Polarization-insensitive nonlinear optical loop mirror demultiplexer with twisted fiber

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We experimentally demonstrate reduction of the polarization sensitivity of a nonlinear optical loop mirror (NOLM) from 5 to 0.5 dB by use of 550 m of twisted dispersion-shifted fiber with a twist rate of 8 turns/m (24 turns/beat length). The twisting of the fiber induces circular birefringence and equates the parallel- and the orthogonal-polarization nonlinear phase-shift terms. Experimental results show that the polarization sensitivity monotonically decreases from 5 dB for nontwisted fiber to 0.5 dB for fiber that is twisted at a rate of 8 turns/m, and the twist rate should be more than 4 turns/m (>10 turns/beat length) for emulation of circularly polarized fiber. The minimum polarization sensitivity occurs when the control-pulse polarization is aligned with one of the eigenmodes of the twisted fiber. With the fiber twisted at a rate of 8 turns/m in the NOLM, the nonlinear transmission is 23% at a switching energy of 4 pJ/pulse. Simulations confirm the observed behavior and show that the remaining polarization sensitivity results from energy transfer between orthogonal modes of the signal pulse. © 1999 Optical Society of America

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The nonlinear optical loop mirror (NOLM) is an attractive candidate for all-optical demultiplexing of 40-Gbit/s and higher-rate data streams.[1] However, the 5-dB sensitivity to the signal input polarization state in a typical NOLM is an obstacle to its applications in a real system, in which the signal polarization varies with environmental conditions. We experimentally demonstrate reduction of the polarization sensitivity of the NOLM from 5 dB to as low as 0.5 dB by twisting 550-m dispersion-shifted (DS) fiber at a rate of 8 turns/m (24 turns/beat length). The twisting of the fiber creates circularly polarized fiber (CPF) and equates the parallel- and the orthogonal-polarization nonlinear phase-shift terms. The difference in these nonlinear terms is the fundamental cause of polarization sensitivity in a NOLM. We find that the polarization sensitivity of the NOLM can be reduced significantly when the twist rate is greater than ~4 turns/m (>10 turns/beat length), making the fiber similar to CPF. We also find that the minimum polarization sensitivity occurs when the polarization of the control pulse is aligned with one of the eigenmodes of the twisted fiber. Numerical simulations agree with the experimentally observed behavior and predict that the polarization sensitivity should approach 0.3 dB with CPF. The remaining polarization sensitivity arises from energy transfer between orthogonal-polarization modes of the fiber.

Previous methods of reducing the polarization sensitivity of the NOLM relied on either changing the switch architecture or using long fiber lengths. In one method, Uchiyama *et al.* switched the orthogonal-polarization modes independently by cross splicing two pieces of polarization-maintaining (PM) DS fibers of the same length and launching the control pulse at 45° to the axis of the PM fiber.[2] To build this PM NOLM one must make all the components with PM fiber, which complicates the device. Rather than splitting the control pulse, one can use two diodes so that each diode is launched onto a different control axis.[3] Additionally, Olsson and Andrekson demonstrated two other methods. The first method randomizes the polarizations of the pulses by use of long lengths (13 km) of DS fiber with moderate polarization-mode dispersion and a specific zero dispersion λ_0 to increase the walk-off length.[4] The second method uses a birefringent crystal as a full-wave plate for the signal wavelength and a half-wave plate for the control wavelength in the loop.[5] Long fiber lengths increase the environmental sensitivity, and the walk-off restrictions limit the wavelength range of operation. The birefringent crystal can also limit the operating wavelength range. Whitaker *et al.* used a fixed signal polarization by splitting the two orthogonal modes of the signal pulse and using a polarization rotator to make the two modes parallel.[6] Splitting one signal pulse into two separate signals lowers the operating signal data rate.

