All-Optical Switching in Phase-Shifted Fiber Bragg Grating

Andrea Melloni, Marco Chinello, and Mario Martinelli

***Abstract*—A low-power all-optical-switching in a phase-shifted grating has been experimentally demonstrated at 1.55 μm. The grating is written in a standard fiber for communication and the switching is based on the cross-phase modulation induced by an intense pump pulse on a low intensity probe. An extinction ratio of more than 6 dB has been achieved for 1 kW pulse peak power. The strong enhancement of the nonlinear effect due to the group velocity reduction and the switching polarization dependence have been theoretically investigated and experimentally confirmed.**

***Index Terms*—Fiber gratings, nonlinear optics, optical switches.**

BRAGG gratings in optical fibers are excellent devices for studying nonlinear phenomena [1]. In particular, experiments based on Kerr phenomenon, interplay between two or more beams, interplay between dispersion and nonlinearity, pulse shaping and optical switching are possible thanks to the exceptional flexibility in the choice of the grating parameters. With the present technological state, for example, the physical length and the index modulation depth can be varied over many order of magnitude. Therefore, even if the nonlinear refractive index in standard optical fibers is very low, nonlinear effects in a fiber Bragg grating (FBG) continues to attract the attention of many researchers. Recent results, both theoretical and experimental, demonstrated very interesting phenomena which suggest new applications and devices in the optical communications field. All optical switching [2]–[4], optical push broom [5], grating solitons [6] and all-optical gates [7] are only an example of the many researches in this field.

In this letter, we report results of an all-optical switching experiment in a phase-shifted FBG in standard fibers for communications. A low power, continuous-wave (CW) probe beam transmitted through the grating is switched off (on) by an intense pump pulse. The switching is based on the cross-phase modulation (XPM) that the pump induces on the probe inside the grating, with the nonlinear effect strongly enhanced by the presence of the phase-shifted grating. The power switching properties draw advantage from the steep edges of the notch that allow a high extinction ratio even with an extremely small wavelength shift [2]. The experimental results are confirmed by numerical simulations.

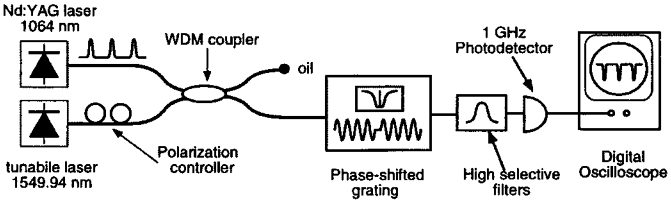

Fig. 1. Experimental setup.

In the past some other all-optical switching experiments in gratings have been reported [3], [4]. In one of the first experiments realized by Larochelle in 1990 [3], small changes of the transmitted intensity for pump pulse peak power up to 5 kW have been observed. In [4] Eggleton reports a self-switching in a long-period fiber grating at a wavelength of 1052 nm. In the present experiment an extinction ratio of more then 6 dB has been measured for 1 kW of pulse peak power, the most effective all-optical switch in gratings at 1.55 μm, according to the authors' knowledge.

In our experiment, the pump pulse is longer than the grating and it is copropagating with the probe. The probe is very weak and does not induce any nonlinear effects. The experimental setup is shown in Fig. 1. A narrow linewidth tunable laser, accurately centered in the transmission peak of the grating, is used as a low power probe. This CW probe is coupled by means of a fiber WDM coupler to a high power Q-switching Nd : YAG pulse laser emitting at 1064 nm. A polarization controller provides a means for changing the relative state of polarization between pump and probe. The pump pulsewidth is between 7–16 ns, depending on the energy output level and the pulse rate is 10 Hz. Both beams copropagate in the grating, well isolated from environmental acoustic noises to ensure a good stability of its transfer function. The probe signal is then filtered from the pump and detected by a photodetector having a 1-GHz bandwidth. The pump pulsewidth and energy are measured at the grating output.

