Soliton Interaction in Fiber Bragg Gratings: Optical AND Gate Formation

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Relatively high anomalous dispersion within a fiber Bragg grating is balanced by self phase modulation associated with the Kerr effect and results in soliton formation in length scales two orders of magnitude shorter($\sim$10cm) than in traditional fibers. A chirped grating is used to simulate an AND gate by using coupled gap solitons as the inputs. The power, duration, and delay between such coupled solitons controls the switching ratio of the gate, which has been demonstrated to be as high as 65dB.

1   Introduction

High bit rate optical fibers are the future of telecommunications and optical computing. For the past several decades, advances in research have shown that all-optical switching has the potential to replace electrical systems and subsequently lead to higher bit rate (40Gb/s+) networks. Several research groups have duplicated electrical logic devices with optical soliton interactions in a fiber. One special class of fiber, a fiber Bragg grating (FBG), has been used to duplicate an AND gate while using relatively short lengths of fiber($\sim$10cm). The use of solitons yields low signal loss and distortion while allowing for longer propagation lengths conducive to multiple gate interactions.

We begin by describing the relevant aspects of FBGs, gap solitons, and optical AND gates. Ultimately, we move on to review a numerical simulation of an all-optical chirped FBG AND gate by Shapira and Horowitz[1].

2   Background Information

2.1   Fiber Bragg Gratings

Fiber Bragg Gratings (FBGs) are spectral filters formed inside segments of optical fibers. These spectral filters result from a small periodic index change (typically $10^{-3} - 10^{-4}$) within the fiber resulting in multiple small relections. When the period between these reflecting structures gives rise to constructively interfering reflections, the corresponding range of wavelengths is strongly reflected. The cumulative effect is to reflect a narrow spectrum ($\sim$.2nm) while transmitting the remaining wavelengths. The center of the reflected spectrum, given by the Bragg wavelength, is determined by the period of the index change, Λ, the average refractive index, n, and is given by Eq.(1). The reflected spectrum is referred to as the photonic bandgap of the Bragg grating.

$$\lambda_{Bragg} = 2n\Lambda \qquad (1)$$

By creating FBGs with linearly varying periodic structures, it is possible to produce a chirped grating that reflects a wider spectrum ($\sim$10's of nm). These chirped FBGs, Fig.(1),

produce anomalous dispersion which, for high intensities of light, can be balanced through self phase modulation (SPM) associated with the Kerr effect. This balance of dispersion and SPM make FBGs attractive for soliton studies. Other applications of FBGs include fiber telecommunications systems and optical amplification. Coupled with dispersion compensating fibers, data rates in excess of 40 Gb/s are envisioned for the future.
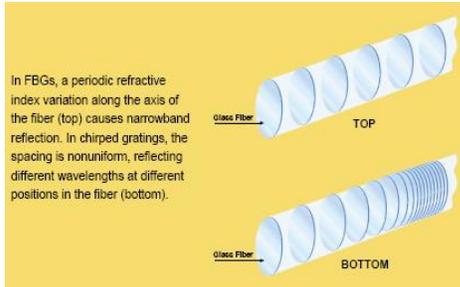
Figure 1: FBG and chirped FBG.

2.2 Gap Soliton Formation

A Bragg soliton is a solitary wave that propagates within an FBG as the result of balancing dispersion and SPM from the Bragg reflections. These solitons propagate without any significant change in shape and can be transmitted into other fibers. As compared to typical fiber solitons, Bragg solitons form two orders of magnitude earlier in length: centimeters compared to tens of meters. A gap soliton is a subclass of Bragg soliton where the center wavelength of the spectrum is located within the photonic bandgap of the Bragg grating. Fig.(2) shows the relative size of the gap soliton and photonic bandgap. A gap soliton may still have portions of its spectrum outside of the photonic bandgap. If this is the case, the portion of the spectrum outside of the bandgap will be transmitted while the remainder is reflected.

