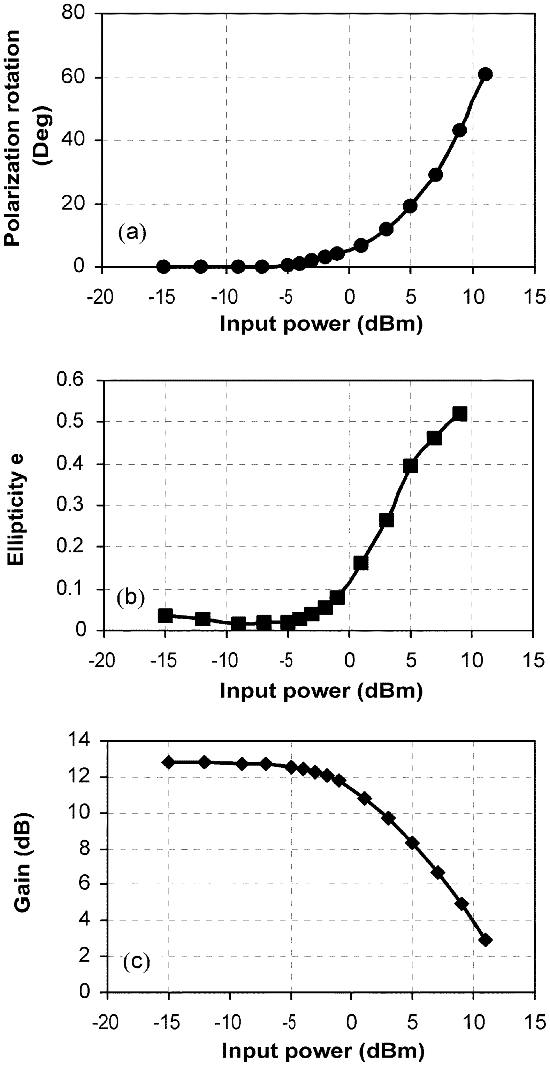

Fig. 3. Evolutions of the state of polarization at the output of the LOA versus the input power. (a) The relative evolution of the azimuth θ with respect to that for the linear regime. (b) The evolution of the ellipticity e with the variation of the input power. (c) Saturation characteristic of the LOA. Bias current to the LOA: 250 mA; signal wavelength: 1550 nm.

izer is $\rho \approx 0.0006$ (32 dB). The LOAs used in our experiments are from Genoa Corporation. The length of the devices is approximately 1 mm, and the gain is 13 dB. Two different LOAs were measured and both have a similar polarization dependence. Here we show the typical results of one of the two LOAs. The polarization dependence of gain of the LOA is 0.1 dB.

Fig. 3(a) shows the relative evolution of the azimuth θ with respect to the value in the linear regime, while Fig. 3(b) gives the evolution of e for varying input power. For the sake of comparison, the saturation characteristic is given in Fig. 3(c). The bias current to the LOA is 250 mA. It can be clearly seen that in the linear regime both θ and e are independent of the input power, which means that there is no change in the polarization state when the input power increases in the linear regime. Once the linear regime is exceeded, both θ and e change rapidly, showing a significant polarization rotation and a remarkable change in the degree of ellipticity with increasing input power. As A is a measure of the strength of the elliptical vibration and its square is proportional to the power of the light, its evolution depends on the saturation characteristic of the LOA.