The grating used in the experiment is 20 mm long and the index profile is Gaussian apodized with a phase-shift in the center. The comparison between the measured and the simulated intensity transfer function of the grating is shown in Fig. 2. The notch full width at half maximum is 450 MHz and is located at 1549.94 nm. The agreement is very good and the small asymmetry noticeable in the response is probably due to a phase-shift slightly different from $\lambda/4$. Moreover, the measured intensity transmission in the notch is limited to 0.89, probably due to a displacement of the phase-shift from the grating center.

Manuscript received August 2, 1999; revised October 8, 1999. This work was supported by CoreCom, Consorzio Elaborazione e Commutazione Ottica Milano, Italy.

A. Melloni is with the Dipartimento di Elettronica e Informazione, Politecnico di Milano, 20133 Milan, Italy.

M. Chinello is with CoreCom, Consorzio Elaborazione e Commutazione Ottica Milano, 20131 Milan, Italy.

M. Martinelli is with the Dipartimento di Elettronica e Informazione, Politecnico di Milano, 20133 Milan, Italy and also with CoreCom, Consorzio Elaborazione e Commutazione Ottica Milano, 20131 Milan, Italy

Publisher Item Identifier S 1041-1135(00)00346-3.

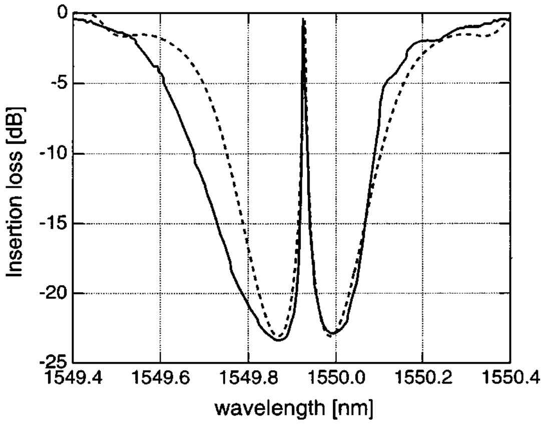

Fig. 2. Measured (—) and calculated (- - - -) transmission response of the phase-shifted grating used in the experiment.

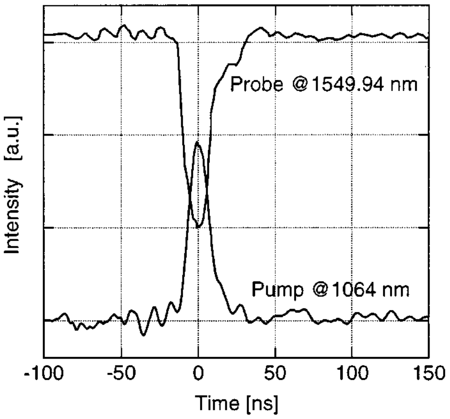

Fig. 3. Pump and probe intensities measured at the grating output.

The pump, propagating in the grating, induces a nonlinear variation of the refractive index that shifts the whole spectral response of the grating toward higher wavelength. For small shifts, the shape of the notch remain undistorted and, in the hypothesis that the pump pulse is longer than the grating, the effect is a simple detuning of the probe respect to the notch. This detuning is due to the cross interaction with the pump and it is, in a first approximation, proportional to the pulse pump power [8], [9]. The pulse dug in the CW probe is a negative replica of the pump pulse as the pulsewidth is very long as regards the response time of the device and the delay it introduces (see Fig. 3). The switching effect shown in Fig. 3 was observed for a pump peak power of 730 W. Because the pump is detuned far away from the Bragg wavelength, it is not affected by the grating. Moreover, the length of the fibers, which are multimode at the pump wavelength, have been shortened as much as possible. In this context, the effects of the fiber dispersion and nonlinearity on the pump pulses are negligible, as experimentally verified.

