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All-Optical Modulation and Demultiplexing Systems with Significant Timing Jitter Tolerance through Incorporation of Pulse-Shaping Fiber Bragg Gratings

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Abstract

We demonstrate the use of a superstructured fiber Bragg grating to pre-shape optical pulses to obtain more-optimal operation of nonlinear, all-optical switches. Specifically we demonstrate the conversion of 2.5ps soliton pulses into 20ps rectangular pulses at the input to both fiber and semiconductor optical amplifier (SOA-) based switches and show that rectangular switching windows can be achieved thereby providing a 5-10-fold reduction in timing jitter sensitivity. Error-free, penalty-free OTDM switching was readily achieved over a +/- 7ps timing mismatch range for the square pulse driven fiber NOLM switch versus a +/- 1ps range for the switch driven directly with the 2.5ps laser pulses.

I. Introduction

Single channel data rates approaching the Tbit/s level have now been reported for optical time division multiplexing (OTDM) systems placing increased demands and tolerances on the techniques used to multiplex and demultiplex the optical data bits [1]. Consider for example the case of optical demultiplexing. As OTDM data rates increase, and the pulses used get correspondingly shorter, the synchronization requirements placed on the locally generated pulses used to control the switch operation can become a limiting practical issue. The key to reducing time jitter tolerance in such devices is to establish a rectangular temporal switching window [2,3]. This reduces the absolute accuracy for temporal bit alignment and provides optimal resilience to timing jitter-induced errors. A fiber based nonlinear optical loop mirror (NOLM) demultiplexing scheme that provides good ultrafast performance and tolerance to timing-jitter of either, or both, of the control and data signals has been demonstrated previously [3,4]. These schemes use the difference in group velocity and the resultant 'walk-off ' between the control and data signals within the nonlinear medium to define the rectangular switching window. This consequently requires tight specification and control of both the data and signal wavelengths, and the dispersion characteristics of the fiber. Whilst this approach is applicable to fiber based switches it is complex and cannot be applied to switches based on highly nonlinear semiconductors and within which there are no appreciable dispersive propagation effects over the length scales of relevance. Simple, robust techniques that can help reduce time jitter tolerances and that are applicable to a variety of switching mechanisms are thus of great interest.

The most obvious way to generate a rectangular switching window is to use rectangular control pulses and to eliminate, or at least minimize, all dispersive effects within the device. However, until recently it has not been straightforward to reliably generate short (<20ps) rectangular pulses. In this paper we report the use of superstructured fiber Bragg gratings

(SSFBGs) to convert the output of an actively mode-locked, 2.5ps fiber laser, an excellent source of short pulses of a well-defined soliton shape, to 20ps rectangular pulses [5]. These pulses are then used to control the operation of two sorts of nonlinear switch. High quality, ~15-20ps rectangular switching windows are obtained, providing +/-7ps, 15ps timing jitter tolerance, in switches based on both the Kerr effect in dispersion shifted fiber (DSF), and four-wave mixing in a semiconductor amplifier (SOA).

II. Experiment setup and results

Our experimental setup is shown in Fig.1. Pulses from a 2.5ps, 10GHz, regeneratively mode locked erbium fiber ring laser (EFRL) operating at 1557nm were first split using a coupler into two separate channels. The first channel was gated down to 2.5GHz and modulated to provide a 2^7-1 pseudorandom data sequence of 2.5ps pulses at 2.5 Gbit/s using a high-speed LiNBO$_3$ modulator. These pulses were then fed onto a pulse-shaping SSFBG fabricated with the correct phase and amplitude reflectivity profile to convert the 2.5ps solitons into 20ps rectangular pulses. The characteristics of the particular grating and details of how it both operates and performs as a rectangular pulse generator have been previously reported [5]. The measured triangular autocorrelation profile of the rectangular pulses so generated along with their optical spectrum (see inset Fig. 2) is shown in Fig. 2, along with the autocorrelation of the original 2.5ps soliton laser pulses.