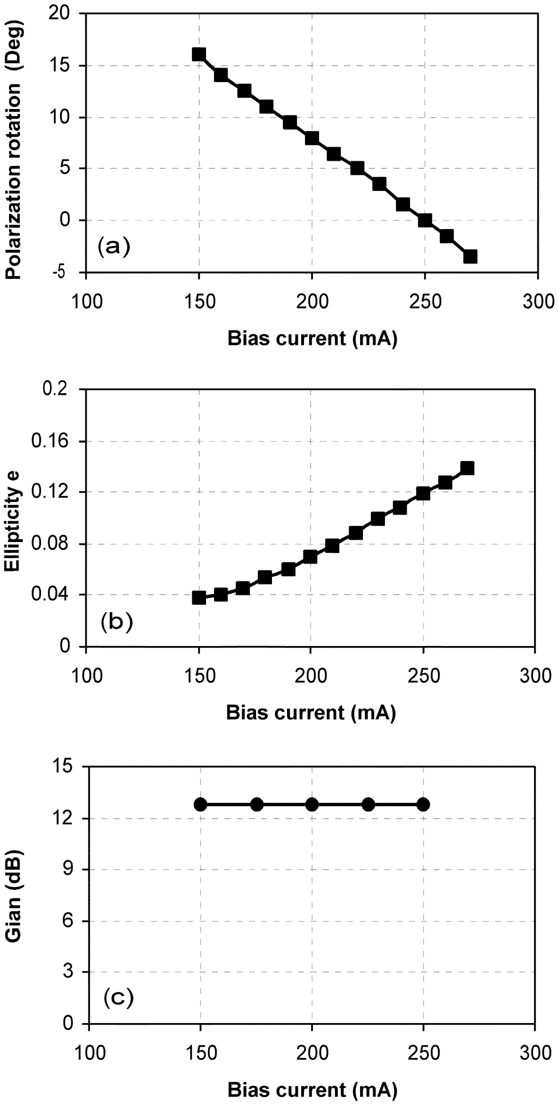

Fig. 4. Evolutions of the state of polarization at the output of the LOA versus the bias current in the linear regime. (a) The relative evolution of the azimuth θ with respect to that for 250 mA. (b) The evolution of the ellipticity e with the variation of the bias current. (c) Gain of the LOA. Input power -10 dBm; signal wavelength: 1550 nm.

Fig. 4 gives the evolution of the state of polarization at the output of the LOA with changing bias current. For the sake of comparison, the gain as a function of the bias current is given in Fig. 4(c). The input power to the LOA is -10 dBm. One can see that both the azimuth θ and ellipticity e change linearly with increasing bias current, while the gain remains constant.

Although the exact input polarization is difficult to measure since the LOA has a pigtail of standard single-mode fiber (SMF), the input polarization can be changed by using the polarization controller before the LOA. Significant polarization rotations but with different amounts are observed for different input polarizations, indicating input polarization sensitivity of the polarization rotation.

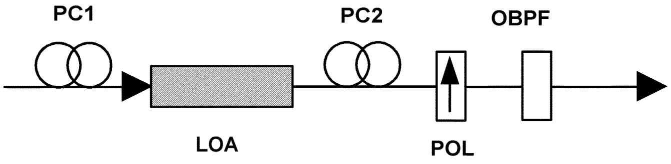

Fig. 5. Structure of the 2R regenerator based on polarization rotation in a single LOA.

It should be noted that the evolution of the polarization state as shown above is not exactly that of the LOA itself. It also contains contributions from the polarization controller after the LOA. As will be seen further, however, it is the overall evolution of the polarization state that is important and useful in the case of a standard SMF pigtailed LOA.

IV. Application in Optical Regeneration

The nonlinear behavior of the polarization due to the effective birefringence in LOAs does not affect the performance of the device in optical amplification applications, but it degrades performance in some optical signal processing applications, especially for LOA-based interferometric structures used in optical signal processing. In order to reduce this undesired influence, the TE and TM mode profiles should be made as similar as possible thus reducing the birefringence. On the other hand, an optically controlled effective birefringence in the LOA could also be used as a new type of nonlinearity for optical signal processing. Here, an all-optical 2R regenerator based on the nonlinear effective birefringence in the LOA is demonstrated.

