J. Opt. Commun. 19 (1998) 2, 67–71

Journal of Optical Communications

Switching Contrast and Extinction Ratio Degradations due to Asymmetric Directional Gain/Loss and Pulse Pedestal in Optical Switching using Nonlinear Optical Loop Mirrors

Chun-Kit Chan, Lian-Kuan Chen, Kwok-Wai Cheung

Summary

For ultrahigh speed optical TDM systems using nonlinear optical/amplifying loop mirrors (NOLM/NALM) to perform multi-/demultiplexing, the switching contrast and the extinction ratio are the two key parameters affecting the system's bit-error-rate performance. We point out that due to the asymmetric gain/loss of the two counter-propagating directions in the loop and the pulse pedestal effects, both of the above parameters are always degraded. In this paper, theoretical and numerical analyses of the such degradations based on both self-phase modulation (SPM) and cross-phase modulation (XPM) with different input pulse shapes are presented. The results provide better understanding of the performance limitation of loop mirrors as ultrafast multi-/demultiplexers.

1 Introduction

Recently, ultrahigh speed all-optical time-division multiplexed (TDM) systems are of great interest. A single-wavelength TDM system with bit rate as high as 400 Gbit/s has been demonstrated [1]. In order to perform multi-/demultiplexing in such high-speed optical networks, optical switching devices with ultrafast response are required. Much work has been concentrated on nonlinear optical loop mirrors (NOLM) [2] and nonlinear amplifying loop mirrors (NALM) [3] since they are fiber-based devices and thus they are simple and easy to realize. NALM has an optical amplifier placed asymmetrically within the loop, and so NOLM is a special case of NALM with unity gain.

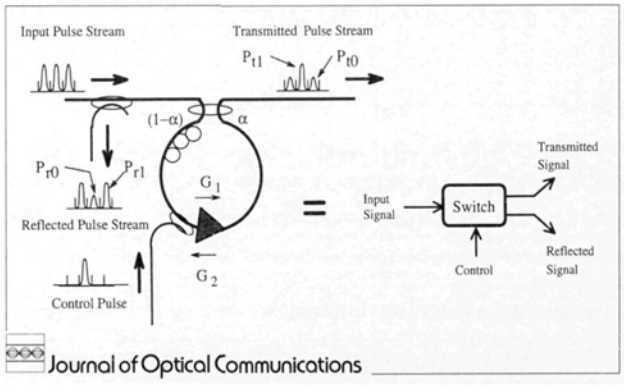

Fig. 1: Switching contrast and extinction ratio in NOLM/NALM

Switching contrast and extinction ratio are two key parameters determining the performance of a switching device. There is a subtle difference between them: the former is defined as the relative power ratio of the switched and unswitched signals whereas the latter is that of the switched '1' and '0' (see Fig. 1). Thus we have:

$$\text{Switching Contrast} = \begin{cases} \dfrac{P_{t1}}{P_{r0}} \text{ (in transmit state)} \\ \dfrac{P_{r1}}{P_{t0}} \text{ (in reflected state)} \end{cases}$$

$$\text{Extinction Ratio} = \begin{cases} \dfrac{P_{t1}}{P_{t0}} \text{ (in transmit state)} \\ \dfrac{P_{r1}}{P_{r0}} \text{ (in reflect state)} \end{cases} \quad (1)$$

Note that, in Figure 1, 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. Therefore, all four parameters in (1) have different values and have different significances. For instance, in our high-speed all-optical tunable-channel multiaccess network demonstration [4] which used NALM as ultrafast channel multi/demultiplexer, the switching contrast and the extinction ratio in the reflect state determine the channel multiplexing effectiveness while those in the transmit state affect the channel demultiplexing effectiveness. 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

Address of authors:

Department of Information Engineering
The Chinese University of Hong Kong
Shatin, N.T., Hong Kong

Received 19 July 1996

previously [5, 6]. Practically, the overall gains of the two counter-propagating signals after passing through the loop are not necessary the same and thus leads to the degradation in the switching contrast of the NOLM/NALM as will be shown later. Moreover, we also show that the pulse's pedestal effect also leads to switching contrast and extinction ratio degradations. In this paper, we present these causes and effects of such degradation both theoretically and numerically. The results can explain the observed functionality degradation of NOLM/NALM and can facilitate the design of NOLM/NALM for ultrafast optical switching.

