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Nonlinear switching in a 20cm long fibre Bragg gratings

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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. This is a marked improvement from the switching results shown in shorter gratings.

In a nonlinear Bragg grating a wide variety of nonlinear effects have been predicted to occur from optical bistability[1] and soliton formation[2] to enhanced 2nd harmonic generation[3]. 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[4] 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[5].

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.[6,7] 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[8]. As the frequency of the light moves closer towards the centre of the band gap such a simplified description is no longer valid and the full nonlinear coupled mode equations must be used[4]. 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[9,10] which confirmed some of the earlier theoretical predictions. However there were some undesirable features of this set of experiments. Firstly, the gratings had a cosine apodisation profile and the pulses used were tuned to the short wavelength edge of the grating. Hence the solitons spent a significant fraction of the time propagating outside the local bandgap in addition the detuning of the soliton from the bandgap was constantly changing altering the propagation characteristics. Secondly, the length of the grating was approximately equal to the soliton period and this 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 to enhance the coupling of light into the grating[11]. 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 peak reflectivity. For these reasons we fabricated a 20cm FBG with the intention of examining nonlinear propagation in it. The grating 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.

Clearly in order to use such gratings high power narrow-linewidth pulses must be used whose frequency bandwidth is smaller than the bandwidth of the grating. In our earlier experiments we used a directly modulated diode pulse whose rising edge was strongly chirped and which had a spectral width greater than the grating. However the rest of the pulse which contained most of the energy was unchirped and gave useful results. As a result of the chirped leading edge $\sim$ 10% of the light was transmitted through the grating in the form of a 100ps pulse even in the linear region. This pulse maintained its relative shape which allowed an estimate to be made of the soliton energy compared to the input pulse but for switching experiments it limited the switching contrast ratio considerablely. Hence in these experiments we used an externally modulated diode in order to reduce the amount of chirp on the leading edge of the pulse.

The gratings were written using a fixed phase mask -scanning fibre technique[12] which is capable of producing 1m long gratings with essentially arbitrary phase and amplitude along their lengths. Furthermore the 20cm long grating was apodised over the first and last 4cm regions, with a $\cos^2$ profile, to reduce the out-of-gap reflections and to improve the nonlinear coupling into the grating. The measured reflection profile of the grating used in the experiments reported here is 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 the grating strength $\kappa = 0.8\,\mathrm{cm}^{-1}$.

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[13]. 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. A small fraction of the light from the diode (before modulation) was coupled into a wavemeter allowing accurate measurement of the wavelength.

The input pulses were then coupled into the FBG as in our previous experiment[9]. The maximum coupling achieved was $\sim 30\%$. The transmitted light was coupled into a 90:10 fibre coupler allowing simultaneous measurements of both the spectrum and temporal pulse shape. The temporal shape was measured using a fast PIN photodiode and a sampling oscilloscope giving a temporal resolution of the system of $\sim$ 50ps. Initially we measured the linear transmission of the grating as a function of the detuning and typical results are shown in Fig. 2. The solid line in Fig. 2 shows the transmitted pulse spectrum when it is detuned to lie on the short wavelength (λ=1536.220nm) side of the grating's bandgap. The dashed line shows the transmitted spectra for a pulse tuned to lie near the centre of the bandgap (λ = 1536.238nm). The vertical solid line indicates were the peak of the 2nd spectrum should be. Note that for the peak 50dB extinction can be seen as expected given the length and strength of the grating.

After measuring the linear transmission we selected a wavelength near the short wavelength edge of the bandgap where the linear transmission was -35dB and measured the transmissivity as a function of the input power (for pulses with a repetition rate of 4kHz and a width of 5ns). These results are shown in Fig. 4 which shows a clear exponential increase in the transmission as the power is increased giving a 23dB increase in the switched energy at high powers. These results were obtained by measuring the output pulse shapes and then integrating to find the transmitted energy. 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.

