# Switching Contrast Degradation in Ultrafast All-Optical Switching using Nonlinear Amplifying Loop Mirrors

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ABSTRACT

Nonlinear amplifying loop mirror (NALM) is a novel ultrafast all-optical switching device for high speed optical time-division multiplexed systems. It requires less input switching power than NOLM. Switching contrast is an important factor affecting the bit-error-rate performance of the device. We have shown that due to the asymmetric gain of the two counter propagating directions in the loop, the switching contrast is degraded. Theoretical and numerical analysis of switching contrast degradation based on both self-phase modulation (SPM) and cross-phase modulation (XPM) are presented. The results are quite important in system design of high-speed optical TDM using NALM as all-optical multi-/demultiplexers.

## I. INTRODUCTION

Recently, ultra-high speed all-optical time-division multiplexed (TDM) systems are of great interest. System bit rate as high as 200 Gbit/s has been demonstrated [1]. All-optical switching devices based on the fiber nonlinearity have been studied and demonstrated extensively. Much work has been concentrated on the nonlinear optical loop mirrors (NOLM) since it is inherently a balanced interferometer and therefore environmentally stable [2]. However, due to the weak nonlinearity of optical fiber, either long fiber loop length (several km) or high input switching power ($\sim$ 1W) is required. Such high input switching power is not quite practical for real systems. Moreover, when the splitting ratio of the coupler used is not 50/50, the switching contrast will be much degraded [3]. In view of these problems, a modified NOLM with an optical amplifier placed inside the fiber loop, named nonlinear amplifying loop mirror (NALM), has been proposed [4]. Figure 1 shows the configuration of an NALM. The optical amplifier used can be fiber amplifiers, Raman amplifiers or semiconductor amplifiers. It is placed asymmetically inside the loop to attain different intensity-dependent phase shifts of the two counter-propagating signals and thus switching can be achieved according to their relative phase difference. This device requires much reduced input switching power and ideally, 100% switching can be achieved.

Switching contrast is an important issue to determine the performance of a switching device. It is defined as the relative power ratio of the switched and unswitched signals. A poor switching contrast will degrade the system bit-error-rate (BER) performance. In [5], it has been shown that the power contrast between '1' and '0' of an optical pulse stream modulated by a Mach-Zehnder modulator is usually degraded by the extinction ratio of modulator's transfer characteristics and it can be improved by passing the modulated optical pulse stream through an NALM. In this way, the BER as well as the received power penalty are much improved. However, we have found that in certain cases,

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the overall gain of the two counter-propagating signals after passing through the loop may not be the same and thus the switching contrast of the NALM is degraded. In this paper, the causes and effects of such phenomenon have been studied and are presented in section II and III respectively. Theoretical and numerical analysis of an NALM have been done to show the switching contrast degradation due to such asymmetric overall gain. These results are quite important in the system design of the ultra-high speed TDM systems using NALM as all-optical multi-/demultiplexers.

## II. Asymmetric Gain in NALM

Figure 1 shows a typical configuration of an NALM. The splitting ratio of the coupler is close to 50/50. The optical amplifier is placed close to one end inside the fiber loop to attain asymmetric intensitydependent phase shift by self-phase modulation (SPM) between two counterpropagating signals. Two input signals are transmitted to the other output port (in transmit state) or reflected to the input port (in reflect state), depending on their acquired intensity-dependent phase difference. So, switching is achieved.

In the conventional analysis of the switching characteristics, it is assumed that the overall gain of the two counter-propagating signals are the same and the splitting ratio of the coupler is exactly 50/50. That is, the input signal is split equally after being input into the loop and when the two signals recombine at the coupler, they should have equal power levels but with different phase shifts [4].

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

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

$$\text{Maximum switching Contrast} = \frac{|E_t|^2}{|E_r|^2} = \infty$$

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 switching characteristics is shown in Figure 2. Note the infinite maximum switching contrast and thus 100% switching can be achieved. Practically, this is not always valid. The possible reasons are summarized as follows:

(a) *Types of Optical Amplifiers used*

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

(b) *Gain Saturation / Compression in Optical Amplifiers*

When an optical amplifier is saturated, the output power becomes constant and is independent of the input power. That is, different input powers will give the same output power. In an NALM, for high repetition rate, the amplifier is very likely to be saturated. Since the powers of the clockwise and counter-clockwise signals before entering the amplifier are usually different due to asymmeteric location of the optical amplifiers in the fiber loop, their optical gains will also be different. Moreover, since fiber amplifiers have longer gain-recovery time (in $ms$ range) [6], the fluctuation in the saturation power is not significant as compared to the high repetition rate of the pulse stream. However, in semiconductor amplifiers, due to their shorter gain--recovery time ($< ns$) [7], the gain variation would be significant.

