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NONLINEAR SWITCHING USING BRAGG GRATINGS

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1 Introduction

Fibre Bragg gratings (FBGs) consist of a periodic modulation of the refractive index along the core of the fibre. This periodicity creates a photonic bandgap and results in strong reflectivity near the Bragg wavelength. The narrow bandwidth and large dispersion of FBGs makes them ideal for linear dispersion compensator and for add/drop filters in WDM systems. In the nonlinear regime Bragg gratings are bistable devices[1] and thus could potentially form the basis of all-optical switches. Recently we have demonstrated three types of nonlinear switching in Bragg gratings: a simple self-induced nonlinear switch, an all-optical AND gate, and a pump induced switch (the optical pushbroom). To understand these switches it is necessary to recall the basic nonlinear properties of Bragg gratings.

In the CW regime it is well know that Bragg gratings are bistable with one state having zero reflectivity while in the other the transmission is vanishing small[1], although the input powers are the same in each case. These different states have radically different field structures inside the grating. In the low transmission state the field structure decays exponentially along the grating, i.e similar to the linear field profile. In the high transmission state the field structure has a resonant profile which is symmetric about the centre allowing perfect transmission. This resonant structure is called a gap soliton[2] as the frequency of the light lies within the grating's photonic bandgap and as the behaviour can be described using a nonlinear Schrödinger equation. Although the original gap solitons were stationary it was soon shown that they could propagate through a grating with any speed between zero and the speed of light[3]. To understand this it is necessary to recall that the group velocity of light propagating through a photonic crystal falls to zero at the band edge and rapidly increases to that of the background medium over a very small frequency range (thus the dispersion of a Bragg grating is many orders of magnitude greater than that of the bare fibre[4]). By choosing the central frequency of the gap soliton it is possible to tune its velocity over a wide range[5].

Gap solitons form the basis of two of our nonlinear switches. In the first switch we examined the response of a Bragg grating to a single pulse with varying intensities. As expected[6] when the intensity was sufficient a gap soliton was formed at the front of the grating which then propagated along the length of the structure before releasing its energy. This results in a very sharp transition from a high reflecting state to a low one. Such a sharp transition is a desirable characteristic when designing switches as it allows excellent contrast between the off and on states.

The all-optical "AND" gate shown below also relies crucially on the sharp threshold for switching. By choosing the intensity of the input pulses correctly it is possible to construct a switch whereby if only one pulse is present it is reflected by the grating but if both are coincident upon the grating then the gap soliton formation threshold is exceeded and both pulses are transmitted. This has been described theoretically by a number of authors[7, 8] and it is believed that we are the first to observe it experimentally.

The last type of switch demonstrated here relies on the cross phase modulation effect of a strong pump pulse to switch a weak CW probe which is tuned to lie near the grating. To a good approximation the pump pulse can be thought of as a moving wall of refractive index which introduces a Doppler shift on

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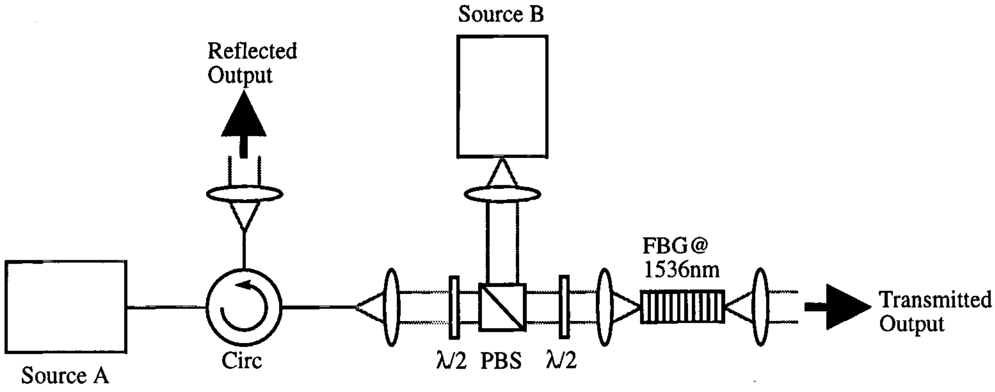

Figure 1: Schematic of experimental setup.

the probe beam. This frequency shift combined with the large group velocity dispersion of the grating results in a compressed pulse at the output of the grating.

