Fundamental Switching Contrast and Extinction Ratio Degradations in Ultrafast All-Optical Switching using Nonlinear Optical Loop Mirrors

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Introduction: Nonlinear optical loop mirrors (NOLM) [1] and nonlinear amplifying loop mirrors (NALM) [2] are two good high-speed time-division multi-/demultiplexers. Two key parameters in determining their performance are the switching contrast and the extinction ratio. As shown in Figure 1, the switching contrast (in transmit state) is (P_{t1}/P_{r0}) while the extinction ratio (in transmit state) is (P_{t1}/P_{t0}). The middle pulse experiences both self-phase modulation (SPM) and cross-phase modulation (XPM) (by the control pulse) while the first and the third pulses experience no XPM. A poor switching contrast degrades the extinction ratio of the switched signal, which in turn degrades the bit-error-rate (BER) performance. Although complete switching can be achieved in NALM theoretically, only incomplete switching was shown in most of the experimental results reported previously [2]-[3]. In this paper, we explain the degradation both theoretically and numerically.

Asymmetric Directional Gain in NALM: In the conventional analysis of the switching characteristics of NALM, it was assumed that the overall gains of the two counter-propagating signals are the same and the splitting ratio of the coupler is exactly 50/50. Thus, the maximum switching contrast, which is defined as the ratio of the maximum transmitted power to the minimum reflected power for the same input power, can go to infinity and 100% switching can be achieved. Practically, the two directional gains inside the loop are not always symmetric. Consider when the loop has directional gains, G_1 and G_2, and the coupler has splitting ratio, α and $(1-\alpha)$, as shown in Figure 1. The expressions for the transmitted intensity $|E_t|^2$ appeared in [2] can be re-written as:

$$|E_t|^2 = G_1(1-\alpha)^2|E_{in}|^2 + G_2\alpha^2|E_{in}|^2 - 2\sqrt{G_1G_2}\alpha(1-\alpha)|E_{in}|^2 cos[|E_{in}|^2(G_1(1-\alpha)-\alpha)\tfrac{2\pi n_2 L}{\lambda}] \quad (1)$$

$$\text{Maximum switching contrast} = \frac{G_1(1-\alpha)^2+G_2\alpha^2+2\alpha(1-\alpha)\sqrt{G_1G_2}}{\alpha(1-\alpha)(G_1+G_2-2\sqrt{G_1G_2})} \quad (2)$$

For $\alpha = 0.5$, the expression (2) can be simplified to $\left(\frac{\sqrt{\Delta G}+1}{\sqrt{\Delta G}-1}\right)^2$, where $|E_{in}|^2$ is the input intensity and ΔG is the directional gain difference with $\Delta G = (G_1/G_2)$. Figure 2 shows the dependence of the switching contrast for different gain directional differences. It is shown that for high asymmetric directional gain, the degradation in switching contrast is quite severe. For example, the switching contrast is 25 dB for 1 dB gain difference and it deteriorates to 13 dB for 3 dB gain difference.

Analysis: The analysis above is mainly based on routing which involves the intensity-dependent phase shift due to SPM only. Now we consider the effects of asymmetric gain and input pulse shape on individual pulse switching. The induced switching contrast and extinction ratio degradation can be analysed by means of numerical integration of a set of coupled nonlinear Schrödinger equations with initial values: $A_s = \sqrt{(1-\alpha)G_1P_s}$, $A_r = i\sqrt{\alpha P_s}$, $A_p = \sqrt{G_1P_p}$.

$$\frac{\partial A_p}{\partial \xi} + \frac{i}{2}sgn(\beta_p)\frac{\partial^2 A_p}{\partial \tau^2} + \frac{\Gamma}{2}L_{Dp}A_p = i\gamma_p L_{Dp}(|A_p|^2 + 2*|A_s|^2)A_p \quad (3)$$

$$\frac{\partial A_s}{\partial \xi} + \frac{i}{2}sgn(\beta_s)\frac{\partial^2 A_s}{\partial \tau^2} + \frac{\Gamma}{2}L_{Ds}A_s = i\gamma_s L_{Ds}(|A_s|^2 + 2*|A_p|^2)A_s \quad (4)$$

$$\frac{\partial A_r}{\partial \xi} + \frac{i}{2}sgn(\beta_r)\frac{\partial^2 A_r}{\partial \tau^2} + \frac{\Gamma}{2}L_{Dr}A_r = i\gamma_r L_{Dr}|A_r|^2 A_r \quad (5)$$

where P_k is the input power, A_k is the normalized amplitude, γ_k is the nonlinear coefficient, β_k is the group-velocity dispersion (GVD) coefficient, L_{Dk} is the dispersion length, Γ is the fiber loss per km, $sgn(\cdot)$ is the signum function and the subscript $k \in (p,s,r)$ indicates the control, copropagating signal and counterpropagating signal respectively. The transmitted power is $|\sqrt{1-\alpha}A_s + i\sqrt{\alpha G_2}A_r|^2$ while the reflected power is $|i\sqrt{\alpha}A_s + \sqrt{(1-\alpha)G_2}A_r|^2$.