2 Asymmetric directional gain/loss in NALM

In the conventional analysis of the switching characteristics of NALM, it is 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. When the two signals recombine at the coupler, they should have equal power levels but with different phase shifts [3]. The resultant transmitted and reflected power are:

$$|E_r|^2 = \frac{1}{2}G|E_{in}|^2\left\{1+\cos\left[|E_{in}|^2(G-1)\frac{\pi n_2 L}{\lambda}\right]\right\} \quad (2)$$

$$|E_t|^2 = \frac{1}{2}G|E_{in}|^2\left\{1-\cos\left[|E_{in}|^2(G-1)\frac{\pi n_2 L}{\lambda}\right]\right\} \quad (3)$$

where G is the gain of the optical amplifier, $|E_{in}|^2$ is the input intensity, $|E_t|^2$ is the transmitted intensity and $|E_r|^2$ is the reflected intensity. The maximum switching contrast is defined as the ratio of the maximum transmitted power to the minimum reflected power for the same input power. The switching characteristic is shown in Fig. 2. Note the maximum switching contrast can go to infinity and thus 100% switching can be achieved. Practically, this is not always valid due to the asymmetric gain inside the loop. The possible reasons for the asymmetric gain are summarized as follows [7]:

(a) Types of Optical Amplifiers used

The gain in the forward and backward directions may not be the same in most types of optical amplifiers, including fiber amplifiers and semiconductor amplifiers. The effect of asymmetric directional gain is even more significant in semiconductor amplifiers and Raman amplifiers.

(b) Pumping Directions in Fiber Amplifiers

When the fiber amplifier is either forward pumped or backward pumped or even pumped bidirectionally, optical gains for the two directions will be different.

(c) Asymmetric Splitting Ratio of the Coupler

Practically, unbalanced normal mode loss [8] often exists in fiber couplers and thus it is quite difficult to achieve an exact 50/50 splitting ratio. Such power asymmetry of two counter-propagating pulse streams imposes a fundamental finite bound in the switching contrast.

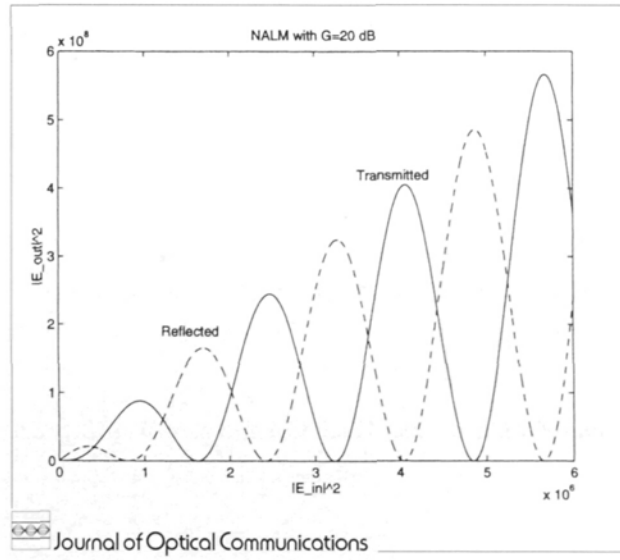

Fig. 2: Switching characteristics of an NALM with symmetric gain and 50/50 coupler splitting ratio

(d) Intensity-dependent Loss

The amplified signal experiences the stimulated Rayleigh back-scattering [5] and this leads to asymmetric overall gain/loss between the two counter-propagating signals in the loop.

