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All optical switching in a highly birefringent and a standard telecom fiber using a Faraday mirror stabilization scheme

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Abstract

All-optical switching at 1.5 μm based on induced nonlinear polarization rotation is demonstrated in both a polarization maintaining and a standard telecom fiber. Excellent switching stability is obtained in both cases by removing any detrimental temperature or pressure induced changes of the output polarization state with a Farady mirror stabilization scheme.

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Keywords: Kerr effect; All-optical switching; Faraday mirror

1. Introduction

Considering the high bit rates of future optical fiber communication systems, optical signal processing could soon become a necessity. In order to demux a single channel from a 100 Gb/s time division multiplexed (TDM) signal e.g., a switching time of about 5 ps will be required. All-optical switching techniques based on the optical Kerr effect [1–6] are very attractive in that respect due to the ultrafast Kerr response [7–9] of less than a few fs. Indeed, an all optical Kerr switch was demonstrated recently to read out a 10 Gb/s channel from a 40 Gb/s TDM signal [10]. Besides the standard switch parameters like switching ratio, insertion loss or switching time, the stability of the switch is an important issue. Variations in the input control or signal polarizations as well as changes of the intrinsic birefringence of the Kerr medium will affect the switch. Variations of the input signal polarization can be dealt with by adopting a polarization diversity scheme, like e.g. in Ref. [10]. In order to keep the switch stable internally, the control pulse polarization should be kept as stable as possible by using a proper set-up. Moreover, changes in the signal polarization in the Kerr medium (typically a polarization maintaining PM fiber) due to changes in the intrinsic fiber birefringence have to be avoided since they can greatly reduce the extinction ratio of the switch. An active correction scheme (e.g. a polarization controller [11] with a feedback loop) is typically not rapid enough to correct the fast, acoustical perturbations, and may not work at all for large changes due to its limited range of operation.

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To avoid these problems, we use on one hand a non-interferometric switch [1], and on the other hand a passive stabilization scheme. In interferometric switches like Sagnac loops or Mach–Zehnder interferometers (IF), the switching is based on a phase-shift induced between the two different propagation directions or arms, respectively. If the signal is not carefully launched into an axis of a PM fiber, it will split into four different polarization modes, two in each propagation direction or interferometer arm, respectively. In addition to the phase-shift between the two different propagation directions or interferometer arms, additional ‘local’ phase-shifts between the polarization modes with the same propagation direction (or within the same IF arm) will degrade the switch quality. In the switch presented here, this problem is avoided by uniquely using this ‘local’ phase-shift between the two signal polarization modes in a single fiber, thereby reducing the relevant mode number to two. Having two modes only, we can then use a passive stabilization scheme that works both for fast and slow, arbitrarily large changes in the fiber birefringence. Although in this work an optical fiber is used to induce a nonlinear phase-shift, it should be noted that the stabilization scheme holds as well for any other Kerr elements (e.g. semiconductor saturable absorbers SOA).

2. Principle of operation

As mentioned above, the principle of the optical Kerr switch presented here is based on an induced phase-shift between the two signal polarization modes in a single fiber. It is induced by powerful control signal pulses that lead to a different phase-shift (via the optical Kerr effect) for signal components with the same and orthogonal polarization, respectively. The corresponding change in the output signal polarization is maximized if the control signal polarization matches the polarization of one of the two signal polarization modes during the entire propagation in the Kerr fiber. By inserting a polarizing beam splitter (PBS), the signal is switched between the two PBS output ports depending on the amount of the induced phase-shift.