Assume that a 1-Gb/s signal pulse stream at 1555nm with pulse width 6ps (FWHM) and peak power 1mW is input into an NALM as in Figure 1. A 100-Mb/s control pulse stream at 1551nm with pulse width 10ps (FWHM) and peak power 8mW is injected into a dispersion-shifted fiber loop with zero-dispersion wavelength at 1553nm so as to minimize walkoff. The fiber loss is 0.25dB/km. The loop length is optimized to achieve maximum switching contrast. Figure 3 shows the experimental results of the pulse stream with the middle pulse switched out by an NALM as in Figure 1. It shows that the pedestal remained is very noticeable and will lead to severe extinction ratio degradation. Three common input pulse shapes: Gaussian, hyperbolic-secant and Lorentzian, are considered in our numerical analysis using expressions (3)-(5). The Lorentzian pulse shape gives the highest pedestal whereas the Gaussian gives the lowest. Figure 4(a) shows the switching contrast of the transmitted pulse stream for different directional gain differences and Figure 4(b) shows the corresponding extinction ratios. It is shown that Gaussian pulse has the highest switching contrast for zero gain difference due to its lowest pedestal but it gives the greatest degradation when the gain difference deviates from zero. On the other hand, the extinction ratio performance for the three pulse shapes seems to be the same. Since the pedestal power is usually small no matter which kind of pulse shape it is, its SPM-induced phase shift by the NALM is small and the NALM acts as a reflector to reflect such low-power pedestal. Therefore, the extinction ratio is improved and is independent of the input pulse shape.

Conclusion: It was clearly shown in previous reports [2-3] that 100% switching could not be achieved in NOLM/NALM experimentally. This work provides an explanation to such phenomenon. In summary, we have shown that in ultrafast all-optical switching using NOLM/NALM, the extinction/contrast ratio is degraded due to the pedestal effect and directional gain difference. Possible solutions to solve this problem are to use the walk-off effect or to use an additional NOLM to improve the extinction ratio.

References:

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3. E. Yamada, et al., "Reduction of Amplified Spontaneous Emission from a Transmitted Soliton Signal Using a Nonlinear Amplifying Loop Mirror and a Nonlinear Optical Loop Mirror", *IEEE J. Quantum Electron.*, vol. 30, no. 8, pp. 1842-1850, 1994.

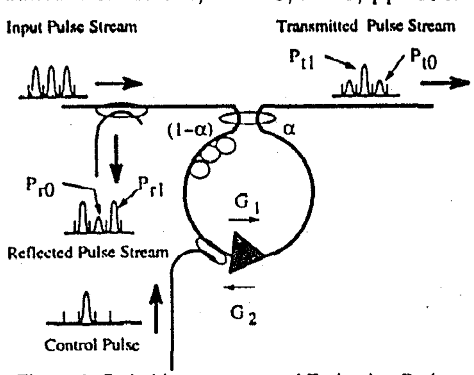

Figure 1: Switching contrast and Extinction Ratio in NOLM/NALM

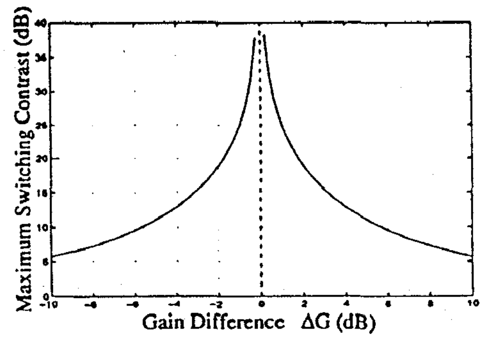

Figure 2: Maximum switching contrast vs gain difference (ΔG)

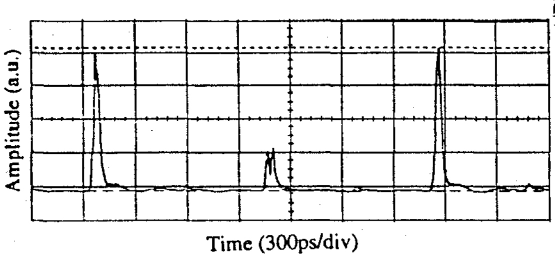

Figure 3: Experimental Result: Waveform of reflected pulse stream. (Middle pulse switched out)

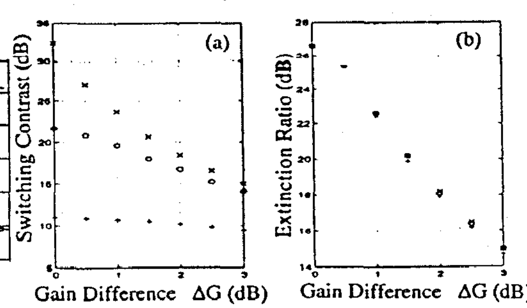

Figure 4: (a) Switching contrast, (b) extinction ratio, vs gain difference for Gaussian(x), Sech(o), and Lorentzian (+) pulse shape.