The other component of the 10 GHz, 2.5ps pulse stream split-off from the laser was first amplified and then fed to the control port of a dual-wavelength NOLM that we employed as a wavelength converter (WC). The WC-NOLM incorporated a 1km long DSF with a zero dispersion wavelength of λ_0= 1550nm. This nonlinear switch allowed us to modulate the output of a continuous-wave DFB laser operating at 1544nm using the 1557nm control pulses. By appropriately setting the loss and polarization of light within the WC-NOLM, and filtering out the 1557nm control pulses at the loop output, we were able to generate a 10 GHz train of high-quality, 3.5ps pulses at 1544nm (Fig.2). Importantly, for this demonstration, this pulse train was synchronized to 2.5Gbit/s data stream generated within the first channel. Having generated these two synchronized pulse streams at two different wavelengths, we were in a position to measure the switching characteristics of two-wavelength nonlinear switches controlled by either 2.5Gbit/s, 20ps rectangular pulses, or 2.5ps soliton pulses at 1557nm.

The first switch that we investigated was a dual-wavelength NOLM similar to that used for the wavelength conversion process. In this instance however, the control signal was now a data-modulated signal, and the signal to be switched was a 10 GHz train of 3.5ps optical pulses at 1544nm. The system thus operated as an all-optical modulator in this configuration and which for convenience we refer to as an M-NOLM. Note that by reversing the input and control signals the system could be configured to act as an all-optical demultiplexer. The 1544nm pulse train incident to the switch was first passed through a tuneable delay line to allow us to adjust the arrival time of the 1544nm pulses relative to the rectangular control pulses. By adjusting and measuring this relative arrival time delay and monitoring the loop output at 1544nm, (for a suitable control pulse power), we were able to determine the switching window of the device and to establish its sensitivity to timing-jitter.

In Fig. 3 we plot both the experimentally observed and theoretically predicted switching window of the M-NOLM operating at 1544nm using both 20ps square and 2.5ps control pulses. A good rectangular switching characteristic with a 3dB width of 20ps is obtained using the rectangular control pulses as opposed to a value of 4ps when driving the switch directly with pulses from the laser. Note the slight asymmetry in the switching window that is both predicted theoretically and observed experimentally. This arises from pulse walk-off effects between the pump and probe beams within the NOLM. The effect though is small since the DSF used in the M-NOLM had a length of only 1km, a zero-dispersion wavelength of 1554nm, and a dispersion slope of 0.07ps/nm^2-km. These results show that we can expect to achieve around 5 times greater tolerance to timing-jitter by converting the control pulses to rectangular pulses in this instance.

In order to confirm the system impact of using rectangular control pulses we performed

BER measurements on the M-NOLM switch performance. These results are summarized in Fig. 4. Error-free, penalty-free performance was readily achieved over a +/-7ps delay range for the rectangular pulse driven switch versus a +/-1ps range for the switch driven directly with the 2.5ps laser pulses.

Next we investigated the switching window of a SOA based switch employing four-wave mixing (FWM) as the optical switching mechanism. The experimental set up was essentially the same as that used for the NOLM. However it is to be appreciated that the optimum switching powers required for the SOA based scheme (~7dBm average power at 10Gbit/s) were substantially lower than those required for the NOLM (~15dBm at 2.5Gbit/s). Note also that we had to change the wavelength of the 10 GHz switching pulses from 1544nm to 1550nm to achieve an adequate phase matching condition. A demultiplexed FWM signal is evidently observed at the wavelength of 1543nm, as shown in the SOA output spectrum inset within Fig. 5. In Fig. 5 we plot the experimentally measured switching window. As with the fiber based switch an excellent rectangular switching window is obtained, allowing for timing jitter tolerance of +/-7ps.

III. Conclusion

We have experimentally demonstrated that SSFBGs can be used to reliably re-shape ultrashort optical pulses in order to provide more optimal and jitter-tolerant operation of nonlinear optical switches based on both fiber and semiconductor nonlinear components. This approach is particularly attractive for use with SOA based switching devices for which there is no ready way of shaping the switching window other than through direct control of the pulse shape. It is to be appreciated that this approach could be applied to ultra-high speed (>100Gbit/s) systems, since it has already been shown that state-of-the-art SSFBG technology can produce high quality gratings capable of generating square pulses with rise/fall times less than 1ps [5]. We consider the SSFBG approach to represent an extremely powerful and flexible way of manipulating the temporal characteristics of pulses and that it could play an important role in future high-speed, high capacity optical communication systems and networks.

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Figure captions

Figure 1. Experimental setup for an OTDM switch with a pulse-shaping fiber grating.

