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Nonlinear Self-Switching and Multiple Gap Soliton Formation in a Fibre Bragg Grating

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Abstract: We report for the first time the experimental observation of quasi-cw, nonlinear switching and multiple gap soliton formation within the bandgap of a fibre Bragg grating.

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The interplay of the Kerr-induced nonlinear refractive index changes and dispersion in nonlinear Fiber Bragg Gratings (FBGs) leads to a plethora of nonlinear phenomena, the most striking of which is perhaps the formation and propagation of gap solitons [1]. Whilst a considerable amount of theoretical work has been performed in this area [1,2,3,4] experimental observations of nonlinear grating behaviour are limited, principally by the difficulty in getting sufficiently high power densities within the core of a FBG in a suitable spectral and temporal range. In order to reduce the nonlinear threshold for gap soliton formation one can use the somewhat weaker dispersive properties of FBGs outside of the band gap and indeed recent experiments have yielded the first strong evidence of Bragg grating gap soliton formation by this means [5,6]. However, the strongest and most manifestly nonlinear effects are predicted to occur at wavelengths within the band gap, close to the Bragg wavelength of the grating structure and it is therefore essential to make measurements within this regime. In this paper we report what we believe to be the first clear experimental observation of nonlinearity within the band gap of an FBG, namely nonlinear self-switching and, at higher intensities, multiple gap soliton formation.

Our experiments are made within the quasi-cw regime using nanosecond pulses of a physical length several times that of the FBG. Earlier theoretical work (see Ref[1] and reference therein) show that Bragg gratings under CW excitation should exhibit optical bistability within their band-gap. Stability analysis indicates that under certain operating conditions robust, bistable operation is obtained allowing for optical switching. In other operating regimes instability occurs resulting in the formation of periodic trains of gap solitons, that once formed propagate stably through the grating. The instability has been equated to some form of modulation instability [1,6].

The experimental set-up is shown in Figure 1. High power nanosecond pulses were coupled into a FBG through a polarising beam-splitter and quarter wave-plate arrangement that decoupled the incident and reflected signal pulses, allowing simultaneous measurements of the incident, transmitted and reflected beams. The placement of a $\lambda/2$ waveplate before this PBS allowed control of the power incident on the grating. The transmitted, reflected and incident signals were detected with a single-mode fibre coupled PIN photodiode and sampling oscilloscope. Our temporal resolution was ~50ps. The fibre grating was written into a germanosilicate fibre with a mode-area of 30μm^2 (N.A.=0.25, λ_C=1250nm) using a moving fibre/phase-mask scanning beam technique [7]. The grating was 8cm long, unchirped, with a 0-π sinusoidal apodisation profile along its length. The grating had 98% reflectivity at its peak wavelength of 1536nm and was measured to have a transform-limited, 3dB bandwidth of 3.8GHz. The grating was mounted in a glass capillary and angle polished front and back to remove unwanted reflections from these surfaces. The high power pulses were obtained from a large mode area, erbium doped fibre amplifier chain seeded with 10ns pulses from a directly-modulated, wavelength-tunable, semiconductor DFB laser [8]. The source was capable of producing nanosecond pulses with energies >100μJ and peak powers >100kW at kHz repetition rates. For the purposes of this experiment the source was operated at 4kHz repetition rate giving 25μJ pulses with ≈2ns duration (see insert Figure 1). Note that the pulse is highly asymmetric due to amplifier saturation effects and has a sharp ~30ps feature on the leading edge due to chirp on the diode seed pulse. This feature becomes more prominent when examining the pulse transmission through the FBG with the pulse spectrum tuned to lie within the band-gap (see Fig 2, trace a). The chirped spike lies outside the band gap and is transmitted whereas the main body of the pulse is reflected (see Fig.3, trace a). Although aesthetically undesirable this feature actually proved a valuable calibration aid, giving a direct measure in the transmitted pulse time domain of the input pulse power. Note that the corresponding physical pulse lengths were significantly longer than the grating, we were therefore well within the quasi-cw regime and anticipated clean switching and the potential to generate a significant number of gap soliton pulses. The pulse spectrum at the FBG input was measured to have a 3dB spectral bandwidth of 1.2GHz, considerably less than the FBG bandwidth. The central wavelength of the source could be continuously and accurately temperature-tuned to wavelengths in and around the FBG band gap.

We set the source wavelength close to the short wavelength side of the center of the bandgap and examined the grating pulse transmission and reflection characteristics as a function of increasing peak power. The transmission results are summarised in Figure 2. At low powers (Figure 2, trace a) the pulse is seen to be almost completely reflected from the grating other than our chirped rising edge marker. However as the pulse peak power is increased strong pulse reshaping becomes apparent. Figure 2 traces b-d show various stages in the growth of the nonlinearly transmitted pulses. Initially one gap soliton is formed (around 3kW peak power), however as the intensity is increased more solitons are generated. Each subsequent pulse then narrows to ~100ps and moves forward allowing additional pulses to form at the rear of the bunch. We observed the generation of up to 5 gap solitons in our experiments (Figure 2, trace d). Note that the absence of Raman scattering or other nonlinear spectral distortion was confirmed by direct spectral measurements. The corresponding effects of the pulse formation are readily observed in the reflected domain, see Figure 3 traces a-d where progressively larger 'chunks' of energy are seen to be switched from the front of the pulse.