The reason for the increase in the transmissivity at high powers is due to the formation of gap solitons which propagate along the grating. Indeed we saw evidence of this previously using an 8cm grating and this has been predicted theoretically as well. In Fig. 4 we show the output pulse shapes for a range of launched input powers – 463W and 1081W for Fig 4(a) and 1523W and 1795W for Fig. 4(b). In Fig. 4b 6 distinct pulses can be seen which correspond to the formation of six gap solitons which then propagate through the grating. The formation of gap solitons through modulational instibility is at present poorly understood and is a highly nonlinear problem as can be seen in Fig. 4b where at higher powers the peak intensities of the 2nd and 3rd peaks are either higher or equal to the intensity of the front peak even though the input pulse is monotonically decreasing. 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.

For the high power trace in Fig. 4(b) the widths of the four main peaks are 166ps, 130ps, 190ps and 210ps respectively. In addition the time between the peaks is 310ps, 350ps and 390ps. For gap solitons it is known that narrower solitons should have an increased peak power[5] which is the case here. In addition more intense solitons should move faster than less intense ones which is in agreement with the data on the pulse arrival times shown here. However as we do not know when the solitons were formed it is not possible to determine the actual velocity of the solitons without breaking the grating at some point and looking at the output.

As the grating used in this experiment had the same refractive index modulation depth and apodisation profile as the 8cm grating used in the earlier experiments[9] the solitons should be formed at approximately the same powers as previously and have similar pulse widths. This is indeed the case suggesting that the solitons were formed in the first few centimetres of the grating and then propagated unchanged through the rest of the grating and this agrees with what we see in numerical simulations. To further test this longer gratings with the same parameters should be used in future experiments. We have examined the propagation in a 40cm grating using the same source[14] but in that case stimulated Brillouin scattering restricted the amount of energy we could usefully couple into the fibre to below that needed to see the formation of multiple solitons. Indeed even with the 20cm grating we saw evidence of Brillouin scattering which reduce the transmission through the grating to less than 20% at high powers even at wavelengths far from the Bragg wavelength. By using weaker grating it should be possible to reduce the threshold for soliton formation below that for SBS.

We have presented experimental evidence of nonlinear propagation in long fibre Bragg gratings. In a 20cm grating we obtained excellent switching and observed 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. The gap solitons formed are similar to those obtained in shorter gratings showing experimentally that such pulses are stable and can propagate over significant lengths (in soliton units). For the pulse lengths and spectral widths used we find that the maximum input intensity is limited by the onset of stimulated Brillouin scattering.

