Soliton switching using cascaded nonlinear-optical loop mirrors

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We demonstrate multiple-peaked switching in a nonlinear-optical loop mirror and present an experimental investigation of device cascading in the soliton regime based on a sequence of two independent nonlinear-optical loop mirrors. Cascading leads to an enhanced switching response with sharper switching edges, flattened peaks, and increased interpeak extinction ratios. We observe that pulses emerging from the cascade retain the sech^2 temporal profile of a soliton with minimal degradation in the spectral characteristics.

The importance of the nonlinear-optical loop mirror[1] (NOLM) in ultrafast all-optical processing has already been established.[2,3] The inherent stability and simplicity of the device make it an ideal element in more complex photonic switching architectures. Integral to the construction of all-optical systems is the requirement for concatenation of simple devices to produce higher levels of functionality. Application of this principle has led to the development of an all-optical signal regenerator[4] and an all-optical memory,[5] both of which are based on a combination of a control-pulse-switched three-port NOLM configuration and another functional element. A primary requirement for any all-optical device, then, is that it be cascadable. In addition, it must not corrupt incoming data, which leads to information loss, or leave the data unsuitable for further processing. Implicit in this is the need for maintenance of both the temporal and the spectral integrity of data during processing.

The cw response of a cascade of self-switched two-port NOLM's has been investigated numerically[6] and experimentally.[7] Results show that cascading leads to a sharpening of the overall switching characteristic, producing steeper switching edges, flatter peaks, and enhanced interpeak discrimination and noise extinction. However, to our knowledge, the effects of cascading in the soliton regime have not yet been investigated. In this Letter we present an experimental study of the response of a sequence of two NOLM's to a train of solitons and investigate the effects of the cascade on these pulses. We demonstrate what we believe is the first multiple-peaked switching in a NOLM and generate an enhanced response in a cascade of two independent NOLM's. We find that cascading sharpens the switching transitions and verify that emerging pulses retain the sech^2 temporal profile that is characteristic of solitons while suffering only minimal spectral degradation. Our results further demonstrate the suitability of the NOLM as a building block in more complex soliton-based data processing schemes.

To predict the response of a NOLM to solitonlike pulses, we use a simple model based on the evolution of the soliton phase.[8] The NOLM transmittivity is given by

$$T = 1 - 2\alpha(1 - \alpha)(1 + \cos\theta), \tag{1}$$

where α is the coupler ratio and

$$\theta = \pi\frac{L}{z_0}\{(1 - 2\alpha)N^2 - [(1 - \alpha)^{1/2} - \alpha^{1/2}]N\}, \tag{2}$$

where L is the loop length, z_0 is the soliton period of the input pulses, and N is the soliton order. The first switching peak is defined by the condition $\theta = \pi$. Using our experimental parameters of $\alpha = 0.4$, $L = 4.3$ km, and a pulse width of 7 ps, giving a soliton period in standard fiber of 1.3 km, we see that the soliton order that corresponds to the first switching peak is given by $N = 1.6$.

In the absence of loss the single-pass switching characteristic is optimally enhanced by cascading two identical NOLM's. Loss in the devices, however, causes degradation of the overall response since the switching peaks of the individual devices no longer coincide. As a result, the experimental configuration of Nayar *et al.*,[7] in which they simulate a cascade by passing the single NOLM output back through itself by using a linear reflector, is not ideal. In the two-device configuration, loss in the first device may be compensated by reducing the switching power of the second device either by a decrease in the coupling ratio α or by a lengthening of the loop. To predict the required increase in loop length, we replace L with the effective length:

$$L_{\text{eff}} = \left[\frac{1 - \exp(-2\Gamma L)}{2\Gamma}\right], \tag{3}$$

where 2Γ is the fiber loss, and we reduce the transmittivity by the factor $\exp(-2\Gamma L)$. Given the parameters above and a fiber loss of 0.2 dB/km, the predicted value is $L = 5.9$ km. We took into account additional losses, e.g., splice and coupler losses, by choosing a length of 6.4 km.

A schematic of the experimental setup is shown in Fig. 1. Transform-limited sech^2 pulses with a full
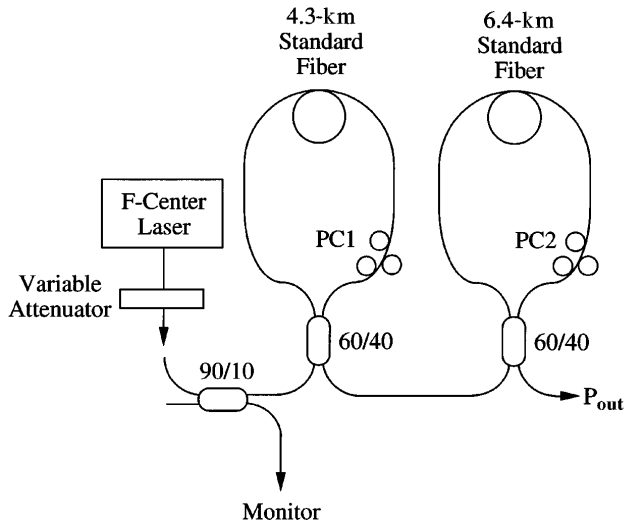
Fig. 1. Experimental setup for demonstration of soliton switching in a cascade of two NOLM's. The color-center (F-center) laser pulse width is 7 ps. PC1, PC2, polarization controllers; P_{out}, power out.