Rather than compensating for the difference in nonlinearities with the architecture, we attempt to solve the fundamental cause of polarization sensitivity by use of CPF. The polarization sensitivity of the NOLM comes from the difference in cross-phase modulation (XPM) for parallel-polarized and cross-polarized pulses. In linearly polarized fiber the parallel- and the cross-polarized nonlinear phase-shift coefficients induced by XPM from the control pulse are 2 and 2/3, respectively, whereas in CPF the coefficients are both 4/3.[7] Therefore, using CPF can fundamentally eliminate the source of polarization sensitivity. CPF can be emulated if we twist the fiber at a much higher rate (>10×) than its linear birefringence or by use of a twist length L_T (the length for one turn) shorter than 1/10 of the beat length L_B.[8] Note that because the birefringence varies for different fibers the necessary number of turns per meter is dependent on the fiber type.

The NOLM is tested in the configuration shown in Fig. 1, in which the source is an erbium-doped fiber laser ($\lambda_1 = 1542$ nm, $\Delta\lambda \sim 2.9$ nm, $\Delta\tau \sim 0.5$ ps). Ten percent of the laser output is amplified and filtered as the control input. The signal input is frequency shifted by 7 nm ($\lambda_2 = 1535$ nm) from the laser wavelength by filtering of the spectrum broadened by self-phase modulation in a 12-m high-nonlinearity fiber ($\lambda_0 = 1534$ nm; n_2 is $\sim 4.5\times$ that of normal DS fiber) with 90% of the laser output. The bandwidth of each filter is 2 nm, and the filtered pulse widths are 1.8 ps. A polarization controller and two 0-order wave plates are used to sweep through all possible polarization states at the signal and the control inputs. The tested fiber in the loop is a 550-m DS fiber with $\lambda_0 = 1518$ nm and a measured linear birefringence $\Delta n \sim 5 \times 10^{-7}$ (beat length, $L_B \sim 3$ m) at a wavelength of 1550 nm.

In Fig. 2(a) we compare the polarization sensitivity of nontwisted fiber (twist rate, 0) and fiber twisted at different rates. To test the polarization sensitivity of the NOLM we vary a half-wave plate from 0° to 90° and a quarter-wave plate from 0° to 180° to adjust polarizations for the control input. For each fixed control polarization we sweep the polarization controller at the signal input through all the possible polarizations to check the polarization sensitivity of the NOLM. We find that the minimum polarization sensitivity occurs when the control-pulse polarization is aligned with one of the polarization eigenmodes of the twisted fiber. To show the change from linear to circular polarization we vary the twist rate from nontwisted to 8 turns/m (24 turns/L_B). The switching sensitivity based on the polarization of the input signal approaches 5 dB in nontwisted fiber, whereas twisting the same fiber at a rate of 8 turns/m (24 turns/L_B) results in a switching variation as low as 0.5 dB. As expected, we find that at a twist rate of 4 turns/m (12 turns/L_B) the slope of the polarization-sensitivity curve levels off because the fiber becomes approximately circularly polarized.

To illustrate the polarization dependence, in Fig. 2(b) we show the nonlinear transmission of nontwisted and twisted fibers at a switching energy of 4 pJ/pulse. To obtain the data we use a polarizer followed by a half-wave plate and a quarter-wave plate in the signal arm to replace the polarization controller and to vary the input polarization states. The polarization sensitivity and the nonlinear transmission results are summarized in Table 1.

The nonlinear transmission is a squared sinusoidal function of nonlinear phase shift caused by nonlinear index change. The peak nonlinear index change induced by the control wavelength has a factor of 2 for linearly polarized fiber and 4/3 for circularly polarized fiber. Thus, if the peak transmission of the NOLM with nontwisted fiber is $\sin^2(\phi_L) = 47\%$, the peak transmission of the NOLM with CPF is expected to be $\sin^2(2\phi_L/3) = 23\%$ with the same fiber length and switching energy. Our experimental result matches this theoretical value well.