(c) *Pumping Directions in Fiber Amplifiers*

Consider the case that the input signal power is $S$ dBm. It is then split into two counter-propagating signals, clockwise signal and counter-clockwise signal. The power of clockwise signal before entering the amplifier is $(S-3)$ dBm and that of the counter-clockwise signal is $(S-L-3)$ dBm where $L$ $dB$ is the fiber loss of the loop. The power degradation of 3 dB is due to the splitting loss at the 3-dB coupler. Assume the system is operated in high repetition rate (> 1 GHz), the amplifier is saturated. For single pumping, the saturated power at the pumping side $(P_{sat-P})$ dBm will be greater than that at the non-pumping side $(P_{sat-NP})$ dBm since the pump power at the non-pumping side is lower. However, for double pumping, such discrepancy in saturated power is small and so $P_{sat-P} \approx P_{sat-NP}$.

(i) Forward pumping w.r.t. clockwise signal
The gain of the amplified clockwise signal is $(P_{sat-NP} - (S-3))$ dBm while that of the amplified counter-clockwise signal is $(P_{sat-P} - (S-L-3))$ dBm. So the gain difference $\Delta G_{fp}$ is $|P_{sat-NP} - P_{sat-P} - L|$ dB.

(ii) Backward pumping w.r.t. clockwise signal
The gain of the amplified clockwise signal is $(P_{sat-P} - (S-3))$ dBm while that of the amplified counter-clockwise signal is $(P_{sat-NP} - (S-L-3))$ dBm. So, the gain difference $\Delta G_{bp}$ is $|P_{sat-P} - P_{sat-NP} - L|$ dB.

(iii) Double pumping
The saturation power at the input and output end will be about the same. So the gain difference $\Delta G_{dp}$ is $|L|$ dB.

Therefore, the loop length determines the gain difference at the fiber amplifier. For a loop length < 12km, L < 3 dB @1550nm. Since $P_{sat-NP}$ is less than $P_{sat-P}$, we get $\Delta G_{bp} < \Delta G_{dp} < \Delta G_{fp}$ and thus backward pumping w.r.t. the clockwise signal can achieve the least gain difference.

(d) *Asymmetric Splitting Ratio of the Coupler*
Practically, it is quite difficult to obtain couplers with an exact 50/50 splitting ratio. Therefore the input power levels of the two counter-propagating signals are usually not the same. They will experience different saturable gain in the optical amplifiers and thus when they recombine at the coupler again, their power levels may be different.

(e) *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.

## III. Switching Contrast Degradation in NALM due to Asymmetric Gain

Consider when the optical amplifier has different directional gains, $G_1$ and $G_2$; and the coupler has different splitting ratio, $\alpha$ and $(1-\alpha)$, as shown in Figure 1. Expressions (1) and (2) can be re-written as:

$$|E_r|^2 = \alpha(1-\alpha)|E_{in}|^2(G_1 + G_2 + 2\sqrt{G_1G_2} \; cos[|E_{in}|^2(G_1(1-\alpha) - \alpha)\tfrac{2\pi n_2 L}{\lambda}] \quad (3)$$

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

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

For $\alpha = 0.5$, maximum switching contrast
$$= \left(\frac{\sqrt{G_1}+\sqrt{G_2}}{\sqrt{G_1}-\sqrt{G_2}}\right)^2 = \left(\frac{\sqrt{\Delta G}+1}{\sqrt{\Delta G}-1}\right)^2$$

where $\Delta G$ is the gain difference with $\Delta G = (G_1/G_2)$. Figure 3 shows the intensity--dependent switching characteristics for 50/50 coupler splitting ratio and Figure 4 shows the dependence of the switching contrast for different gain difference. It is shown that for high asymmetric 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 whole stream routing which involves the intensity-dependent phase shift due to self-phase modulation (SPM) only. Now we consider the effects of asymmetric gain on multi-/demultiplexing using NALM by means of numerical simulation. The intensity-dependent phase shift in this case is due to both self-phase modulation and cross-phase modulation (XPM). We have analysed the multi-/demultiplexing process using numerical integration of the nonlinear Schrödinger equation.