width at half-maximum of 7 ps from a tunable synchronously mode-locked color-center laser operating at 1529 nm were launched into the cascade through a 90/10 fused-fiber coupler. The color-center laser was pumped with a Nd:YAG laser operating at 1064 nm and at a repetition rate of 76 MHz. The NOLM's were constructed with 60/40 ($\alpha = 0.4$) couplers and, as mentioned above, with loop lengths of 4.3 and 6.4 km, respectively, of standard fiber with a measured dispersion of 15 ps/(nm km) at 1529 nm, an effective area A_{eff} of 88 μm^2, and an overall loss of 0.19 dB/km. The peak power for an $N = 1$ soliton in this system is 1.1 W, giving an average power of 0.6 mW at 76 MHz. The measured linear insertion loss of the sequence was 2.8 dB. The individual time-averaged response of each device to the pulse train is shown in Fig. 2. The solid curves show fits to the experimental data points. The first and second peaks of the 4.3-km NOLM characteristic [Fig. 2(a)] occur at average powers (soliton order) of 1.8 ($N = 1.8$) and 4.2 mW ($N = 2.7$), respectively, with corresponding peak transmissions of 82% and 76%. The interpeak extinction ratio (first minimum) is 8.3 dB. The switching peaks of the 6.4-km NOLM [Fig. 2(b)] occur at powers of 1.3 ($N = 1.5$), 2.4 ($N = 2$), and 3.5 mW ($N = 2.5$), with interpeak extinction ratios at the first and second minima of 7.1 and 8.3 dB. The average power transmitted by the first NOLM in the sequence on its first switching peak is 1.4 mW. As Fig. 2(b) shows, this value coincides closely with the input power required for reaching the first peak of the second device, demonstrating that the individual responses are optimally matched, as predicted by our calculations.

To our knowledge, demonstration of self-switching in a NOLM has thus far been shown to only one switching maximum.[9,10] The strong self-Raman generation inherent in the subpicosecond pulse streams used in these earlier experiments leads to soliton self-frequency shift and eventually to the total breakup of higher-order soliton pulses. Both soliton

self-frequency shift, which gives rise to a mismatch in arrival time at the coupler, and pulse breakup were seen to cause the device to fail beyond the first peak point as a result of incomplete interference.[10]

By use of relatively long pulses ($\sim$7 ps) with a much narrower spectral content, the effects of intrapulse Raman generation have been reduced, and, as a consequence, the operating region of the device has been extended to demonstrate multiple-peaked switching. Over the ranges shown in Fig. 2 the experimental results show good agreement with numerical simulations. In addition, the increased loop length resulting from the use of broader input pulses was not found to significantly impair the environmental stability of the NOLM's, and polarization bias was maintained for periods of a few hours. Features were observed at input powers higher than those shown, but these were significantly affected by higher-order soliton shaping in the device arms. Source instability coupled with the high sensitivity of higher-order pulses to input amplitude fluctuations caused these features to be increasingly unstable. At still higher powers, device operation was totally inhibited as a result of observed Raman-induced pulse breakup, as reported in previous experiments.[10]

The switching characteristic of the two-device sequence is shown in Fig. 3. The solid curve again shows a fit to the experimental data. The first two switching maxima occur at 2 mW ($N = 1.9$) and 3.8 mW ($N = 2.6$), with measured peak transmissions of 75% and 66%, respectively. The extinction ratio at the first minimum is 17 dB. By comparing the cascade response with the individual device characteristics we can see that cascading causes a significant sharpening of the switching transitions as well as a flattening of the first peak, yielding a configuration with increased immunity to input amplitude noise.
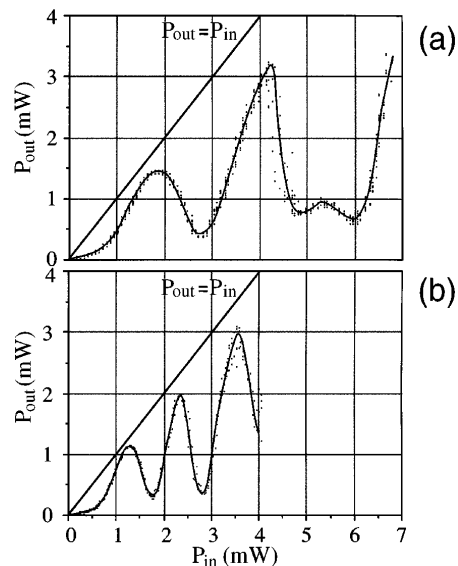