Figure 2. SHG autocorrelation traces of original soliton pulse (—), the pulses generated from a WC-NOLM (---) and a rectangular pulse grating (—); inset: Optical spectrum of the rectangular pulse stream (20ps, 2.5 Gbit/s pulse stream and central wavelength of 1557nm) and 10 GHz, 3.5ps wavelength converted signal at 1544nm.

Figure 3. Switching windows of the NOLM based OTDM demultiplexer with respect to relative timing mismatch between control pulses and data pulses; solid line (—): calculation for rectangular control pulses, dashed line (---): calculation for soliton control pulses, circle (O): experiment for rectangular control pulses, triangle (▽): experiment for soliton control pulses.

Figure 4. BER on the optically modulated signals at the fixed received power of -20 dBm (●: 20ps rectangular control pulses, O: 2.5ps soliton control pulses); inset: BER as a function of received power under optimal time synchronization between control pulses and data pulses

Figure 5. Experimentally determined switching window of a SOA based switch; inset: output spectrum of the SOA after the four-wave mixing process.

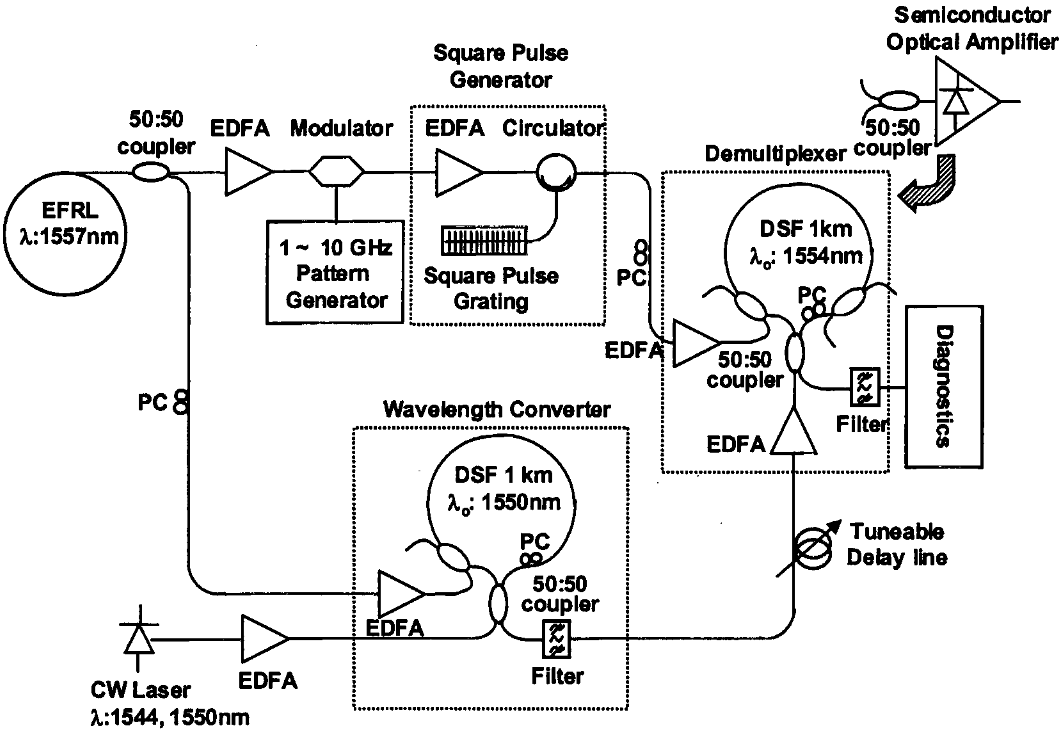

Figure 1

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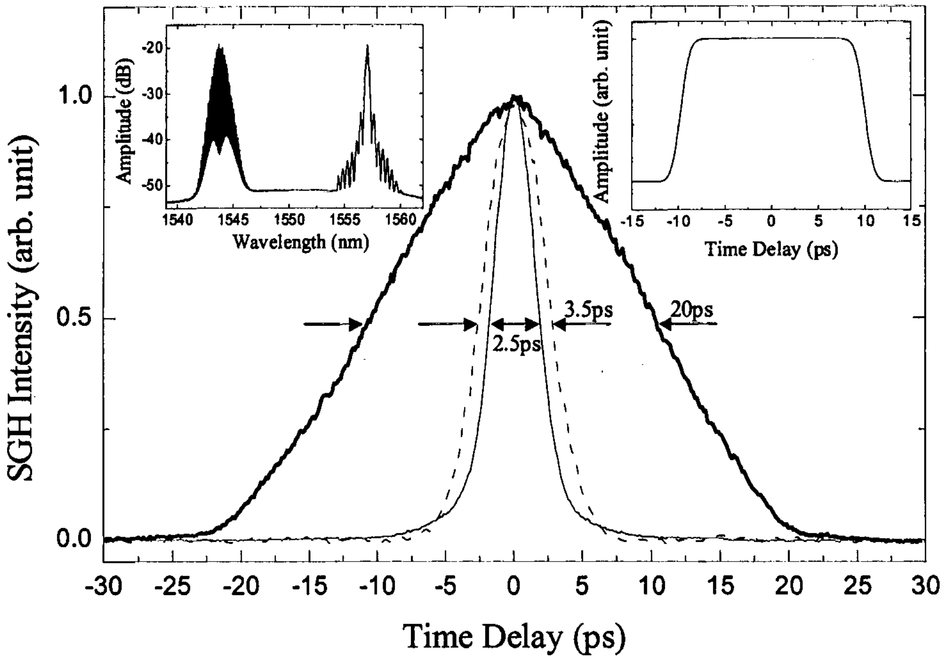

Figure 2

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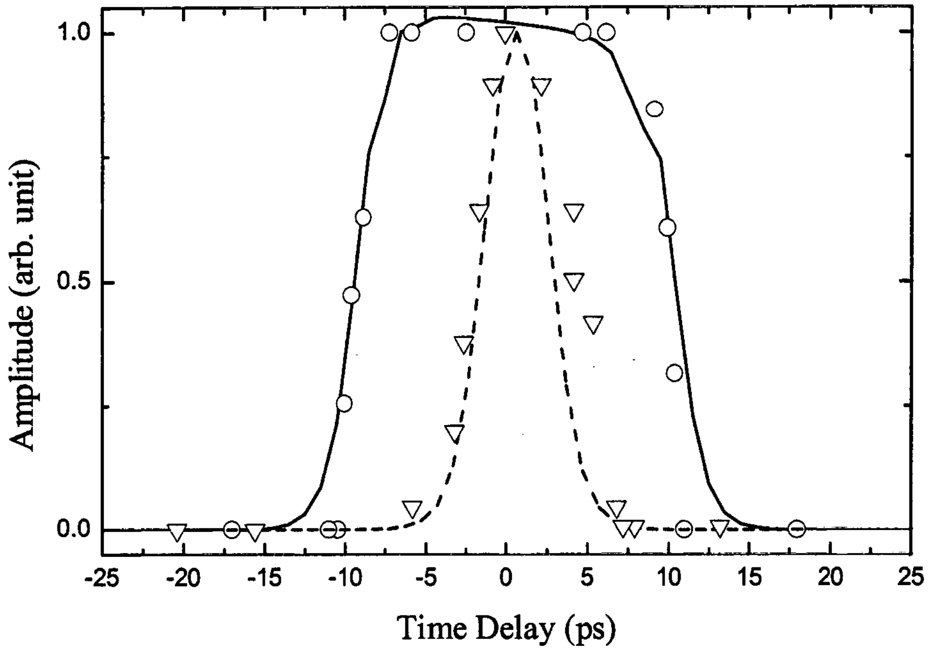