Assume that a 1-Gb/s signal pulse stream at 1555nm with pulse width 6ps (FWHM) and peak power 5mW is input into an NALM. A 200-Mb/s control pulse stream at 1551nm with pulse width 10ps (FWHM) and peak power 40mW is injected into a dispersion-shifted fiber loop and aligned with the signal pulse stream. The optical amplifier is placed in the upper arm of the loop as in Figure 1. Both the control and the signal pulse stream co-propagate in the clockwise direction and the other signal pulse stream propagates in the counter-clockwise direction. It is assumed that there is negligible interaction between the two counter-propagating pulse streams. The loop length is optimized to acheive maximum extinction ratio which is defined as the power ratio of the pulses representing '1' and '0' in the transmitted or reflected pulse stream.

Figure 5 and 6 show the transmitted and reflected pulse streams in the case of symmetric gain and asymmetric directional gain respectively, where the signal pulse stream is modulated with pattern [0011100111] and the control pulse stream is aligned with the fourth and ninth time slot. In the transmitted pulse stream, the 'one' pulses involve both SPM and XPM; whereas in the reflected pulse stream, they involves SPM only. Note the degradation in the extinction ratio in the case of asymmetric gain as shown in Figure 6. Its dependence on the gain difference is illustrated in Figure 7 for 17dB and 19dB clockwise gains. The finite extinction ratio for zero gain difference is due to the pedestal effects [8] imposed by SPM and XPM on the pulse switching. For example, when the gain difference increases from 0 dB to 1 dB, the extinction ratio degradation is about 3 dB.

In most of the previous papers about ultrafast optical switching using NALM, although 100% switching was claimed, it was shown clearly that 100% switching could not be achieved from their experimental results. Such imperfect switching is a fundamental limitation of this device and one possible reason is the asymmetric gain in the loop. The switching contrast and the extinction ratio degradation due to asymmetric gain have been analysed in the previous sections. The impact of extinction ratio on the BER performance has been studied in [9]. So, these results are very important in the system design of NALM.

## IV. Conclusion

In conclusion, we have shown that asymmetric gain in the two counter-propagating directions in NALM results in switching contrast degradation. Theoretical and numerical analysis of switching based on both self-phase modulation and cross-phase modulation were presented. It is shown that when the gain difference increases from 0 dB to 1 dB, the extinction ratio degradation is about 3 dB. The results are quite important in system design of high-speed optical TDM using NALM as all-optical multi-/demultiplexers.

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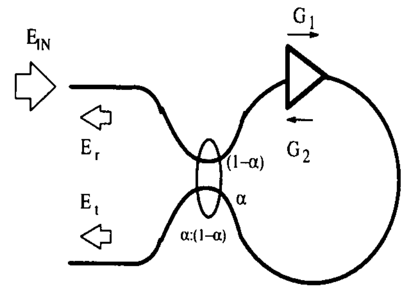


Fig. 1. Nonlinear Amplifying Loop Mirror

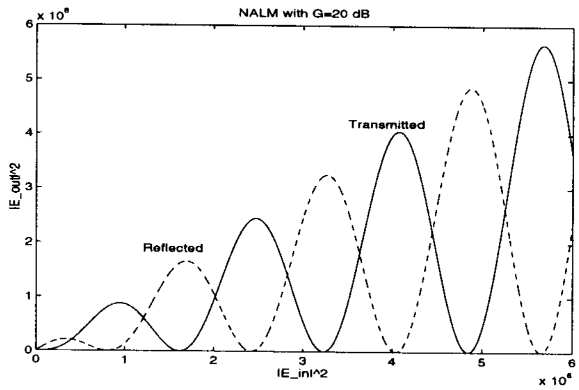


Fig. 2. Switching characteristics of NALM with symmetric gain and 50/50 coupler splitting ratio

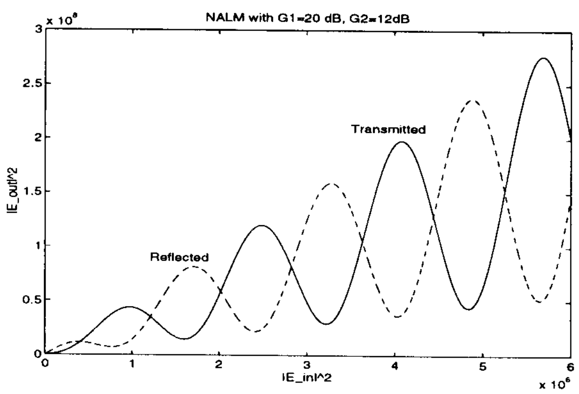


Fig. 3. Switching characteristics of an NALM with asymmetric gain and 50/50 coupler splitting ratio

