Sensitivity Improvement for NRZ Optical Systems using NALM and Narrow-Band Filter

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Nonlinear amplifying loop mirror (NALM) has been shown experimentally to improve the system performance by restoring the extinction ratio (*ER*) in the input signals [1], and by reducing the input amplified spontaneous emission noise (ASE) [2] for systems using return-to-zero (RZ) modulation format. Theoretical treatment for such improvement, from the system point of view, has yet been provided. Here, we present a theoretical analysis on optical systems using NALM with a narrow-band optical filter and under nonreturn-to-zero (NRZ) modulation format. We show these arrangement can eliminate *BER* floor, improve sensitivity, and achieve high system margins. The results can be easily extended to systems using other modulation formats.

Figure 1 shows the system schematic for our analysis. Optical filter 1 (3-dB bandwidth, B_o) is used to obtain a high input optical signal-to-noise ratio SNR_{in} before the NALM (with coupler splitting ratio of α and $1-\alpha$ as shown), and filter 2 (same bandwidth with filter 1) is to minimize the ASE influence from the amplifier located inside the NALM. We assume that (1) a maximum phase shift, $\Delta\Phi_{max}$, introduced by the NALM is π; and (2) the optical amplifier gain of the NALM can fully compensate for the insertion loss caused by the NALM and the optical filter 2.

Figure 2 illustrates how NALM is used to restore ER_{in}, and the reduction of ASE in the input signals. The power output from the NALM exhibits a periodic behavior, depending on the total phase shift and input power given by $P_{out}=P_{in}[\alpha^2+(1-\alpha)^2-2\alpha(1-\alpha)\cos\Delta\Phi]$ where $\Delta\Phi$ is proportional to P_{in} [3]. The "Mark" state (with ASE) is set at the operating condition such that a total phase shift of π, and thus lossless transmission, is experienced by the signals. Accordingly, the transmission of "Space" state (with ASE) will be less than unity. In our analysis, mean values of "Mark" (with ASE) and "Space" (with ASE) are used. The phase shift of "Space" (with ASE) can be easily derived from the given ER_{in} and SNR_{in}. It can be shown that the extinction ratio at the output of the NALM, ER_{out}, is :

$$ER_{out} = \frac{ER_{in}}{\alpha^2 + (1-\alpha)^2 - 2\alpha(1-\alpha)\cos\left[\dfrac{2\cdot SNR_{in} + 1 + ER_{in}}{2\cdot SNR_{in}\cdot ER_{in} + 1 + ER_{in}}\pi\right]} \tag{1}$$

We only consider the case when SNR_{in} is small and ASE from the optical amplifier in the NALM is negligible. Neglecting both signal- and ASE-shot noises and adopting the method from [4], we can show that the Q-factor evaluated at the receiver (3-dB electrical bandwidth B_e) for NRZ system with a PIN detector is:

$$Q = \frac{2\sqrt{B_o / B_e}\cdot\dfrac{ER_{out}-1}{ER_{out}+1}}{\sqrt{\dfrac{4ER_{out}}{R\cdot SNR_{in}\cdot(ER_{out}+1)} + \dfrac{1}{(R\cdot SNR_{in})^2} + \dfrac{i_{cir}^2\cdot B_0}{I_S^2\cdot T_r^2}} + \sqrt{\dfrac{4}{R\cdot SNR_{in}\cdot(ER_{out}+1)} + \dfrac{1}{(R\cdot SNR_{in})^2} + \dfrac{i_{cir}^2\cdot B_0}{I_S^2\cdot T_r^2}}} \tag{2}$$

where
$$R = \frac{2\cdot ER_{in}\cdot(ER_{out}+1)}{(ER_{out}+ER_{in})(1+ER_{in})}$$

In this expression, $T_r = ER_{in}(ER_{out}+1)/ER_{out}(ER_{in}+1)$ is the signal transmissivity [3], R is the improvement factor for SNR_{in} , I_S is the signal photon current (proportional to the average received power), and i_{cir} is the circuit thermal noise (in pA/Hz$^{1/2}$). The consecutive three terms inside the square roots in the denominator are signal-ASE beat noise, ASE-ASE beat noise and thermal noise, respectively. Note that either the improvement factor R or the transmissivity T_r will be unity, i.e., $ER_{out} = ER_{in}$, when both NALM and optical filter 2 are removed from the system.