2 Experimental Setup

Our experimental setup is shown in Fig. 1. Using the polarisation beam splitter we were able to couple one or two independent pulses in the FBG, in all cases at least one of the pulses was a high power pump pulse. The pump pulses, derived from a directly modulated DFB laser, were amplified to high power ($>$ 20 kW) in an erbium doped fibre amplifier cascade based on large mode area erbium doped fiber and had a repetition frequency of 4kHz. The pump pulse shape was asymmetric due to gain saturation effects within the amplifier chain and exhibited a 30ps rise time and a 3ns half-width (see Fig. 2b). For the gap soliton generation only a single pulse was used, however for the AND gate this pulse was split into two orthogonally polarised components and recombined at the PBS with apprximately zero time delay between the arms. For the optical pushbroom the second source was a a low-power (1mW), narrow-linewidth ($<$ 10 MHz) probe that could be temperature tuned right across the grating's bandgap. Note that, as the optical pushbroom relies on the intensity gradient of the pump, the strength of our interaction is stronger than that which would be achieved using a transform limited pulse of the same FWHM and energy. The spectral half-width of the pump pulses at the grating input was measured to be 1.2 GHz.

The pump and probe were polarization coupled into the FBG and were thus orthogonally polarised within the FBG. A half-wave plate was included within the system allowing us to orient the beams along the grating birefringence axes. Both the reflected and transmitted probe signals could be measured in our experimental system using a fiberized detection system based on a tunable, narrow-band ($<$ 1nm) optical filter with $>$80 dB differential loss between pump and probe (sufficient to extinguish the high intensity pump signal), a low noise pre-amplifier, a fast optical detector and sampling scope. The temporal resolution of our probe beam measurements was $\approx$50ps.

The FBG was centered at 1535.93 nm and was 8 cm long with an apodised profile resulting in the suppression of the side-lobes. The grating had a peak reflectivity of 98% and a measured width of 32 pm as shown in Fig. 2(a) (solid line). In Fig. 2(a) the horizontal scale gives the difference in nanometres from the centre wavelength. Also shown in Fig. 2(a) is a theoretical model of the reflection spectrum which shows that the grating is slightly chirped on the short wavelength side. The grating was mounted in a section of capillary tube and angle polished at both ends so as to eliminate reflections from the fibre end faces and was appropriately coated to strip cladding modes.

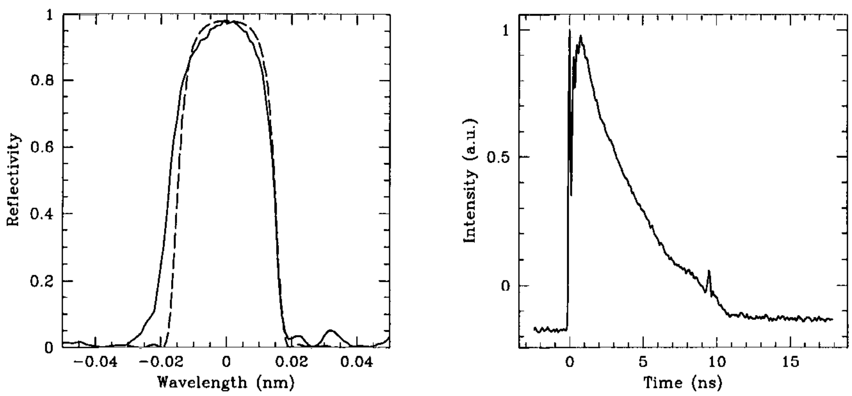

Figure 2: (a) Reflection Spectrum of the Bragg Grating used in the experiments. The solid line is the measured spectrum and the dashed line is the theoretical model. (b) Input pulse profile.

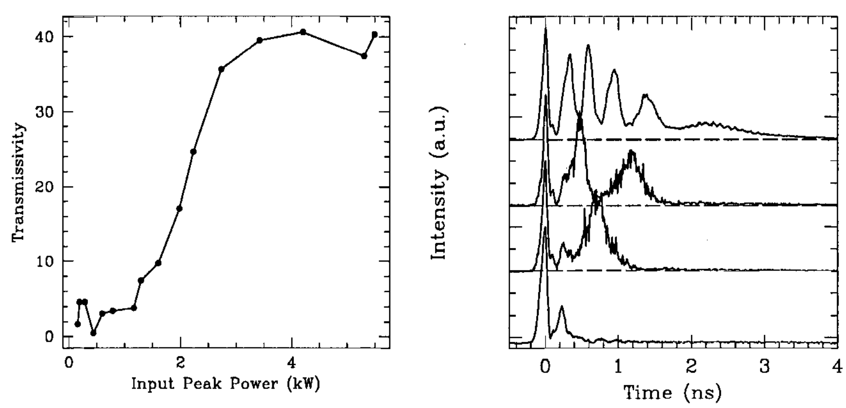

Figure 3: (a) Self-Switching of a Bragg grating. Note that the transmission increases from 2% in the linear regime to over 40% at high peak powers. Fig. (b) shows the output pulse shape for a range of increasing peak powers.