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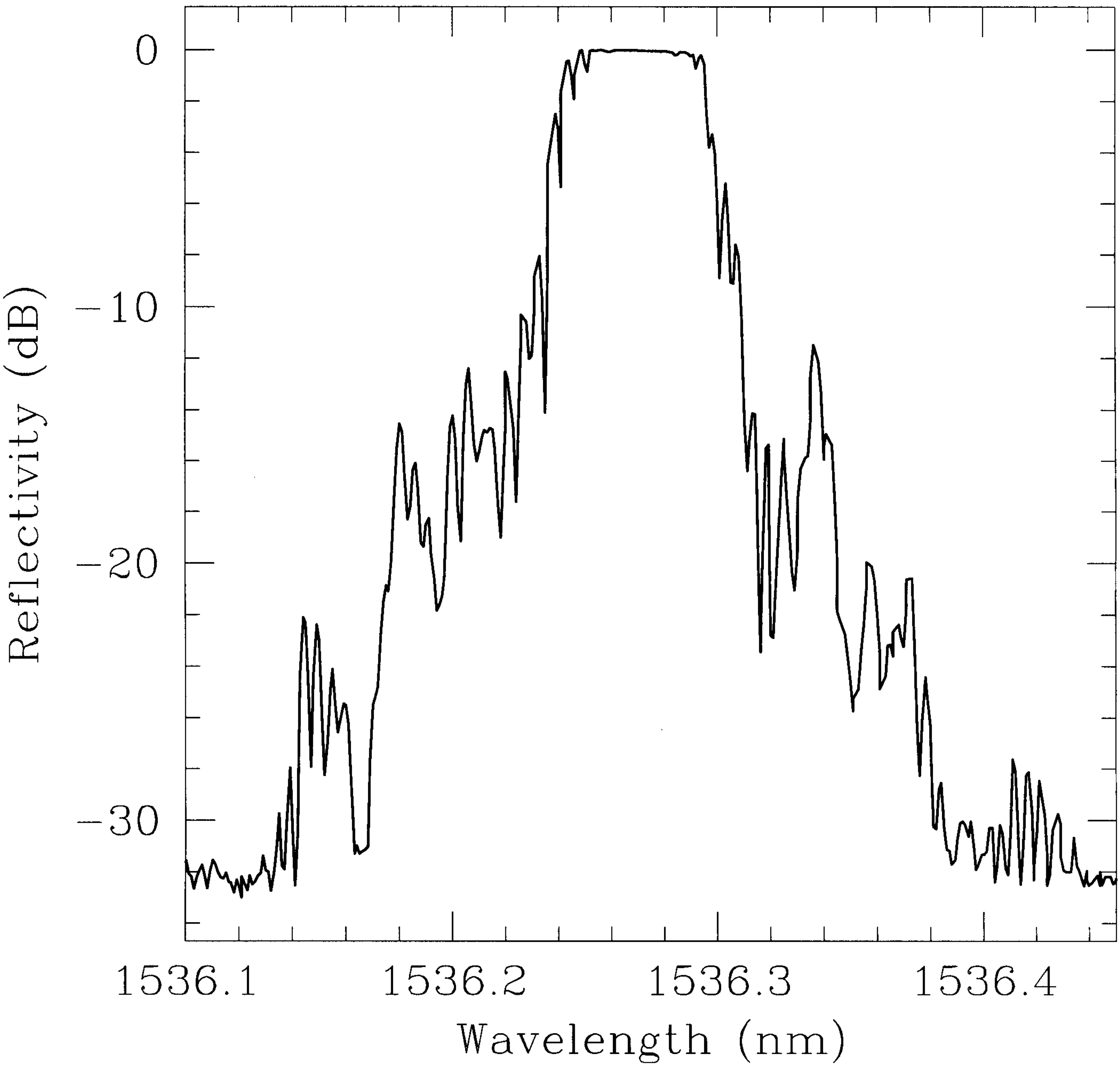
FIGURES