Figure 3 shows the comparison of system *BER* versus received optical power for different ER_{in} and SNR_{in} with (solid line) and without NALM (dash line). We used the following parameters: B_o=0.1nm, α=0.5, i_{cir}=5pA/Hz$^{1/2}$, B_e=1.7GHz (signal bit-rate = 2.5Gb/s) in the calculations. Two improvements can immediately be observed for system employing NALM. There is a significant improvement in sensitivity (~2.5 dB) and elimination of *BER* floor over system without NALM. These improvements are largely derived from the improvement in extinction ratio in the signal. In Fig. 3, the *BER* curve C with NALM (ER_{in}=4 and SNR_{in}=25) almost coincides with curve A but without NALM (ER_{in}=8 and SNR_{in}=50), suggesting NALM system can achieve better system margins for *ER* and *SNR* than those without.

In summary, we show theoretically that there is (1) a substantial improvement in sensitivity, (2) *BER* floor elimination, and (3) better system margins for optical systems employing NALM under NRZ modulation format. The methodology and the results can easily be extended to different modulation formats.

Reference:

1. B. E. Olsson and P. A. Anderson, "Noise Filtering with the Nonlinear Optical Loop Mirror", *J. Lightwave Technol.*, vol. 13, pp. 213-215, 1995.
2. B. E. Olsson and P. A. Anderson, "Extinction Ratio Improvement Using the Nonlinear Optical Loop Mirror", *IEEE Photon Technol. Lett.*, vol. 7, pp. 120-122, 1995.
3. K. Smith, N. J. Doran and P. G. J. Wigley, "Pulse shaping, compression, and pedestal suppression employing a nonlinear-optical loop mirror", *Opt. Lett.*, vol. 15, pp. 1294-1296, 1990.
4. J. Song, C. Fan, Y. Yao and C. Feng, "Signal self-restoration characteristic and bit-error-rate performance of terrestrial cascaded Erbium-doped fiber amplifier systems", *IEE Proc.-Optoelectron.*, vol. 142, pp. 94-96, 1995.

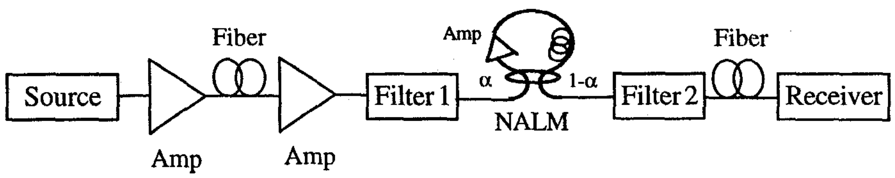

Fig. 1 The optical system used for the analysis

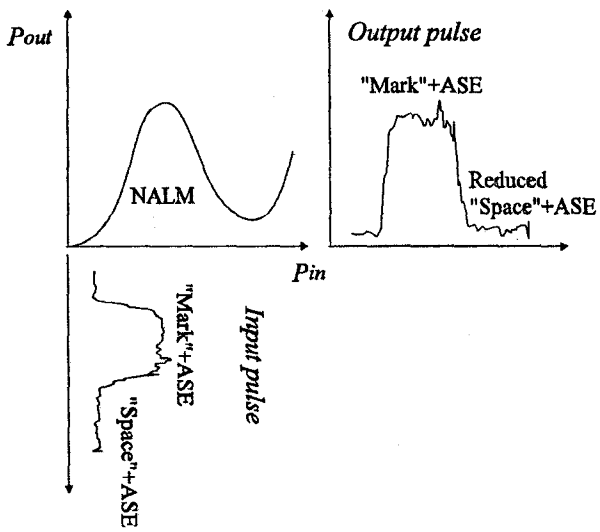

Fig. 2 Illustration of *ER* restoration and ASE reduction.

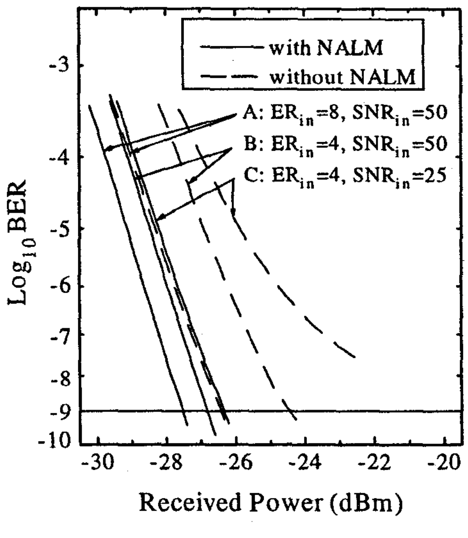

Fig. 3 *BER* versus received power without and with NALM at various ER_{in} and SNR_{in} values.