On the other hand, the propagation of the weak CW probe field is affected by the filter: in the filter notch, apart from an irrelevant attenuation of 0.5 dB, the probe group velocity v_g is strongly reduced. This fact enhances the interaction between the probe light and the grating by the factor v_g^{-1} [9]. This is the effect of the narrow band Fabry–Perot resonator formed by the two gratings divided by the phase shift. The enhancement is due to a longer interaction time between the probe light and the dielectric respect to the classical XPM in the bare fiber. A pictorial description of this effect is given by a field that rebounds between the two partial reflectors before getting out the cavity. The number of rebounds, or in other terms the photon lifetime in the cavity, is proportional to the inverse of the notch bandwidth. Hence, the enhancement of the nonlinear effect is greater for a narrower notch bandwidth with its corresponding reduction in group velocity. This effect can be used for reducing the switching power. However, the narrow band gap which is required to obtain a low group velocity has the detrimental effect of slowing down the time response of the device. Although the Kerr effect is practically instantaneous, the time response of the phase-shifted grating is limited by the notch bandwidth. In the present experiment the time response is nearly 1 ns.

In the notch center, the group velocity is strongly dependent on the wavelength and hence also the nonlinearity, a situation very different from bare fibers where n_2 is essentially independent of frequency. The transmission peak shift $\Delta\lambda_s$ experienced by the probe is given by

$$\Delta\lambda_s = \frac{4bn_2P_p\Lambda}{A_{\text{eff}}v_g} \tag{1}$$

where b is the polarization coefficient of the Kerr effect that has a value ranging between 1 and 1/3, depending on the state of polarization between pump and probe [10], P_p is the pump pulse peak power, Λ is the grating period, A_{eff} is the cross effective area [10] and v_g is the probe group velocity in units of c/n [9]. In (1) a factor 2 coming from the XPM has been included. The nonlinear refractive index n_2 includes both the Kerr and the electrostriction contribution and it is about 2.7×10^{-20} m^2/W. The near-field mode distribution have been derived using the Hankel transform of the measured far-field pattern at 1550 and 980 nm. The cross area, $A_{\text{eff}} = 73\ \mu\text{m}^2$, was then calculated as the overlap integral between the mode fields, as described in [10]. Simulations show that the group velocity v_g at 1549.94 nm is 0.21 times smaller than the group velocity in the bare fiber, enhancing the nonlinear effect nearly by a factor of 5. The probe wavelength must be accurately tuned to the notch center because v_g increases moving away from the peak transmission and, hence, reducing the enhancement.

To theoretically determine the output intensity of the probe, the transmission of the grating is simply calculated at the wavelength detuning given by (1). In Fig. 4, the extinction ratio, that is the output probe amplitude normalized to the amplitude at the notch center, is shown verses the peak pump power, up to 1 kW. In Fig. 4 numerical results are shown as a continuous line for the parallel ($b = 1$) and the orthogonal ($b = 1/3$) pump and probe relative states of polarization. Experimental results, relative to the case $b = 1$, are shown as circles. In practice, this condition is difficult to meet and the marks represent the maximum extinction ratio obtained by moving the polarization controller. Note that for a 1-kW pulse peak power the extinction ratio is about 7 dB. Moreover this result could be even improved if special fibers or materials are employed.

The wavelength shift $\Delta\lambda_s$ linearly depends on the polarization coefficient b. However, the polarization effect on the extinction ratio is related to the pump power due to the nonlinear

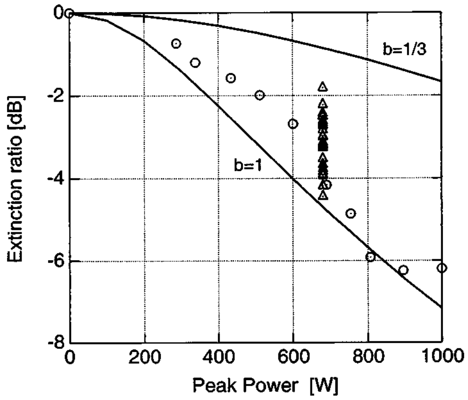

Fig. 4. Switching results. Theoretical extinction ratio for the states $b = 1$ and $b = 1/3$ are reported in continuous line. Marks refer to experimental results.

relationships between the transmission transfer function and the $\Delta\lambda_s$. Triangle marks refer to the measured extinction ratios at $P_p = 670$ W for different relative states of polarization. At this power level the measured ratio between the maximum and minimum extinction ratio is 2.0, in good agreement with the factor 2.3 theoretically calculated. The small discrepancy is due to the difficulty in meeting the two extreme polarization conditions inside the grating.

