Nonlinear switching in a 20cm long fibre Bragg grating

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Abstract

We report experimental observation of nonlinear all-optical switching of a 20cm long fibre Bragg grating. The grating is self-switched due to the optical Kerr effect and in the nonlinear regime shows a 20dB increase in the transmissivity.

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1 Introduction

In a nonlinear Bragg grating a wide variety of nonlinear effects have been predicted to occur from optical bistability[1] and soliton formation to enhanced 2nd harmonic generation. Consequently Bragg gratings have been proposed as the basis for optical memories and all-optical logic gates. Most of these proposals rely on the concept of the gap soliton which is a solitary wave capable of propagating through the grating at frequencies within the bandgap. Furthermore gap solitons are able to travel at any speed between zero and the speed of light.

Although light propagation within nonlinear Bragg gratings is well understood theoretically, it is only comparatively recently that experimentalists have been able to test some of the predictions. Eggleton et al.[2] examined nonlinear propagation at frequencies outside the bandgap. At these frequencies the Bragg grating is well described by the nonlinear Schrödinger equation (with some interesting twists) which allow a good theoretical understanding of the results. As the frequency of the light moves closer towards the centre of the band gap such a simplified description is no longer valid and the full nonlinear coupled mode equations must be used. It is in this regime that most of the interesting predictions have been made and it is thus important to perform nonlinear propagation experiments over the entire frequency bandwidth of the grating. Earlier we performed such a series of experiments using an 8cm long apodised grating[3, 4] which confirmed some of the earlier theoretical predictions. However there were two undesirable features of this set of experiments. Firstly, the gratings were strongly apodised and hence the solitons spent a significant fraction of the time propagating outside the local bandgap. Secondly, the length of the grating meant that we were unable to distinguish between effects due to the formation of gap solitons and actual propagation effects.

These considerations led us to the conclusion that in order to fully explore gap soliton behaviour one needs long Bragg gratings with at most a gentle apodisation (which would enhance the coupling of light into the grating). Furthermore, long weak gratings should have a reduced threshold for nonlinear effects allowing switching to be observed at lower powers than shorter gratings with the same reflectivity. For these reasons we fabricated a number of gratings of length 20cm which allowed us to examine the propagation through long fibre Bragg gratings. The gratings used in these experiments had the same maximum refractive index modulation depth as our earlier 8cm long grating. This means that in both cases the intensity needed to see nonlinear effects should be similar ($\sim$ 1 kW) and that the only difference in results should come from the differing propagation lengths.

2 Experimental Results

The gratings were written using a fixed phase mask -scanning fibre technique[5] which is capable of producing 1m long gratings with arbitrary phase and amplitude along their lengths. Furthermore the 20cm long gratings were apodised over the first and last 4cm regions, with a $\cos^2$ profile, to reduce the out-of-gap reflections and improve the nonlinear coupling into the grating. The measured reflection profiles of the grating used in the experiments reported here are shown in Fig. 1, note that its bandwidth is 40pm which is large compared to the bandwidth of the source ($<$ 10pm). By comparing the measured spectra to theoretical ones obtained by solving the coupled mode equations we find that for the gratings in question $\kappa = 0.8\,\mathrm{cm}^{-1}$.

In order to see clearly nonlinear behaviour in our gratings we needed to probe them with high power narrow linewidth radiation. We used an externally modulated laser diode to produce near transform limited 5ns pulses at a adjustable repetition rate of between 1-10kHz. These pulses were then amplified in a series of erbium fibre amplifiers each separated by a acousto-optic modulator which were time gated to reduce the ASE buildup between the pulses. The final stage amplifier is based on a specially fabricated large mode area fibre. After the final stage amplifier the pulses are roughly triangular with a ~ 50 ps rise time and a 2ns fall time (see insert in Fig.2b) and have a spectral width of < 0.01nm.

The input pulses were then coupled into the FBG as in our previous experiment[3]. The maximum coupling achieved was $\sim 30\%$. Both the transmitted and reflected light were detected using a fiberised detection system based around a fast PIN photodiode and a sampling oscilloscope. The temporal resolution of the system was ~ 50ps.

Initially we performed experiments using the 20cm grating shown in Fig. 1 and as expected we were able to see clear evidence of nonlinear propagation. In Fig. 2(a) we show the increase in the transmissivity of the grating at high input powers. In these experiments the pulse was tuned to lie just inside the bandgap on the short wavelength side where the linear transmission was -35dB. Then, as we increased the power, we observed an almost exponential increase in the transmissivity of the device. This increase is due to the formation of multiple pulses which propagates through the grating carrying a significant fraction of the input pulse energy. The output pulse shapes for two different power levels can be seen in Fig. 2b. There is a marked difference in the shape of the transmitted pulse in the nonlinear regime from both the input pulse and the linear transmitted pulse. Integrating the energy contained in the traces we find that the transmitted energy increased by a factor of 1000 in the high power regime even though the incident energy increased by only a factor of 5. This is to our knowledge the best contrast obtained in switching experiments involving nonlinear Bragg gratings and is primarily due to the longer length of grating used.