Fig. 2. Individual time-averaged responses of NOLM's to the input pulse stream of (a) a 4.3-km NOLM and (b) a 6.4-km NOLM. The dots correspond to experimental data points. 1 mW average power $\approx$ 1.9 W peak power.
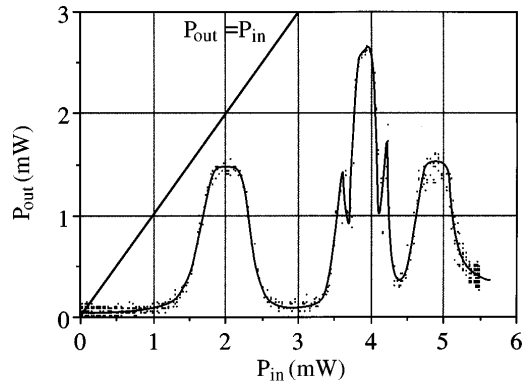
Fig. 3. Time-averaged response of the sequence of NOLM's. The dots correspond to experimental data points. 1 mW average power $\approx$ 1.9 W peak power.
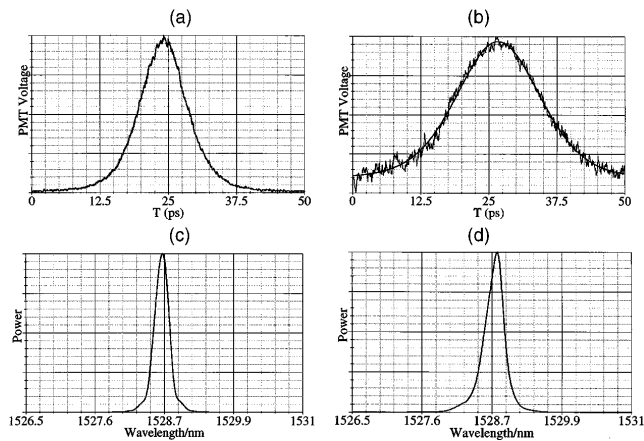

Fig. 4. (a) Autocorrelation of the input pulse stream, (b) autocorrelation and sech^2 fit of transmitted pulses at the first peak of cascade response, (c) spectrum of the input pulse stream, (d) spectrum of transmitted pulses on first peak. PMT, photomultiplier tube.

In addition, it is clear that NOLM cascading results in an order-of-magnitude increase in extinction ratio.

Figure 4(a) shows an autocorrelation of the input pulse stream, and Fig. 4(b) shows the pulses transmitted on the first peak, along with a sech^2 fit. Figures 4(c) and 4(d) show the corresponding spectra. The pulse width of the input stream is 7 ps, with a time−bandwidth product $\Delta\nu\Delta\tau = 0.3$, and the output pulses are of duration 11.7 ps. We calculate $\Delta\nu\Delta\tau$ for these pulses to be 0.4. Figure 4(b) demonstrates that the temporal profile of the emerging pulse maintains an extremely close relationship to its sech^2 fit. The increase in pulse width can be attributed largely

to fiber loss as well as to the pulse shaping and imposed spectral chirp inherent in the use of the NOLM with nonexact solitons. However, by the appropriate choice of design parameters, i.e., a nearly balanced coupler splitting ratio and pulse propagation in the arms near the $N = 1$ soliton power level, these negative effects are contained. Our results therefore demonstrate the temporal and spectral robustness of solitons to a cascade of nonlinear switching elements and the suitability of emerging pulses for further processing.

In summary, we have demonstrated what we believe is the first multiple-peaked switching in a NOLM and enhancement of the device response by cascading. Through the use of relatively long pulses we have reduced the effects of soliton self-frequency shift in the device and extended its operating range as a result. Using a sequence of two NOLM's, the responses of which have been matched to compensate for fiber loss, we find that cascading results in sharpened switching edges, increased interpeak extinction, and a squaring off of the peaks. We have shown that pulses emerging from the sequence retain their soliton characteristics, rendering them capable of further processing. We believe that our results further confirm the robustness of solitons in nonlinear data processing and demonstrate the advantages of the NOLM as an element in such architectures.

References

1. N. J. Doran and D. Wood, Opt. Lett. **13,** 56 (1988).
2. P. A. Andrekson, N. A. Olsson, J. R. Simpson, D. J. Digiovanni, P. A. Morton, T. Tanbun-Ek, R. A. Logan, and K. W. Wecht, IEEE Photon. Technol. Lett. **4,** 644 (1992).
3. D. M. Patrick, A. D. Ellis, and D. M. Spirit, Electron. Lett. **29,** 702 (1993).
4. J. K. Lucek and K. Smith, Opt. Lett. **18,** 1226 (1993).
5. H. Avramopoulos and N. A. Whitaker, Jr., Opt. Lett. **18,** 22 (1993).
6. B. K. Nayar, K. J. Blow, and N. J. Doran, Opt. Comput. Process. **1,** 81 (1991).
7. B. K. Nayar, N. Finlayson, and N. J. Doran, J. Mod. Opt. **40,** 2327 (1993).
8. K. J. Blow, N. J. Doran, and S. J. D. Phoenix, Opt. Commun. **88,** 137 (1992).
9. K. J. Blow, N. J. Doran, and B. K. Nayar, Opt. Lett. **14,** 754 (1989).
10. M. N. Islam, E. R. Sunderman, R. H. Stolen, W. Pleibel, and J. R. Simpson, Opt. Lett. **14,** 811 (1989).