Figure 3

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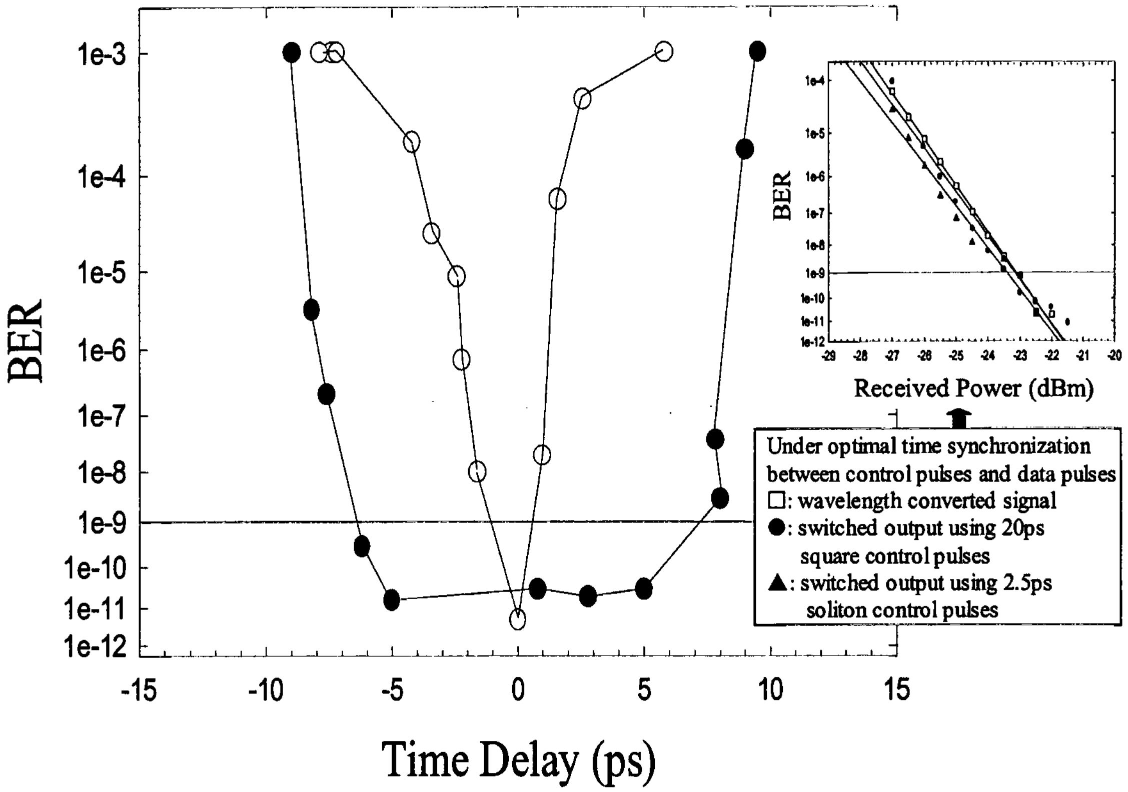

Figure 4

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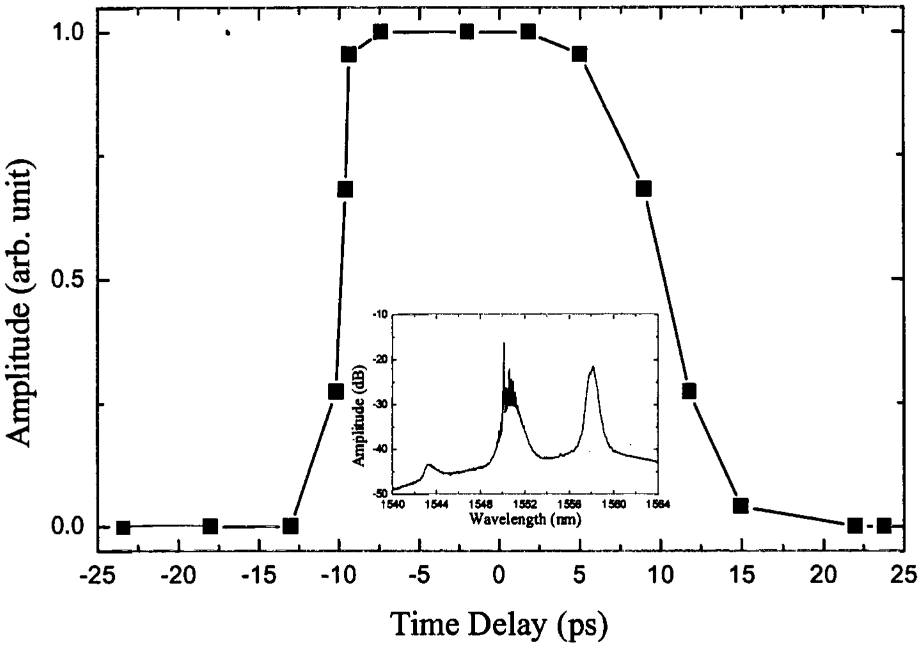

Figure 5

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