It can also be seen that the transmitted pulse shape changes markedly as the power increases. In Fig. 2b the formation of 6 distinct pulses can be seen which correspond to the formation of six gap solitons which then propagate through the grating. This process agrees with the our numerical simulations and we expecte that better agreement will be obtained as we improve the accuracy of our model especially regarding the input pulse shape. We note that we have examined the nonlinear propagation for differing wavelengths right across the bandgap but due to lack of space we do not present these results here.

3 Conclusion

We have presented experimental evidence of nonlinear propagation in long fibre Bragg gratings. In a 20cm grating we obtained excellent switching and observe the formation of multiple gap solitons. The formation of multiple gap solitons results in a 20dB increase in the transmissivity of the device. These results are also in agreement with our numerical modelling although much work needs to be done to accurately model the system and to properly decouple the pulse formation and propagation effects. For the pulse lengths and spectral widths used we find that the maximum input intensity is limited by the onset of stimulated Brillouin scattering. However it should be possible to overcome SBS by increasing the bandwidth of the pulse and thus we expect to be able to see nonlinear effects in longer gratings in the near future.

Comparing these results to our earlier results with a 8cm grating we find that the threshold for the formation of nonlinear pulses is very similar in both cases. In addition the output pulse shapes are again similar in both instances which is to be expected if as we have claimed these pulses are gap solitons. This suggests that we can study the propagation of solitons by using identical gratings of varying lengths provided that the refractive index modulation is identical in all cases. In addition we intend to look at long weak gratings as in these cases the power threshold for soliton formation should be below the SBS threshold.

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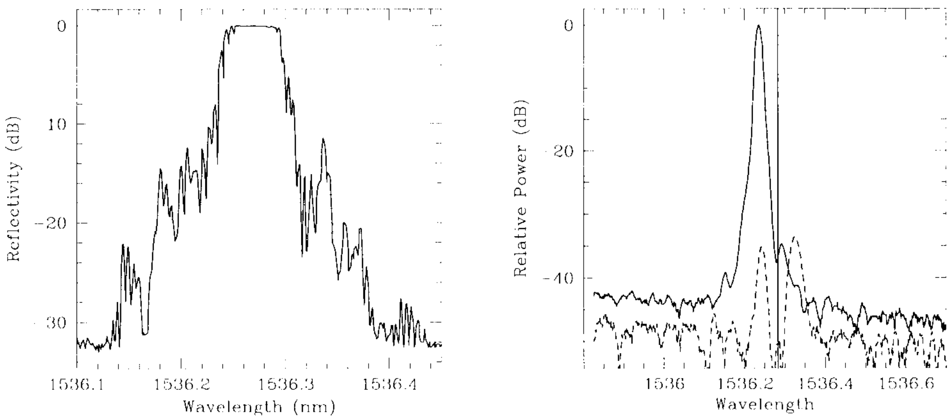

Figure 1: Measured reflection spectrum of the 20cm grating and pulse extinction. Fig.b shows the transmitted spectra of pulses tuned to lie either outside (solid line) or within (dashed line) the grating's bandgap. Note that an extinction of greater than 50dB can be seen.

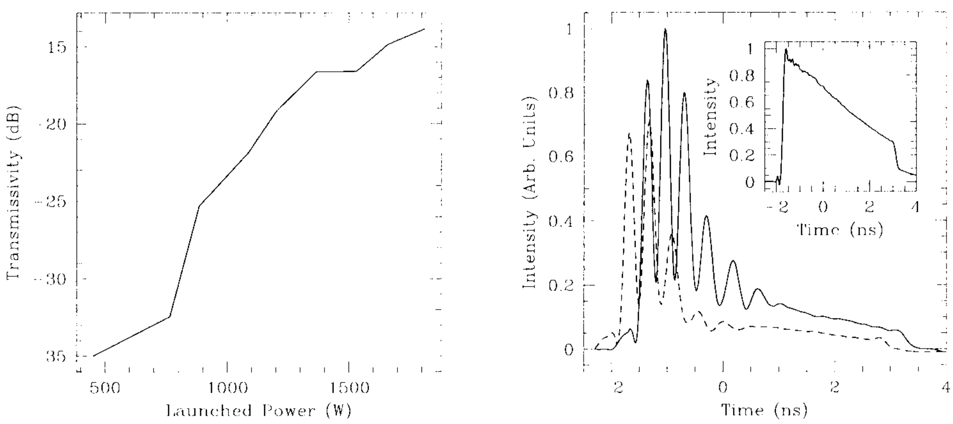

Figure 2: Nonlinear increase in the transmissivity of the grating at high powers and associated pulse formation. Note that at high powers the pulse has broken up into 5 distinct pulses.