For a control pulse linearly polarized along one of the birefringent axis of a PM fiber, it is easy to show that the phase shift $\Delta\phi$ acquired by a signal linearly polarized at 45° is [12]

$$\Delta\phi = \tfrac{8}{3}\pi\left(\frac{L_{\mathrm{eff}}}{\lambda}\right) n_2 \frac{P}{A_{\mathrm{eff}}}, \qquad (1)$$

where n_2 is the nonlinear refractive index of the fiber, λ is the signal wavelength, A_{eff} is the effective area of the fiber and P is the peak pump power. Fiber losses are included in the effective length $L_{\mathrm{eff}} = (1/\alpha)[1 - \exp(-\alpha L)]$ where L is the length and α the fiber loss coefficient. For a PBS adjusted so that all the signal is at output port 2 when the control pulse is absent, the signal at output port 1 becomes

$$T = \sin^2\frac{\Delta\phi}{2}, \qquad (2)$$

where the induced phase shift $\Delta\phi$ is given by Eq. (1). A different wavelength is conveniently used for the control pulses so that they can be combined with the signal using a wavelength division multiplexer (WDM). As a consequence, a walk-off between the control pulses and the signal is introduced, ultimately limiting the switching time. A large walk-off also enlarges the required control peak power because of a reduced interaction length (i.e. smaller L_{eff} in Eq. (1)). To keep the switch fast and efficient, either a fiber with low group dispersion has to be used, or the wavelength separation should be kept as small as possible. The latter leads to a trade-off between the switching time (determined by the walk-off) and the extinction ratio (determined by the WDM filtering). For a detailed analysis, the reader is referred to Ref. [3].

It is very important to notice that the transmission given in Eq. (2) holds only for a fixed intrinsic birefringence of the fiber. Any fluctuation of this birefringence, caused e.g. by temperature drifts or pressure changes, leads to an additional phase-shift randomly changing the bias of the switch. In order to reduce this effect detrimental for the switch stability,

[1] ‘Non-interferometric’ in the sense that the signals being interfered are not from two physically separate arms. Of course linear optics is always interferometric in a strict sense of the word (superposition principle).

different methods have been proposed [3,11]. A very promising solution is to make a double pass of the fiber by means of a Faraday mirror (FM) [13–16]. The FM transforms any input polarization state to the orthogonal one upon reflection. Consequently, the signal components that were polarized parallel to the fast axis during the forward propagation will be polarized parallel to the slow axis during the return path and vice versa. The overall acquired phase is therefore the same for any input polarization, and the intrinsic birefringence is automatically removed as long as it is stable during a single go-and-return path. In this way, fluctuations with frequencies up to about 0.5 MHz (200 m long fiber) can be removed.

Although the application of a FM is widely spread in linear optics, we believe to be the first ones having demonstrated its usefulness for nonlinear optics as well. Especially, we showed in Ref. [6] both theoretically and experimentally that only the linear phase fluctuations are removed, whereas the purposefully induced nonlinear effects of the go and return-path add up. This allowed to measure the nonlinear polarization rotation in an optical fiber.

3. Set-up

The setup of the Kerr switch using the described stabilization scheme is shown in Fig. 1. The control signal was generated by a directly modulated DFB

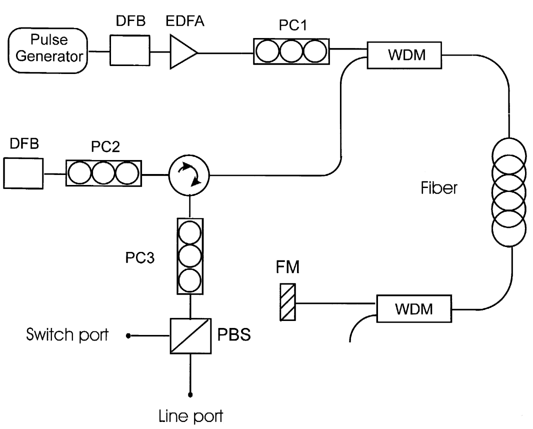

Fig. 1. Experimental setup. DFB distributed feedback laser, EDFA erbium doped fiber amplifier, PC polarization controller, FM Faraday mirror, PBS polarizing beam splitter, WDM wavelength division multiplexer