3 Switching contrast degradation in NALM due to asymmetric gain/loss and pedestal effects

Consider when the total gains in two counter-propagating directions are G_1 and G_2, and the coupler has splitting ratio, α and $(1-\alpha)$, as shown in Fig. 1. (2) and (3) can be re-written as:

$$|E_r|^2 = \alpha(1-\alpha)|E_{in}|^2\left\{G_1+G_2+2\sqrt{G_1G_2}\cos\left[|E_{in}|^2(G_1(1-\alpha)-\alpha)\frac{2\pi n_2 L}{\lambda}\right]\right\} \quad (4)$$

$$|E_t|^2 = G_1(1-\alpha)^2|E_{in}|^2 + G_2\alpha^2|E_{in}|^2 - 2\sqrt{G_1G_2}\alpha(1-\alpha)|E_{in}|^2\cos\left[|E_{in}|^2(G_1(1-\alpha)-\alpha)\frac{2\pi n_2 L}{\lambda}\right] \quad (5)$$

Maximum switching contrast =

$$\frac{G_1(1-\alpha)^2+G_2\alpha^2+2\alpha(1-\alpha)\sqrt{G_1G_2}}{\alpha(1-\alpha)\left(G_1G_2-2\sqrt{G_1G_2}\right)} \quad (6)$$

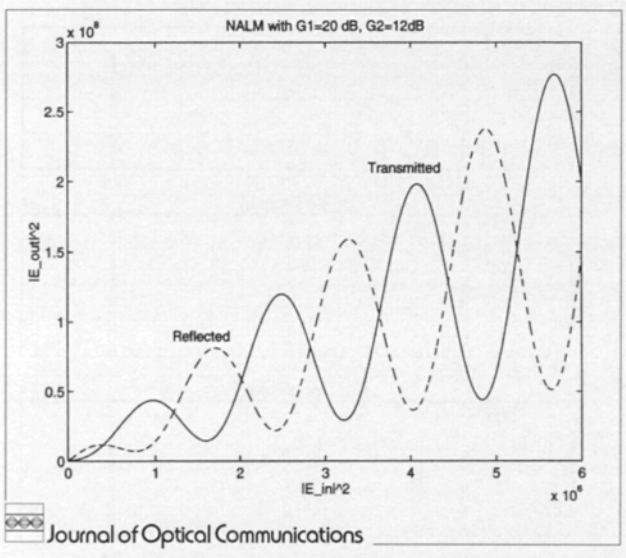

Fig. 3: Switching characteristics of an NALM with asymmetric gain (8dB difference) and 50/50 coupler splitting ratio

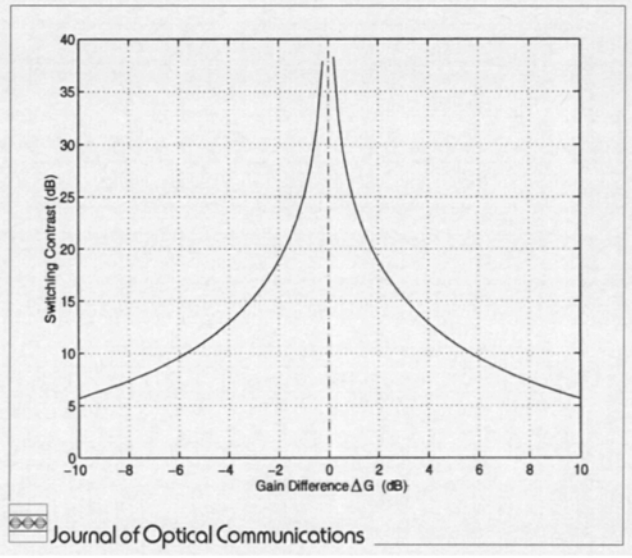

Fig. 4: Maximum switching contrast vs gain difference ΔG

For $\alpha = 0.5$,

Maximum switching contrast =

$$\left(\frac{\sqrt{G_1}+\sqrt{G_2}}{\sqrt{G_1}-\sqrt{G_2}}\right)^2 = \left(\frac{\sqrt{\Delta G}+1}{\sqrt{\Delta G}-1}\right)^2 \qquad (7)$$

where ΔG is the directional gain difference with $\Delta G = (G_1/G_2)$. Figure 3 shows the intensity dependent switching characteristic of a NALM with a 50/50 coupler and Fig. 4 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.