2.3 Optical AND Gate Operation

Optical AND gates can be formed through numerous techniques, and here we will focus on an optical AND gate resulting from coupled gap
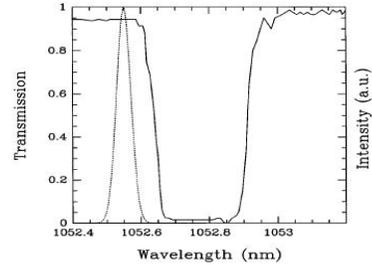
Figure 2: Example of transmission through the BFG, showing the photonic bandgap. The dotted curve illustrates the spectrum of wavelengths in a typical soliton.

solitons inside a FBG. In general, an AND gate must take two boolean inputs of either 'true' or 'false' value, giving an output of 'true' only when both inputs are 'true'. Here we consider how the absence and presence of two gap solitons can function as these two inputs.

A single gap soliton is reflected by the FBG. This corresponds to one 'true' and one 'false' input in the optical AND gate, yielding a 'false' output. However, it is possible to introduce another gap soliton to shift the spectral center of the first soliton. If this shift is sufficiently large, one soliton no longer has a center wavelength within the photonic bandgap and is transmitted through the FBG. The other soliton remains in the gap and is reflected. It should be noted that by tuning the amount of shift, one can control the percentage of the soliton energy that is transmitted. This necessitates a cut-off condition for a 'true' value from the gate. Usually, this cut-off condition is given in terms of gain(dB) with respect to the single soliton case, and can be taylored to specific systems.

3 Numerical Results Using Soliton Interaction

3.1 Numerical Results

The numerical simulation given by Shapira and Horowitz[1] uses a multi-region chirped FBG as shown in Fig.(3). This chirped FBG can act like an AND gate for two solitons of sufficiently large power and sufficiently small time delay. In Re-

gion I the velocity of the first soliton is slowed down by the chirped grating. When two solitons are launched, this velocity reduction serves to increase the interaction of the two solitons by bringing them closer spatially. As a result, for solitons with center wavelength near the short wavelength side of the bandgap, one of the solitons increases in frequency and transmits while the other decreases in frequency and is backreflected. See Fig.(4) for a diagram of this process. Region II is a region of constant grating in which the transmitted soliton stabilizes. Finally, region III is chirped with the negative slope of Region I and restores soliton parameters near to their initial states.
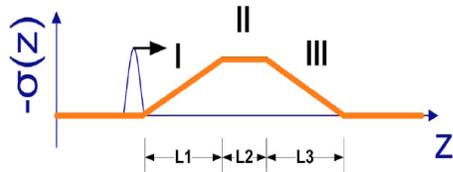
Figure 3: Schematic structure of the chirped FBG. Region I is used to obtain the soliton interaction and to reflect a single soliton. Region II is used to stabilize the transmitted soliton. Region III is used to obtain a soliton at the output of the device with parameters similar to those of the input soliton.
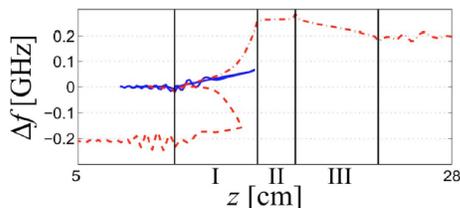
Figure 4: Central frequency shift of the solitons Δf as a function of the location when a single soliton is launched (solid curve) and when two solitons are launched (dashed and dashed–dotted curves, corresponding to the trailing and the forward solitons, respectively). The vertical lines mark the different regions of the grating.

The propagation of pulses within a FBG can be analyzed by use of the coupled-mode equation[1]

$$\pm i\partial_z u_\pm + iV_g^{-1}\partial_t u_\pm + \kappa u_\mp \qquad (2)$$

$$+\Gamma(|u_\pm|^2 + 2|u_\mp|^2)u_\pm + \sigma(z)u_\pm = 0$$

where $u_\pm$ is the slowly varying amplitude of the forward and backward propagating waves, $\sigma(z)$ is the chirp parameter, $\kappa = 9000m^{-1}$ is the grating amplitude, $\Gamma = .005m^{-1}W^{-1}$ is the nonlinear coefficient, $V_g = c/n_{eff}$ is the fiber group velocity, and $n_{eff} = 1.45$ is the effective refractive index.