3 Results

3.1 Gap Soliton Formation

In the initial experiments we examined the self-switch of a single optical pulse which was tuned to lie just inside the bandgap on the high frequency side. We measured the transmitted energy as a function of the input power and the result is shown in Fig. 3(a). In Fig. 3(b) we show the output pulse shapes as a function of increasing power. The front two peaks which are present in all the traces are due to the chirp on the rising edge of the input pulse (caused by directly modulating the laser diode). As this peak is unaffected by the grating it can be used to directly measure the input pulse energy allowing accurate measurements of the transmitted pulse energy.

Fig. 3(a) shows that using a single high intensity pulse it is possible to switch the transmission from 2% to 40%. This remains to date the best switching results which have been demonstrated in a Bragg grating using this geometry. Previously nonlinear experiments in FBGs have been restricted to frequencies outside[9, 5] the bandgap where the grating was totally transmissive in the linear regime. This switching is a direct result of the formation of gap solitons inside the grating which then propagate through the FBG. This can be seen very clearly in Fig. 3(b). The 2nd trace which corresponds to an

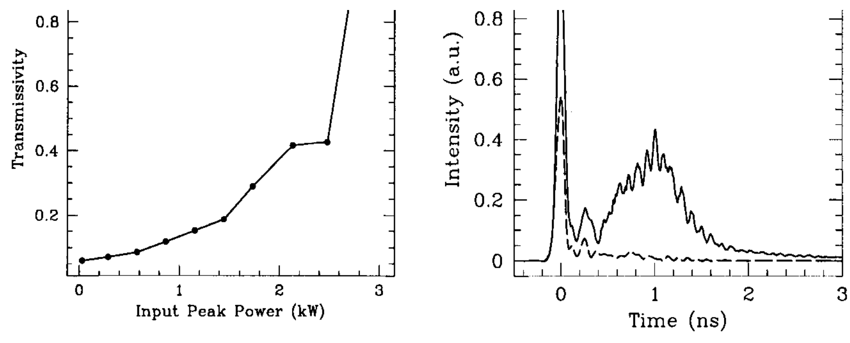

Figure 4: (a) Power dependence of the AND gate; note the sharp threshold near 2.5 kW. Fig. (b) shows the separate (dashed line) and combined (solid line) output trace for an input peak power of 3 kW.

input peak power of 3 kW shows the formation of a single gap soliton. As the input power increases still further more gap solitons form at the rear of the input pulse with the previous solitons narrowing and moving forward in the time frame. Fig. 3(b) shows quite clearly the particle nature of the gap solitons with additional solitons of similar energy being formed rather than a single soliton with more and more energy. Gap solitons are thus quite discrete entities[10] with a sharp threshold for their formation. This threshold is particularly crucial in the operation of the logic gate which is demonstrated in the subsequent section.

3.2 An all-optical logic gate

To demonstrate logic gate operation in a Bragg grating we split the input pulse into two using a PBS and then recombined the orthogonally polarised components at the front of the grating. We were able to independently vary the power in each arm as well as tune the frequency of both pulses. Efficient operation of the logic gate required that the power in each arm be slightly more than half that needed to form a gap soliton so that when the pulses were coincident the threshold was exceed and a significant amount of energy would be transmitted. The behaviour of the switch was examined as a function of the power in a single arm and the results are shown in Fig. 4(a). Note that as in Fig. 3(a) there is a sharp threshold of operation at around 2.5 kW. In Fig. 4(b) the output pulse shapes for both the 1 (solid line) and 0 (dashed line) can be seen. As expected the 1 state corresponds to the formation of a coupled gap soliton which contains most of the energy in the pulses. In this case over 17 dB of contrast was observed.

3.3 The Optical Pushbroom

The preceding experiments both relied on soliton formation within the grating which heavily distorted the pulse shape. Also such a switch is unsuitable for WDM applications since the high intensity pump can only be tuned to a single wavelength. The optical pushbroom demonstrates an alternative approach to switching with the pump being far detuned from the grating. For the optical pushbroom we tuned the pump pulse to 1550 nm where it was unaffected by the grating. The probe was then tuned to lie just outside the bandgap on the long wavelength side where the linear transmission was unity. The switching in the presence of the pump is shown in Fig. 5(a). Note that the switching contrast is quite high with the maximum transmission being five times as high as in the linear regime. Furthermore the transmission remains low for a significantly long time. This drop in transmission is due to a combination of two factors. Firstly the optical pushbroom sweeps all the energy stored in the grating out in a short