The analysis above is mainly based on pulse stream self-switching which involves the intensity-dependent phase shift due to SPM only. Now we consider the effects of asymmetric directional gain and input pulse shape on individual pulse switching in which the intensity dependent phase shift is due to both SPM and XPM. The induced switching contrast and extinction ratio degradation can be analysed by means of numerical integration of a set of coupled nonlinear Schrödinger equations [9] with initial values:

$$A_s = \sqrt{(1-\alpha)G_1 P_s},\quad A_r = i\sqrt{\alpha P_s},\quad A_p = \sqrt{G_1 P_p}.$$

$$\frac{\partial A_p}{\partial \xi} + \frac{i}{2}\mathrm{sgn}(\beta_p)\frac{\partial^2 A_p}{\partial \tau^2} + \frac{\Gamma}{2}L_{Dp} = i\gamma_p L_{Dp}\left(|A_p|^2 + 2*|A_s|^2\right)A_p \qquad (8)$$

$$\frac{\partial A_s}{\partial \xi} + \frac{i}{2}\mathrm{sgn}(\beta_s)\frac{\partial^2 A_s}{\partial \tau^2} + \frac{\Gamma}{2}L_{Ds} = i\gamma_s L_{Ds}\left(|A_s|^2 + 2*|A_p|^2\right)A_s \qquad (9)$$

$$\frac{\partial A_r}{\partial \xi} + \frac{i}{2}\mathrm{sgn}(\beta_r)\frac{\partial^2 A_r}{\partial r^2} + \frac{\Gamma}{2}L_{Dr} = i\gamma_r L_{Dr}|A_r|^2 A_r \qquad (10)$$

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 and sgn(·) is the signum function and the subscript $k \in$ (p, s, r) indicate the control, copropagating signal and counterpropagating signal respectively. The transmitted and reflected power are:

$$\text{Transmitted power } P_t = \left|\sqrt{1-\alpha}A_s + i\sqrt{\alpha G_2}A_r\right|^2 \qquad (11)$$

$$\text{Reflected power } P_r = \left|i\sqrt{\alpha}A_s + \sqrt{(1-\alpha)G_2}A_r\right|^2. \qquad (12)$$

Assume that a 1Gbit/s signal pulse stream at 1555 nm with pulse width 6 ps (FWHM) and peak power 5 mW is input into an NALM with α = 0.5 as in Fig. 1. A 100 Mbit/s control pulse stream at 1551 nm with pulse width 10 ps (FWHM) and peak power 40 mW is injected into a dispersion-shifted fiber loop with zero-dispersion wavelength at 1553 nm so as to minimize walkoff. The fiber loss is 0.25 dB/km. The control pulse stream is aligned with the signal pulse stream. It is assumed that there is negligible interaction between the two counter-propagating pulse streams. The loop length is optimized to achieve maximum extinction ratio.

Figure 5 shows the simulated pulse shapes at the outputs of a NALM with symmetric gain. It is shown that even under ideal conditions, the pedestal of the pulse after switching leads to a severe extinction ratio degradation. We have considered three common input pulse shapes: Gaussian, hyperbolic-secant and Lorentzian. Figs. 5 and 6 show the transmitted pulse waveforms for the three different pulse shapes in the cases of symmetric and asymmetric directional gains. The extinction ratio degradation is obvious and the pedestal remained