A good agreement between theoretical and measured data is generally observed. The differences can be attributed to several reasons. First of all the values of the peak power are recovered from pulse energy measurements and, because the pulse rate is very low, we expect an uncertainty of at least the 15%. Moreover, the relative state of polarization between pump and probe inside the grating, cannot be controlled accurately. Another factor of uncertainty, perhaps the most critical, is the group velocity. In (1) we used the theoretical value, obtained by simulating the whole grating and trying to take into account for the asymmetry of the spectral response discussed above, but a measurement of the effective group delay around the notch is necessary to check for the nonlinear enhancement. These elements, together with others such as environmental noise influences, lead to the small discrepancies observed in Fig. 4.

In conclusion, we experimentally demonstrated a low-power cross-phase based, all optical switching in a phase-shifted fiber grating. A switch power of 1 kW ensures an extinction ratio of about 6 dB. This power can be further reduced if highly nonlinear fibers or semiconductor waveguides are used. In spite of the small bandwidth of the device, it remains potentially useful for a number of applications such as all-optical gates, carrier extraction, packet extraction and other all-optical signal processing in FSK systems. Moreover, as it appears from (1), the bandwidth can be increased at the expense of the switching power. At present, in standard fibers the switching power is still too high for applications in the field of optical communications and devices but it has been reduced by orders of magnitude with respect to others published data [3]. The strong enhancement of the nonlinear effect due to the group velocity reduction and the switching polarization dependence was observed and theoretically confirmed.

ACKNOWLEDGMENT

The authors wish to acknowledge Dr. A. Gusmeroli for the effective area measurements.

REFERENCES

[1] C. M. de Sterke, N. G. R. Broderick, B. J. Eggleton, and M. J. Steel, “Nonlinear optics in fiber gratings,” *Opt. Fiber Technol.*, vol. 2, pp. 253–268, 1996.
[2] S. Radic, N. George, and G. P. Agrawal, “Theory of low-threshold optical switching in nonlinear phase-shifted periodic structures,” *J. Opt. Soc. Amer. B*, vol. 12, pp. 671–680, 1995.
[3] S. Larochelle, Y. Hibino, V. Mizrahi, and G. I. Stegeman, “All-optical switching of grating transmission using cross-phase modulation in optical fibers,” *Electron. Lett.*, vol. 26, pp. 1459–1460, 1990.
[4] B. J. Eggleton, R. E. Slusher, J. B. Judkins, J. B. Stark, and A. M. Vengsarkar, “All-optical switching in long-period fiber gratings,” *Opt. Lett.*, vol. 22, pp. 883–885, 1997.
[5] C. M. de Sterke, “Optical push broom,” *Opt. Lett.*, vol. 17, pp. 914–916, 1992.
[6] B. J. Eggleton, C. M. de Sterke, and R. E. Slusher, “Bragg solitons in the nonlinear Schrödinger limit: Experiment and theory,” *J. Opt. Soc. Amer. B*, vol. 16, pp. 587–599, 1999.
[7] D. Taverner, N. G. R. Broderick, D. J. Richardson, M. Ibsen, and R. I. Laming, “All-optical AND gate based on coupled gap-soliton formation in a fiber Bragg grating,” *Opt. Lett.*, vol. 23, pp. 259–261, 1998.
[8] M. J. Steel and C. M. de Sterke, “Schrödinger equation description for cross-phase modulation in grating structures,” *Phys. Rev. A*, vol. 49, pp. 5048–5055, 1994.
[9] B. J. Eggleton, C. M. de Sterke, A. B. Aceves, J. E. Sipe, T. A. Strasser, and R. E. Slusher, “Modulational instability and tunable multiple soliton generation in apodized fiber gratings,” *Opt. Commun.*, vol. 149, pp. 267–271, 1998.
[10] G. P. Agrawal, *Nonlinear Fiber Optics*. San Diego, CA: Academic, 1989.