laser diode with a wavelength of 1559 nm, amplified by an EDFA with a small signal gain of 40 dB and a saturated output power of 23 dBm. The pulses from the DFB laser had a duration of 28 ns with a repetition rate of 1 kHz. This is good enough to demonstrate the usefulness of the stabilization scheme and the basic functioning of the switch – in an application, short control pulses at a high repetition rate could be used. In order to have a larger side-mode suppression of the DFB output at the signal wavelength, an external small pass filter was inserted after the EDFA. Using a WDM, the control pulses were then coupled into the Kerr fiber along with the signal consisting of cw light generated by a second DFB at 1556 nm. The signal power in the Kerr fiber was -1.8 dBm, whereas several Watts of control pulse peak power were available. For the Kerr medium, we first used a PM fiber with a length L of 200 m. The wavelength difference $\Delta\lambda$ of 3 nm between control and signal light consequently leads to a walk-off of about 10 ps (assuming a GVD value of $D = 17$ ps/km nm):

$$\Delta t \simeq DL\Delta\lambda \simeq 10\,\text{ps}\,.$$

This value represents a lower limit for the (0–100)% rise/fall time of the switch. For even shorter switch times, a dispersion shifted fiber (DSF) would have to be used. For the initial adjustment of the switch, the polarization of both control pulses and signal could be set independently by polarization controller PC1 and PC2, respectively. This allows both for the pump to be launched into a birefringent axis of the PM fiber and for the signal polarization to be set at 45° to this axis for a maximum switching ratio at the output. At the end of the PM fiber the pump was removed with a second WDM, whereas the signal was reflected back with a Faraday mirror. After this double pass, the reflected signal is sorted out by a circulator and put on a PBS. The switch is biased by another polarization controller PC3, which allows to set the desired ratio of the signal light at the two PBS output ports. Typically, it was adjusted for maximum power in port 1 (line port), i.e. minimum power in port 2 (switch port) in the absence of control pulses. The switch port, for which Eq. (2) holds, was then monitored using a fast photodiode with a response time of 200 ps. The extinction ratio of the switch mainly depends on the extinction ratio of the PBS (20 dB in our case) and on the pump power suppression at the signal wavelength (60 dB in our set-up). If necessary, higher values could be obtained by using additional polarization selection or filtering. Note that the required control signal peak power (or fiber length) could in principle be reduced to half its value if the pump is not removed at the FM, thereby allowing a double pass of the Kerr fiber. The switch performance is still independent of the control pulse pattern in that case as long as the total power of the control signal within half the round-trip time (1 μs in our case) doesn't change too much, a situation typically realized when switching high bit rate signals.

4. Experimental results

4.1. PM fiber

The experimental results using a 200 m PM fiber as the Kerr medium are shown in Fig. 2.

The proper working of our stabilization scheme was checked by monitoring the output power at the switch port for several hours. After the initial setting of the switch, it was left alone without any re-adjustments for a time period of several hours, while a normal activity in the lab was maintained, with people working around the table. Moreover, a change in the temperature of 5 degrees was observed during that time span. The measured fluctuations of the switch port signal power are shown in Fig. 2a. Besides the measured data points (squares), the mean value (bold line) and the standard deviation σ (thin lines) are shown. As is demonstrated by the figure, the obtained switch stability was rather good (less than 2% fluctuations) when using the Faraday mirror. When it was replaced by a normal mirror on the other hand, thereby removing the stabilization, the switch port signal output power rapidly changed in the range from zero to full switch power. Indeed, it is well known that the polarization of light coupled into both the birefringent axes of a PM fiber – due to its short beatlength of only a few mm – is very susceptible to any perturbation. The use of a stabilization is therefore an absolute necessity.