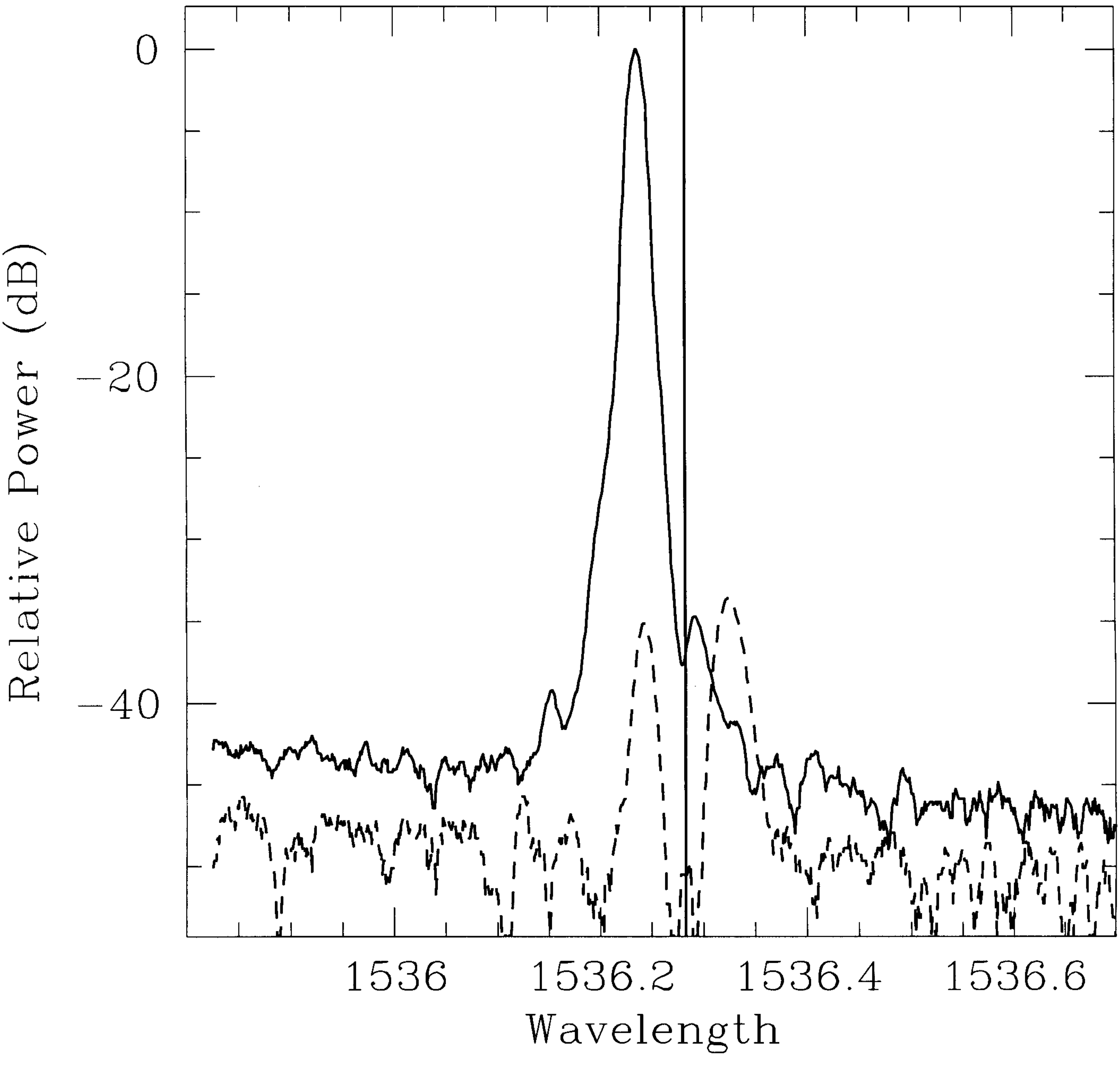
Fig. 1. Measured reflection spectrum of the 20cm grating.