The regenerator basically consists of an LOA followed by a polarization controller and a polarizer, as shown in Fig. 5. The operation of this regenerator is based on the polarization rotation induced by nonlinear birefringence in the LOA, which has been discussed above. For a linearly polarized injected light beam, the state of polarizaton at the output of the LOA will not change with varying input power level in the linear regime. Hence, by setting the polarizer so as to block the output beam, a very low output power (or a logical "0") is obtained below the saturation power of the LOA. Beyond the saturation power of the LOA, the state of polarization of the output from the LOA is changed due to the nonlinear birefringence effects. Both the orientation (i.e., azimuth) and the ellipticity of the polarization vary rapidly with the input power. The polarizer can no longer block the output from the LOA. Hence, a high power level (or a logical "1") is obtained at the output of the polarizer. At the same time, the LOA is saturated and its gain quickly drops with increasing input power, and thus the high power level of the output becomes saturated. As a result, an optical regeneration is realized.

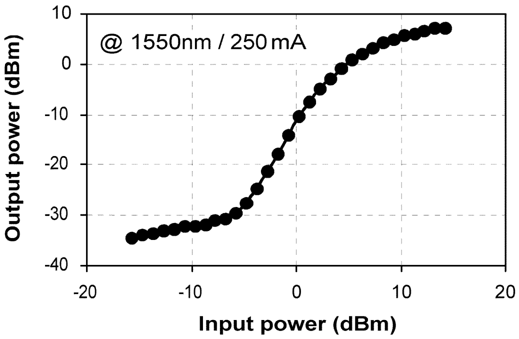

Fig. 6. Static regeneration characteristic.

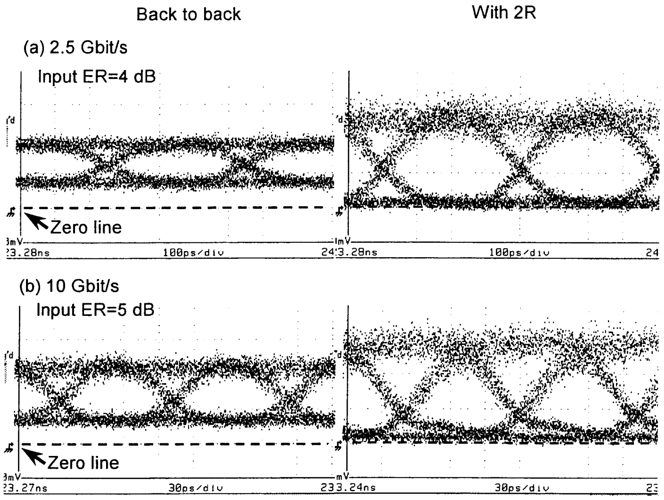

Fig. 7. Eye diagrams with and without 2R regenerator for 2.5 and 10 Gb/s.

In the 2R regenerator, the polarization controller after the LOA is used to linearize the polarization of the LOA output for low input power so that the power level at the output of the regenerator can be minimized for the logical "0." The polarization controller before the LOA is added to adjust the initial polarization of the input signal beam and thus to get an optimum polarization rotation effect. The optical bandpass filter (OBPF) is used to reduce the amplified spontaneous emission (ASE) from the LOA.

Fig. 6 gives the measured static transfer characteristics of the 2R regenerator. It can be seen that a quasi-perfect regeneration is achieved. An extinction ratio (ER) improvement of 15 dB can be obtained for an input ER of 5 dB. The regenerative capabilities of the regenerator under dynamic operation are demonstrated in Figs. 7–9, respectively. Fig. 7 shows the eye diagrams with and without the 2R regenerator for 10 Gb/s [nonreturn to zero (NRZ), $2^{31}-1$ pseudorandom bit sequence (PRBS)] and 2.5 Gb/s (NRZ, $2^{9}-1$ PRBS), respectively. Clearly, the input signal is regenerated. The eyes become much more open after the 2R regenerator. The improvement of ER is shown in Fig. 8. For an input signal with 6 dB ER, more than 5 dB of improvement in ER is obtained at 10 Gb/s. For 2.5 Gb/s, the ER improvement can be up to 8 dB for an input ER of 4 dB. Fig. 9 contains the results from the bit-error rate (BER) measurement for 2.5 Gb/s. A receiver sensitivity improvement of more than 3 dB has been obtained at a BER of 10^{-9} for a degraded signal. For 10 Gb/s, a power penalty of 0 dB was found at a BER of 10^{-9} and no receiver sensitivity improvement has been obtained. This is due to a polarization relaxation and the induced pattern effect at the falling edge of the signal, as seen in Fig. 7, as the LOA used