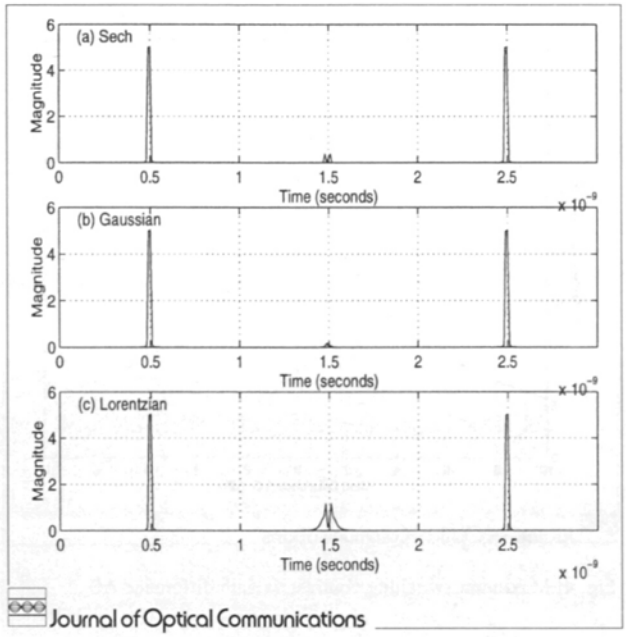

Fig. 5: Waveforms of transmitted pulse under symmetric directional gain for three different input pulse shapes: (a) Sech, (b) Gaussian, and (c) Lorentzian; the control and the signal have the same pulse shape

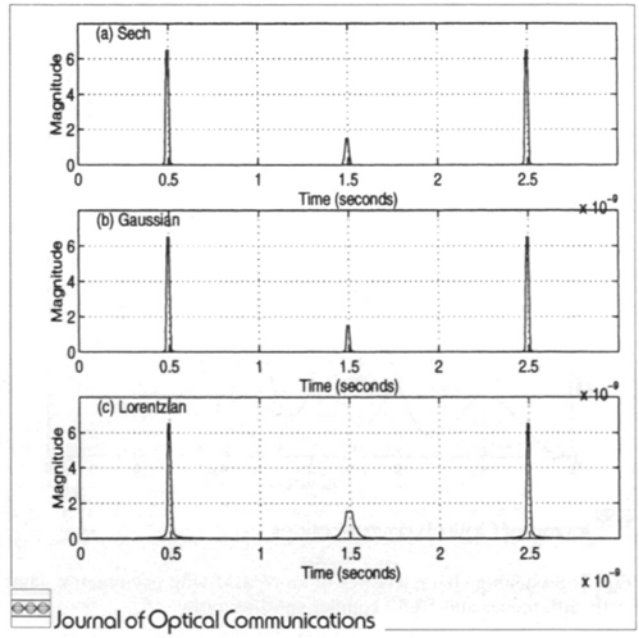

Fig. 6: Waveforms of transmitted pulse under asymmetric directional gain (2 dB difference) for three different input pulse shapes: (a) Sech, (b) Gaussian, and (c) Lorentzian; the control and the signal have the same pulse shape