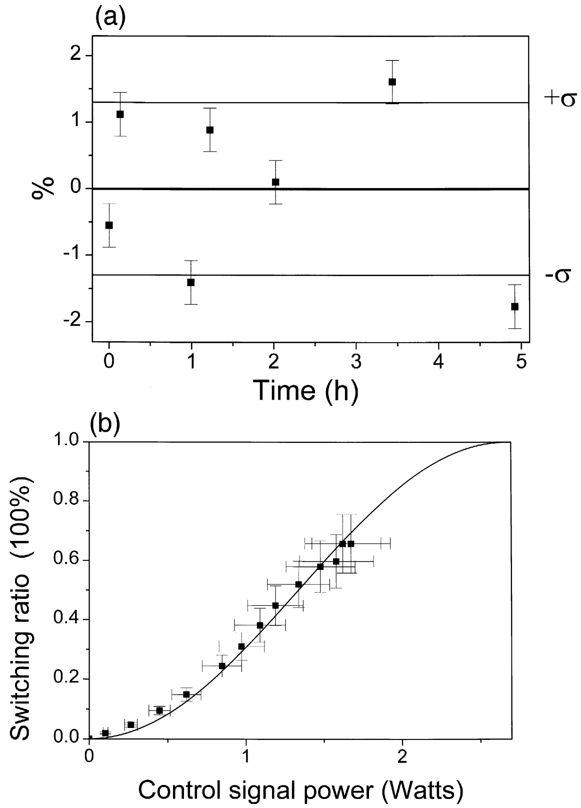

Fig. 2. Switch performance using a 200 m PM fiber. (a) Relative fluctuations of the switch port signal power as a function of time. Measured data (squares), mean value (bold line), and standard deviation σ (thin lines). (b) Normalized switching ratio as a function of the control signal power. Measured data (squares), theoretical fit (solid line).

Fig. 2b gives the normalized switching ratio as a function of the applied control signal peak power. The normalized switching ratio is defined as the ratio of the actually measured power from the switch port, divided by the maximum signal power obtainable from that same port (measured by adjusting PC3 for maximum transmission to the switch port in the absence of control pulses). The experimentally obtained values (squares) are compared with a fit (solid line) using Eq. (2) and requiring a peak normalized switching ratio of 1. As the figure shows, the experimental data corresponds well with the model (χ^2 = 0.8). The maximum switching ratio we could obtain in the measurement was however only 65% for a control peak power of 1.7 W. For higher control powers, the signal started to exhibit strong power fluctuations within the temporal switch window of 28 ns, which inhibited a proper functioning of the switch. As revealed by the optical spectrum, these fluctuations were caused by the onset of concurring nonlinear effects normally absent until much higher peak power times distance values. We believe that our non-optimal control signal source (side-band suppression) was seeding the observed nonlinearities, leading to a much lower threshold power. The observed limit in the switch ratio is therefore not a general problem of the demonstrated switch technique, but was unique to our experimental set-up.

4.2. Standard fiber

Further, we analyzed the possibility to use a standard (i.e. non PM) fiber for the Kerr medium. Besides reducing the switch cost, the assembly of the switch is much easier using standard than PM fiber, and the insertion loss can be reduced as the splice losses are lower. In order for the switch to work properly and efficiently, the part of the signal having the same polarization as the control signal at the input should keep the same polarization as the control during propagation, whereas the orthogonal part should stay polarized orthogonal. Only in this way an important phase shift between these two signal components can build-up. It is obvious that the above requirement is perfectly fulfilled in a PM fiber, where a signal component that is coupled into one of the two fiber axes remains there during propagation. In a standard fiber however, the situation is different. The above requirement, which corresponds, on the Poincaré sphere, to a conservation of the angle between the control and signal Stokes vectors during propagation, is no longer met exactly. This is because the polarization mode coupling (specified by the coupling length h [17]) present in the standard fiber leads to a coupling of the control and signal light into both the (local) fiber axes, where they will evolve differently due to their different beatlengths. The conservation of the angle between the control and signal Stokes vectors consequently depends on the fiber characteristics (coupling length h, beatlength L_b) and on the wavelength difference between the control and signal light. We therefore first verified that this angle conservation was sufficiently good in the standard fiber to be used as the Kerr medium. As a simple estimate, we can use

$$\alpha = 2\pi L\left(1/L_b(\lambda_{\mathrm{signal}}) - 1/L_b(\lambda_{\mathrm{control}})\right),$$

where $L_b(\lambda) = \lambda/(cB)$ and the birefringence B [ps/m] is assumed to be independent of the wavelength. The estimate represents a worst case scenario as the coupling length h is assumed to be much larger than the fiber length L and that both signal and control pulses were coupled into both fiber axes at the input. Using the wavelength difference of 3 nm of our experiment, and a typical value of the signal beatlength of 10 m, we get an angle difference of just 7° after 100 m of fiber, which should not cause any problems. Analysis of the Jones transfer matrix measured at both the signal and control wavelength further suggests that the angle should be sufficiently conserved. However, these simple estimates neglect nonlinear polarization evolution like e.g. a self-rotation of the intense control signal [6].