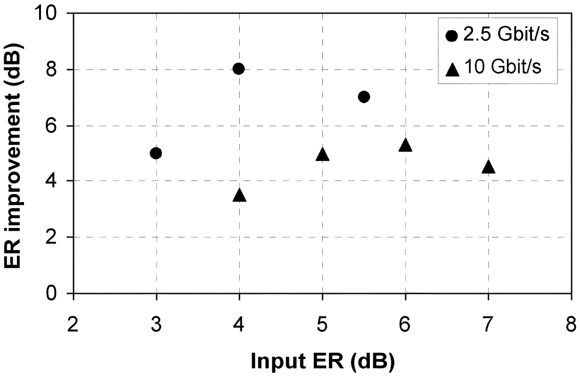

Fig. 8. ER improvement for 2.5 Gb/s (input power, 3 dBm) and 10 Gb/s (input power, 5 dBm).

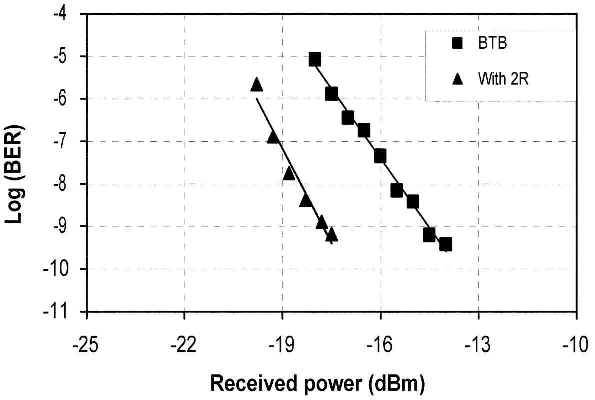

Fig. 9. BER measurement results with and without 2R for 2.5 Gb/s (input power, 3 dBm).

here is not specifically designed for the application proposed above. LOAs with high speed and weak polarization relaxation effect could be fabricated that are better adapted to the optical regeneration based on the nonlinear polarization rotation.

The advantages of this new scheme of all-optical 2R regeneration are its immunity against small-signal distortion in the "0" level and a potentially large ER improvement. This results from the flat gain response for small-signal powers and the sudden drop in gain as soon as the linear power range is exceeded. It should be noted, however, that control of input polarization is required in this new scheme due to the input polarization sensitivity of the polarization rotation, which may be disadvantageous in some circumstances. But it could be extended to an input polarization-insensitive 2R regenerator with some polarization diversity scheme.

V. CONCLUSION

The LOA has been shown to exhibit polarization rotation due to the nonlinear effective birefringence. Both the orientation and ellipticity of the polarization of the output light from the LOA change with increasing input power when the LOA is saturated, but they do not change in the linear regime. Based on this nonlinear change of the state of polarization with input optical power, an all-optical 2R regenerator can be realized using a single LOA. Under static operation, an ER improvement of 19 dB has been obtained for an input ER of 10 dB and a 15-dB ER improvement for an input ER of 5 dB. With a degraded input signal, a receiver sensitivity improvement of over 3 dB at a BER of 10^{-9} has been found for 2.5 Gb/s. For 10 Gb/s, zero power penalty is observed. Significant improvements of ER are obtained for both 2.5 and 10 Gb/s.

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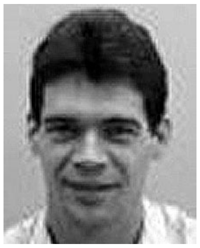

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