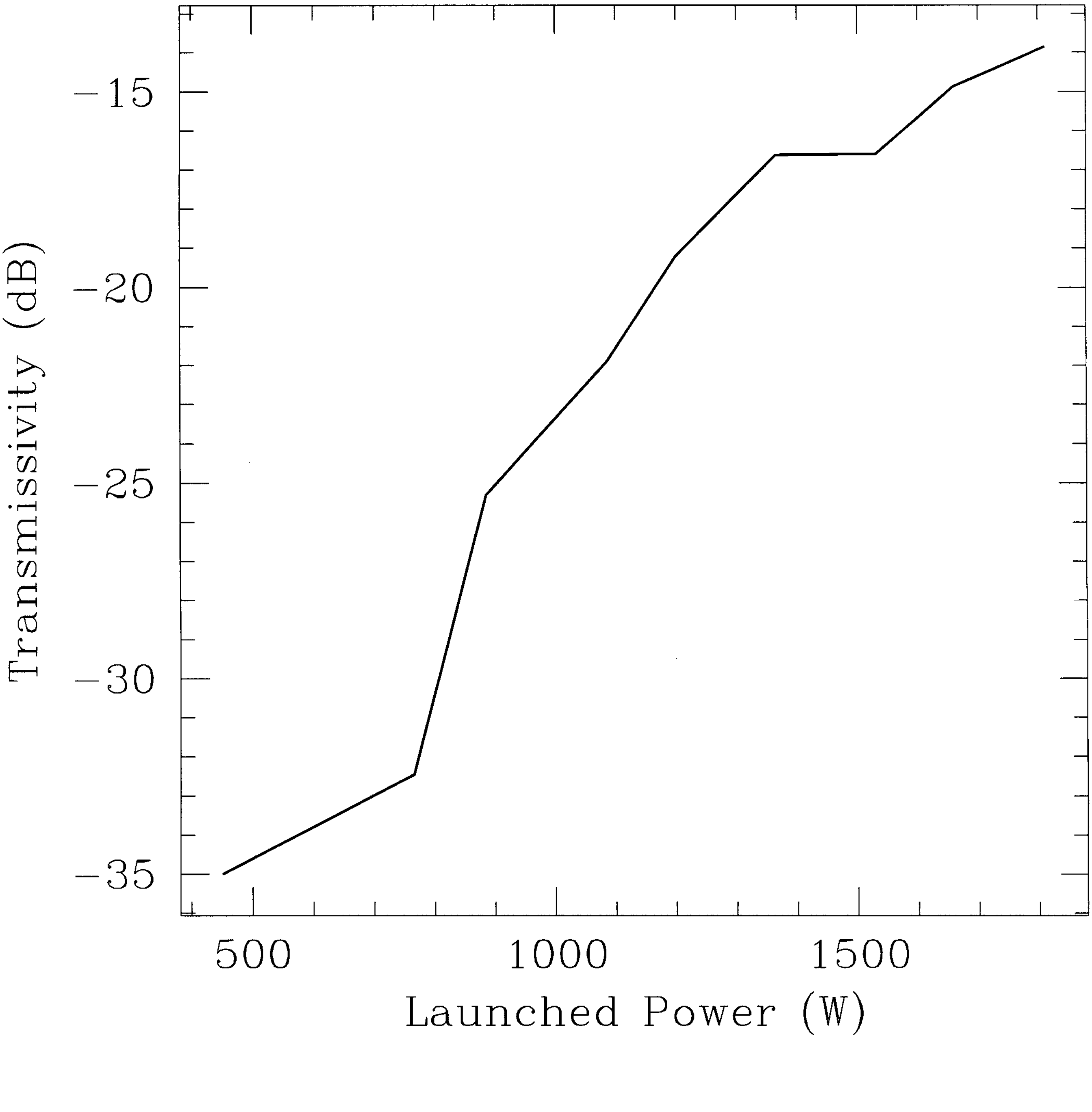
Fig. 2. Transmitted spectra of pulses tuned to lie either outside (solid line) or within (dashed line) the grating's bandgap. The solid vertical line indicates where the peak of the spectrum should be in the second case. Note that an extinction of greater than 50dB can be seen.

Fig. 3. Transmission of the grating as a function of the input power. Note that the transmission is a strong function of the input power indicating that nonlinear switching is occuring.