The testing of the switch was performed in a similar way as described in the previous section. However, as there is no well defined axis into which to couple, the input states of polarization were varied until a maximum in the switching ratio was found, although the differences were not that large due to an apparently small coupling length h of the employed Kerr fiber. This small coupling length quickly leads to a randomization of the fiber axes and makes the results almost independent from the input polarization of the control signal. On the other hand, the effective phase shift acquired by the signal is reduced by this randomization, and we had to use a longer Kerr fiber of 680 m to obtain a sufficiently large rotation of the signal at the fiber output.

As can be seen in Fig. 3a, the stability was once more excellent when employing the FM. Fig. 3b shows the observed switching ratio as a function of the control peak power. The obtained switching ratio corresponds to 90% (for control pulses with a peak power of 2.4 W) before other concurring nonlinear effects once more lead to a pulse break-up. The experimental data are not too different from the ones for the PM fiber (Fig. 2b), i.e. the longer length of the standard fiber ($\Delta L = +480$ m compared to the PM fiber used before) accounts well for the phase-

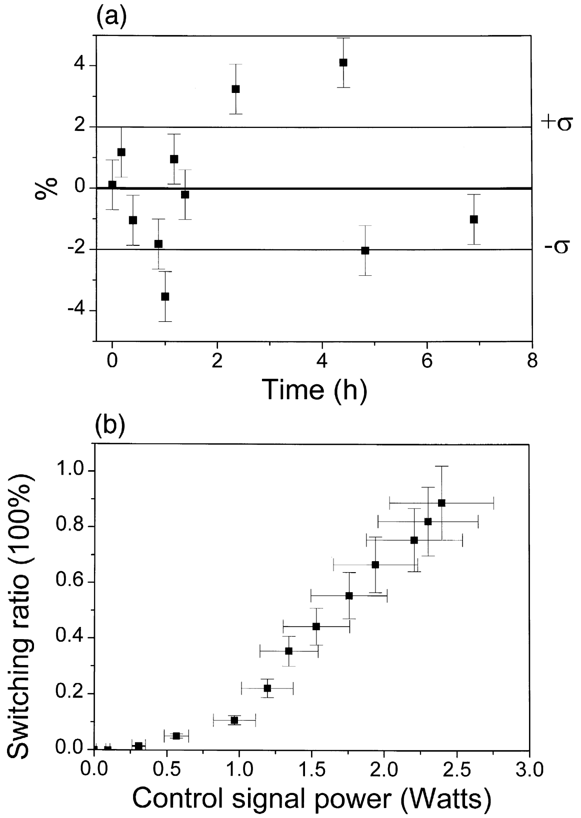

Fig. 3. Switch performance using a 680 m standard fiber. (a) Relative fluctuations of the switch port signal power as a function of time. Measured data (squares), mean value (bold line), and standard deviation σ (thin lines). (b) Normalized switching ratio as a function of the control signal power.

shift reduction caused by the 'polarization scrambling' and the different value of the ratio n_2/A_{eff}. The use of a standard fiber is therefore also interesting from a physical point of view, as the functioning of the switch could be exploited to reveal information about the coupling length of the standard fiber. Such investigations are however beyond the scope of this paper and will be discussed elsewhere.

5. Conclusion

All-optical switching at 1.5 μm based on induced nonlinear polarization rotation was successfully demonstrated in both a polarization maintaining and a standard telecom fiber. The insertion of a Faraday mirror after the Kerr fiber led to a very good stability of the switch for both cases.

In the standard fiber, switching was made possible because the small difference between the control and signal wavelength allowed for a similar evolution of both signals along the fiber – the two corresponding Jones transfer matrices were found to be almost equal – thereby well preserving the angle between the two respective Stokes vectors. As a byproduct, the ratio n_2/A_{eff} can be determined, and using an appropriate model, information about the coupling length h might be extracted as well. Further work in this direction is in progress.

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