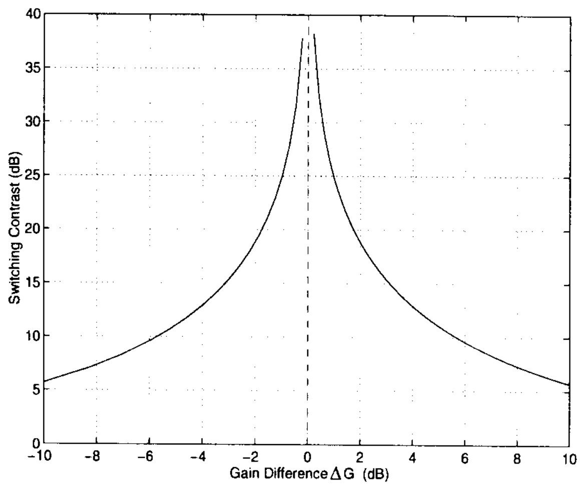


Fig. 4. Switching contrast vs gain difference $\Delta G$

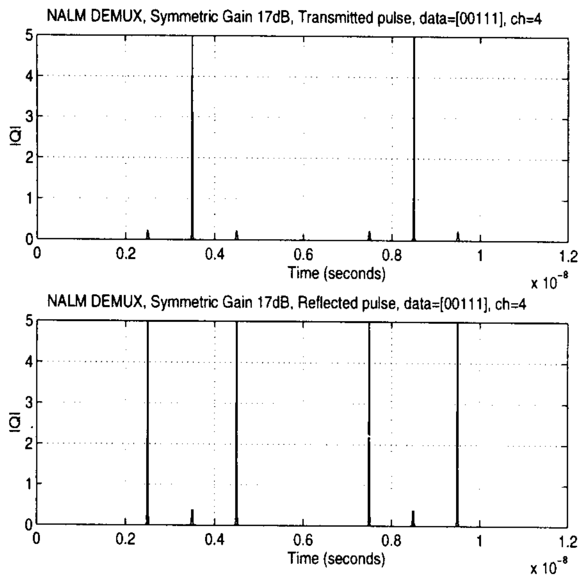


Fig. 5. Multi-/demultiplexing with symmetric gain, clockwise gain=17dB

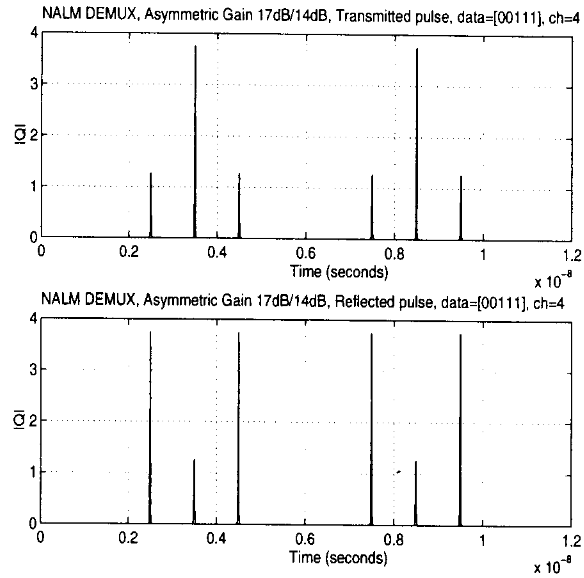


Fig. 6. Multi-/demultiplexing with asymmetric gain, clockwise gain= 17dB and counter-clockwise gain = 14dB

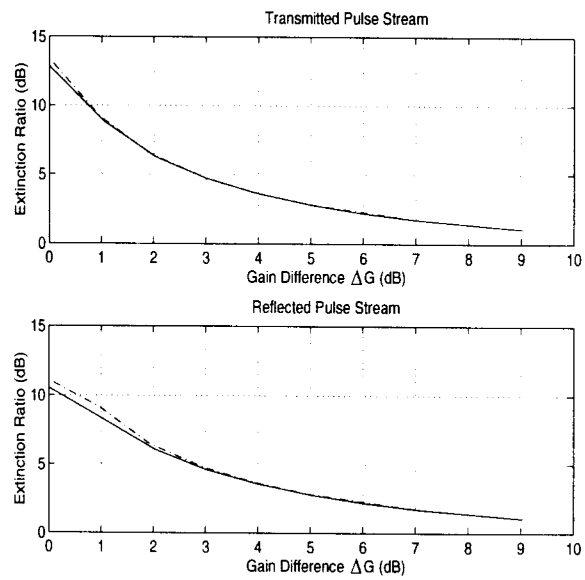


Fig. 7. Maximum extinction ratio vs gain difference $\Delta G$ (Solid line : clockwise gain is 19dB, broken line: clockwise gain is 17dB)