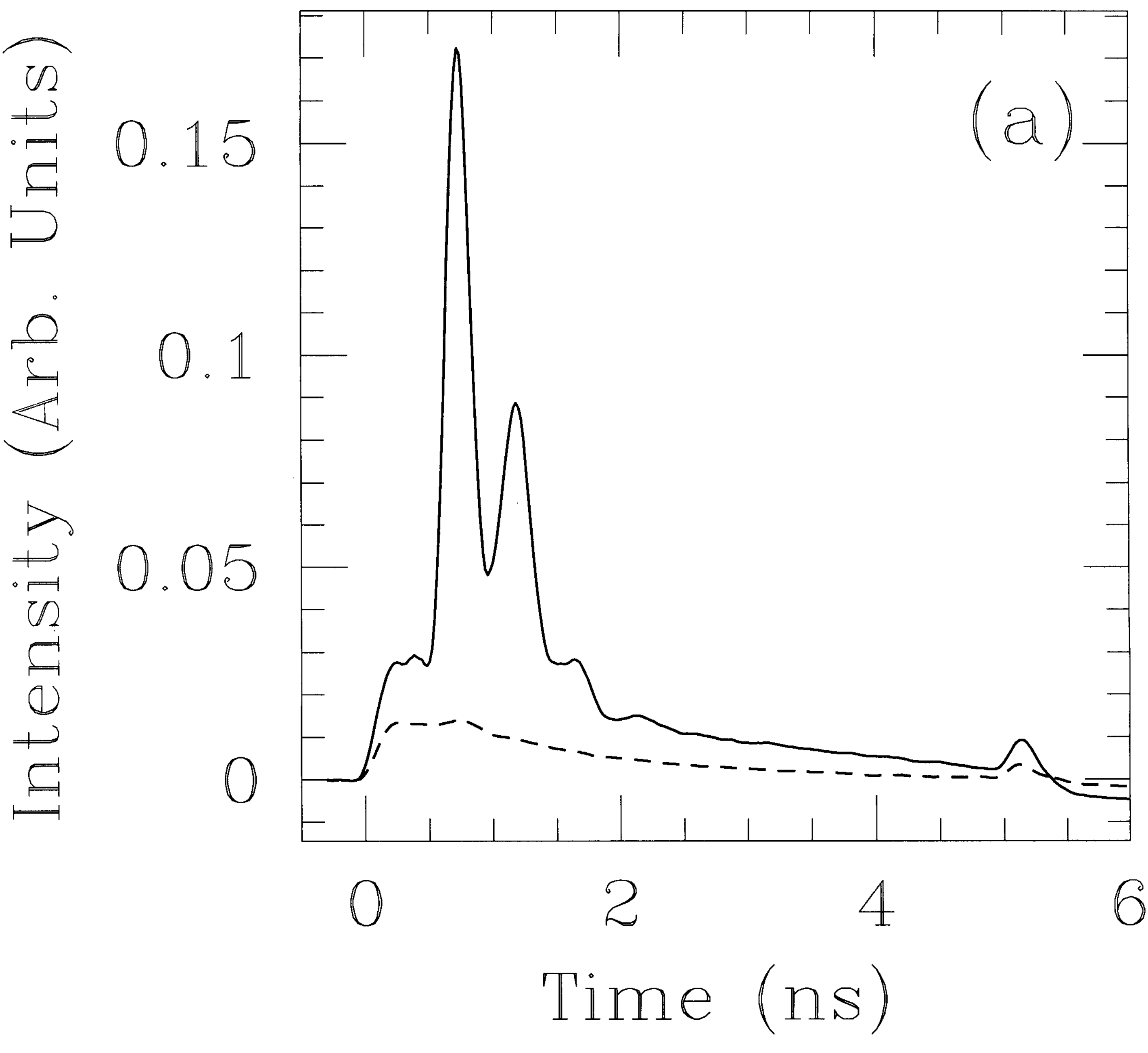
Fig. 4. Pulse formation associated with the formation of gap solitons. Fig.a shows the output for low input powers (launched peak powers of 462W and 1081W for the dashed solid curves respectively) and Fig.b shows the output at high powers (launched peaked powers of 1795W and 1523W for the dashed and solid curves). The insert in Fig.b shows the input pulse shape.


0
−10
−20
−30
Reflectivity (dB)
1536.1
1536.2
1536.3
1536.4
Wavelength (nm)


0
−20
−40
Relative Power (dB)
1536
1536.2
1536.4
1536.6
Wavelength



−15
−20
−25
−30
−35
Transmissivity (dB)
500
1000
1500
Launched Power (W)



