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

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Abstract—In this letter, we demonstrate the use of a superstructured fiber Bragg grating to preshape optical pulses to obtain more optimal operation of nonlinear all-optical switches. Specifically, we demonstrate the conversion of 2.5-ps soliton pulses into 20-ps rectangular pulses at the input to both fiber and semiconductor optical amplifier-based switches, and show that rectangular switching windows can be achieved thereby providing a 5–10-fold reduction in timing jitter sensitivity. Errorfree penaltyfree optical time-division-multiplexing switching was readily achieved over a ±7-μs timing mismatch range for the square pulse driven fiber nonlinear optical loop mirror switch versus a ±1-μs range for the switch driven directly with the 2.5-ps laser pulses.

Index Terms—Optical switches, optical fiber devices, optical time-division multiplexing, optical fiber communication, semiconductor optical amplifiers.

I. INTRODUCTION

SINGLE CHANNEL data rates approaching the terabit/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 “walkoff” 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

II. EXPERIMENT SETUP AND RESULTS

Our experimental setup is shown in Fig. 1. Pulses from a 2.5-ps 10-GHz regeneratively mode-locked erbium-fiber ring laser (EFRL), operating at 1557 nm, were first split using a coupler into two separate channels. The first channel was gated
down to 2.5 GHz and modulated to provide a $2^7 - 1$ pseudorandom data sequence of 2.5-ps pulses at 2.5 Gb/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 2.5-ps solitons into 20-ps 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 2.5-ps soliton laser pulses.

The other component of the 10-GHz 2.5-ps pulse stream, split off from the laser which 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 1-km-long DSF with a zero dispersion wavelength of $\lambda_0 = 1550$ nm. This nonlinear switch allowed us to modulate the output of a continuous-wave distributed feedback laser, operating at 1544 nm using the 1557-nm control pulses. By appropriately setting the loss and polarization of light within the WC-NOLM, and filtering out the 1557-nm control pulses at the loop output, we were able to generate a 10-GHz train of high-quality 3.5-ps pulses at 1544 nm (Fig. 2). Importantly, for this demonstration, this pulse train was synchronized to 2.5-Gb/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 2.5-Gb/s 20-ps rectangular pulses, or 2.5-ps soliton pulses at 1557 nm.

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 3.5-ps optical pulses at 1544 nm. 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 1544-nm pulse train incident to the switch was first passed through a tunable delay line to allow us to adjust the arrival time of the 1544-nm pulses relative to the rectangular control pulses. By adjusting and measuring this relative arrival time delay and monitoring the loop output at 1544 nm, (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 1544 nm, using both 20-ps square and 2.5-ps control pulses. A good rectangular switching characteristic with a 3 dB width of 20 ps is obtained using the rectangular control pulses, as opposed to a value of 4 ps, 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 walkoff 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 1 km, a zero-dispersion wavelength of 1554 nm, and a dispersion slope of 0.07 ps/nm$^2$.km. These results show that we can expect to achieve around five 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 bit-error-rate (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 $\pm7$-ps delay range for the rectangular pulse driven switch versus a $\pm 1$-ps range for the switch driven directly with the 2.5-ps laser pulses.

Next, we investigated the switching window of an SOA-based switch employing FWM as the optical switching mechanism. The experimental setup 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 (~7-dBr
average power at 10 Gb/s) were substantially lower than those required for the NOLM (~15 dBm at 2.5 Gb/s). Note also, that we had to change the wavelength of the 10-GHz switching pulses from 1544 to 1550 nm to achieve an adequate phase matching condition. A demultiplexed FWM signal is evidently observed at the wavelength of 1543 nm, 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 ±7 ps.

**III. Conclusion**

We have experimentally demonstrated that SSFBGs can be used to reliably reshape 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 ultrahigh-speed (>100 Gb/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 1 ps [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.

**References**