We evaluated the percentage energy transmittance of the FBG as a function of peak power both by integration of the transmitted pulse forms and through direct measurements of the incident, transmitted and reflected average powers. Good agreement was obtained between the two approaches. The results are shown in Figure 4 where it is seen that the transmission switches from about 3% in the linear regime to a saturated level of about 40% for peak powers of ~4kW and above, representing ~11dB switching contrast. Note that the data presented in Figure 4 has been processed to eliminate the contribution of the chirped leading spike to the calculated total transmission.

In conclusion, we report the first observation of optical switching and multiple gap soliton generation within the bandgap of a FBG. Switching from 3% to 40% of the pulse energy is obtained for nanosecond pulses at internal field strengths of order 10-15 GW/cm^2. At higher intensities multiple gap solitons were obtained. We have experimentally observed the formation of up to 5 gap soliton with durations in the range 100-500ps. We believe these results to represent a significant step in the study of nonlinear FBG effects and indicate that the combination of high power fiber based 1550nm sources, coupled to recent improvements in FBG fabrication techniques should allow for further advancements in such studies.

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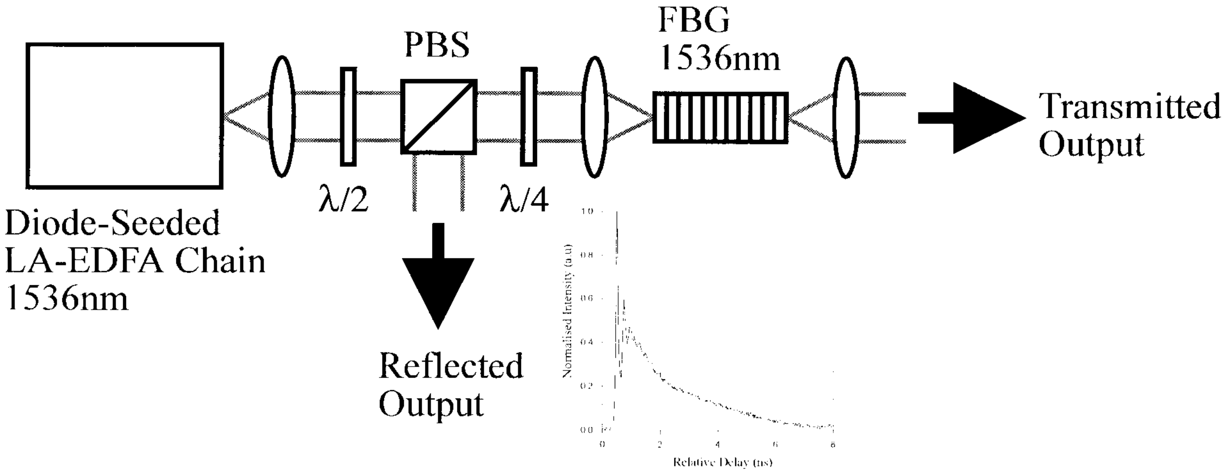

Figure 1: Experimental setup. LA-EDFA: Large mode-area erbium-doped fibre amplifier. PBS: Polarisation beamsplitter. FBG: Fibre Bragg grating. The pulse intensity profile incident on the grating is shown inset.

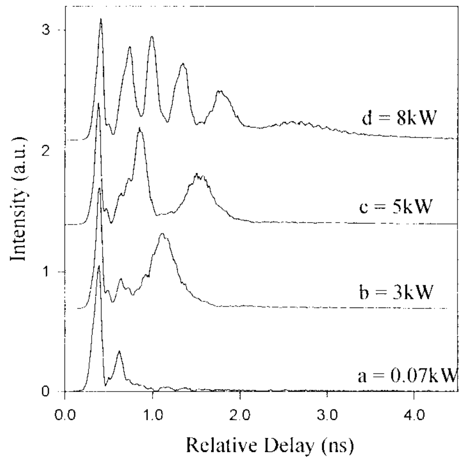

Figure 3: Transmitted pulse intensity profiles with increasing launched peak power from a-d. Each trace is normalised to a peak of 1.

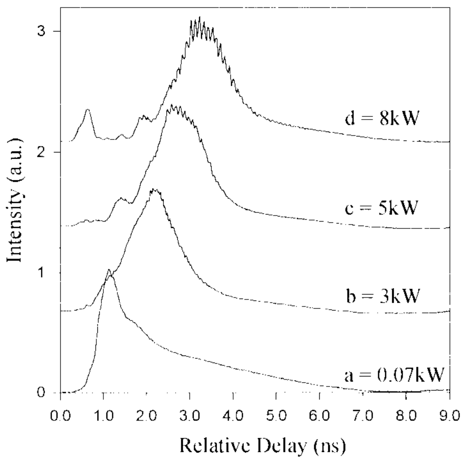

Figure 4: Reflected pulse intensity profiles with increasing launched peak power from a-d. Each trace is normalised to a peak of 1.

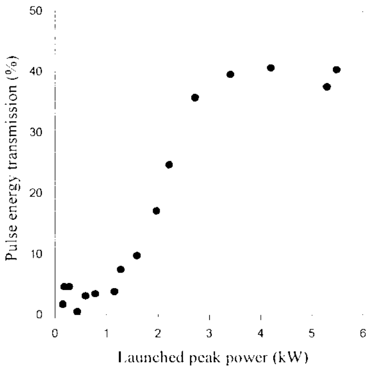

Figure 5: Percentage of pulse energy transmitted through grating.