(a)
Intensity (Arb. Units)
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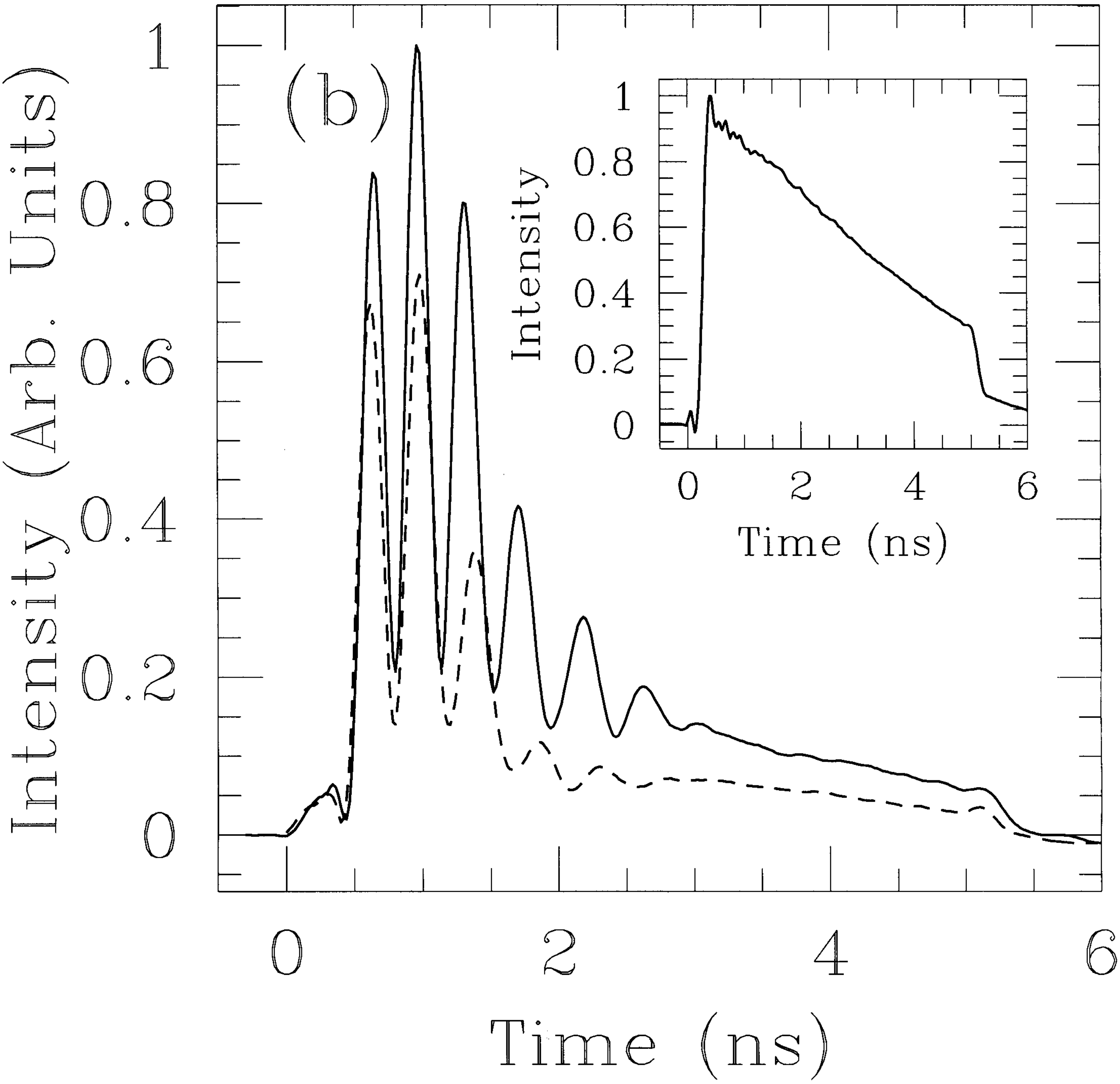
0.1
0.05
0
0
2
4
6
Time (ns)


(b)
Intensity (Arb. Units)
Time (ns)
0
0.2
0.4
0.6
0.8
1
0
2
4
6
Intensity
Time (ns)