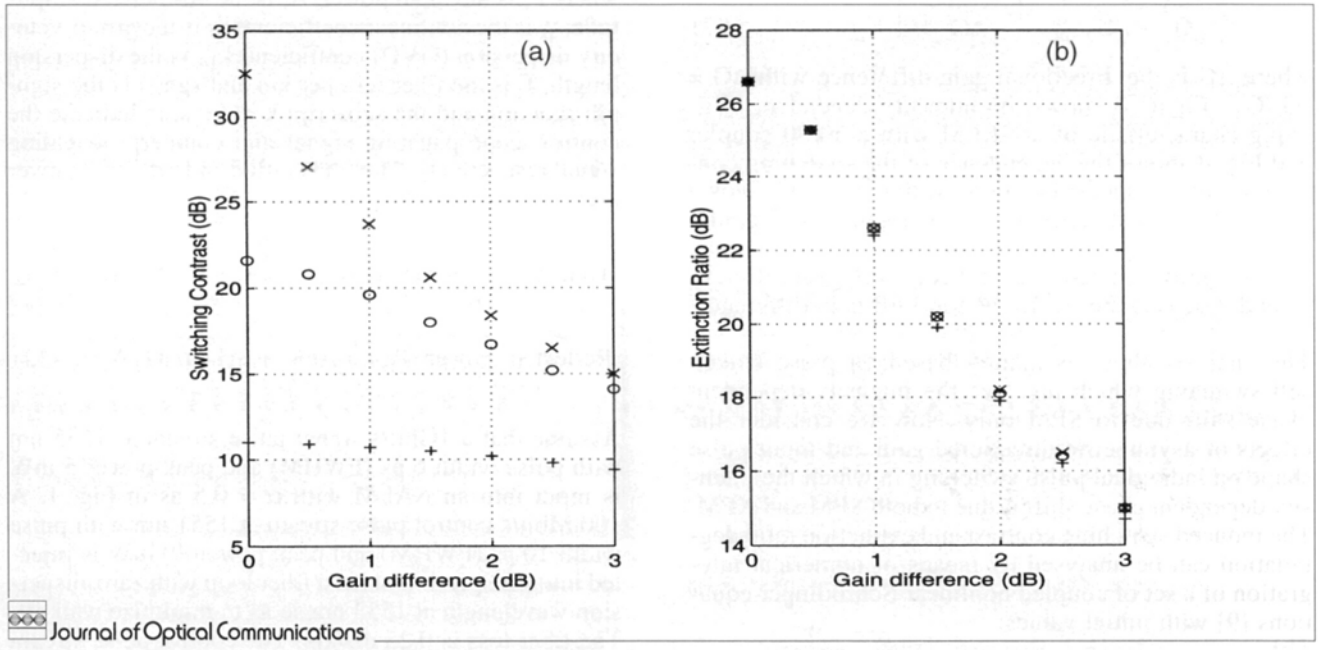

Fig. 7: (a) Switching contrast, (b) extinction ratio, vs gain difference for Gaussian (x), Sech (o), and Lorentzian (+) pulse shapes

after switching for different pulse shapes is noticeable. It is shown that the Lorentzian pulse shape gives the highest pedestal whereas the Gaussian gives the lowest. Figure 7(a) shows the switching contrast of the transmitted pulse stream for different directional gain differences and Fig. 7(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. Moreover, the degradation discrepancy among the three different pulse shapes reduces as the gain difference increases. The pedestal effect is only significant at small gain difference and imposes the fundamental finite bound on the switching contrast. 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 back such low-power pedestal.

Therefore, the extinction ratio of the transmitted pulse stream is improved and is independent of the input pulse shape.

4 Conclusion

It was clearly shown in previous reports 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 [9] or to use an additional NOLM [10] to improve the extinction ratio.

References

[1] S. Kawanishi, et al.: "400 Gbit/s TDM Transmission of 0.98 ps Pulses over 40 km Employing Dispersion Slope Compensation"; OFC'96, San Diego, CA, Paper PD24, 1996

[2] N J. Doran, D. Wood: "Nonlinear Optical Loop Mirror"; Opt. Lett. 13 (1988), 56–58

[3] M. E. Fermann, et al.: "Nonlinear Amplifying Loop Mirror"; Opt. Lett. 15 (1990), 752–754

[4] C. K. Chan; L. K. Chen, K. W. Cheung: "Experimental Demonstration of a High-Speed All-Optical Tunable-Channel Multi-Access (TCMA) Network"; IEEE GLOBECOM, Paper 50.2, Singapore, 1995

[5] B. E. Olsson, P. A. Andrekson: "Extinction Ratio Improvement Using the Nonlinear Optical Loop Mirror"; IEEE Photon. Technol. Lett. 7 (1995) 1, 120–122

[6] E. Yamada, M. Nakazawa: "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. 30 (1994) 8, 1842–1850

[7] C. K. Chan, L. K. Chen, K. W. Cheung: "Switching Contrast Degradation in Ultrafast All-Optical Switching using Nonlinear Amplifying Loop Mirrors"; International Symposium on Communications (ISCOM) '95, Paper ThC2.2, Taipei, Taiwan, 1995

[8] E. Desurvire: "Effect of Normal Mode Loss in nonlinear Optical Loop Mirror Switching," Eletron. Lett. 30 (1994) 7, 580–581

[9] M. Jinno: "Effects of Group Velocity Dispersion on Self/Cross Phase Modulation in a Nonlinear Sagnac Interferometer Switch"; IEEE J. Lightwave Technol. 10 (1992), 1167–1178

[10] D. A. Pattison, et al.: "Soliton Switching Using Cascaded Nonlinear-Optical Loop Mirrors"; Optics Lett. 20, (1995) 1, 19–21