For region lengths of $L_1 = L_3 = 5.11cm$, $L_2 = 2.34$, and chirp parameter slopes of $\sigma_1 = -\sigma_3 = -888.594m^{-2}$, and chirp parameter $\sigma_2 = -45.41m^{-1}$, it can be shown for solitons of 18.85ps duration, 94ps delay, and peak power of 3.02 kW that such a fiber acts as an AND gate. These results, shown in Fig.(5), demonstrate a switching ratio, defined as the ratio of output energies between the two soliton and single soliton case, of about 65dB.

Eq.(3)[1] describes the shift in soliton carrier frequency where Ω is the Bragg Frequency and Ω_0 is the initial detuning of the soliton from the Bragg frequency. For a switching ratio of 65dB from above, the shift resulting from two soliton interaction is .2Ghz. Varying the frequency shift of a single soliton, it was demonstrated that a shift as small as .05 GHz could result in soliton transmission. Typical delay between two solitons for AND gate operation is smaller than 10 times the FWHM of the soliton.

$$\Delta f = \Omega - \sigma(z)V_g - \Omega_0 \qquad (3)$$

4 Summary

The relatively high anomalous dispersion within a FBG is balanced by SPM associated with the Kerr effect and results in soliton formation in length scales two orders of magnitude shorter($\sim$10cm) than in traditional fibers. Using a chirped FBG it is possible to simulate an AND gate by using coupled gap solitons as the inputs. The power, duration, and delay between such coupled solitons controls the switching ratio of the gate, which has been demonstrated to be as high as 65dB.
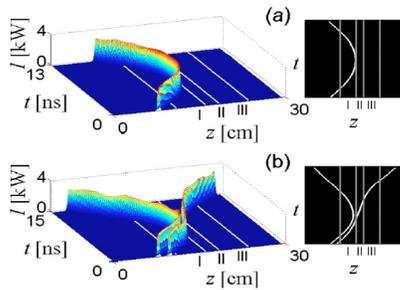
Figure 5: Simulation results showing the intensity I of the wave propagating in the device when (a) a single soliton is launched and when (b) two solitons are launched. The relative phase and the delay between the solitons are equal to 5.1 rad and 94 ps, respectively. The 2D plots give an upper view of the solitons' trajectories. The straight lines mark the different regions of the grating.

References

1. Y.P. Shapira and M. Horowitz, "Optical AND gate based on soliton interaction in a fiber Bragg grating," Opt. Lett. **32**, 1211-1213 (2007).

2. N.G.R. Broderick, D.J. Richardson, and M. Ibsen, Opt. Lett. **25**, 536 (2000).

3. B.J. Eggleton, R.E. Slusher, C.M. de Sterke, P.A. Krug, and J.E. Sipe, Phys. Rev. Lett. **76**, 1627 (1996).

4. D. Taverner, N.G.R. Broderick, D.J. Richardson, M. Ibsen, and R.I. Laming, Opt. Lett. **23**, 259 (1998).

5. S. Pereira and J.E. Sipe, Opt. Express **3**, 418 (1998).

6. N.M. Litchinitser, B.J. Eggleton, C.M. de Sterke, A.B. Aceves, and G.P. Agrawal, "Interaction of Bragg solitons in fiber gratings," J. Opt. Soc. Am. B **16**, 18-23 (1998).

7. R.E. Slusher, B.J. Eggleton, T.A. Strasser, and C.M. de Sterke, "Nonlinear pulse reflections from chirped fiber gratings," Opt. Express **3**, 465-475 (1998).

8. F. Ouellette, "Fiber Bragg gratings," SPIE OE Magazine, 38-41 (January 2001).