To understand the lower limits on polarization sensitivity for the twisted fiber we numerically solve the coupled nonlinear Schrödinger equation in linearly polarized fiber and CPF. The cross-coupling coefficient of the orthogonal axis equals 2/3 for linearly polarized fiber and 2 for CPF,[5] and the parallel-coupling coefficient is 2 for both cases. The simulation curves in Fig. 3(a) verify the observed behavior illustrated in Fig. 2(b). Here, the x axis is the signal launch

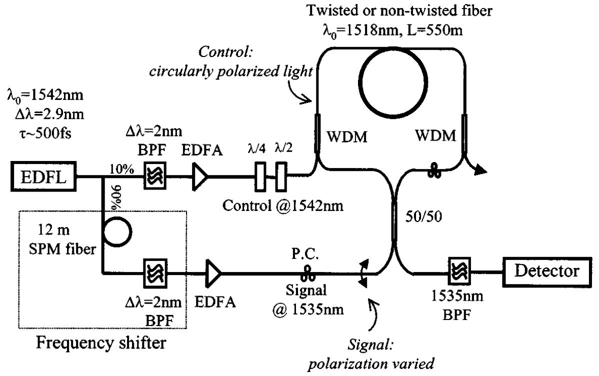
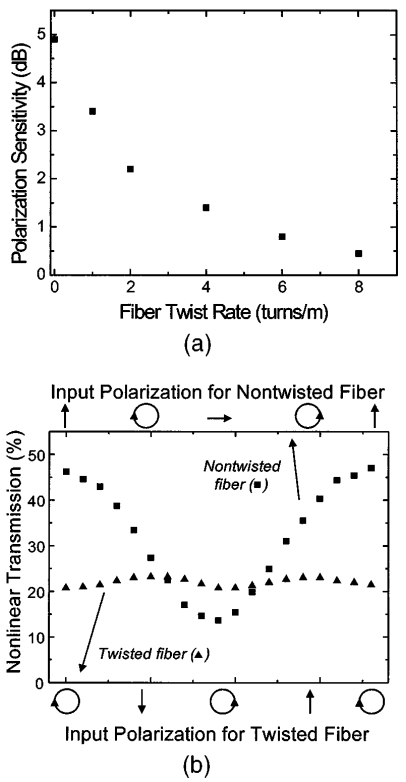


Fig. 1. Experimental setup for testing the polarization-insensitive NOLM: EDFL, erbium-doped fiber laser; EDFA's, erbium-doped fiber amplifiers; BPF's, bandpass fibers; SPM, self-phase modulation; WDM's, wavelength-division multiplexers; P.C., polarization controller.



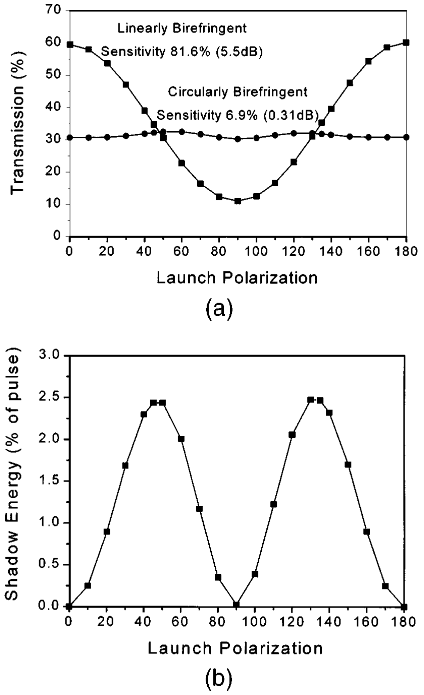
(a)

(b)

Fig. 2. (a) Polarization sensitivity versus fiber twist rate. A 0 twist rate corresponds to nontwisted fiber. (b) Nonlinear transmission versus signal input polarization for nontwisted fiber and fiber twisted at a rate of 8 turns/m.

Table 1. Comparison of the Experimental Results of Nontwisted Fiber NOLM and Twisted Fiber (8 turns/m) NOLM

Parameter	Twisted	Nontwisted
Polarization sensitivity (%)	10	65
Peak nonlinear transmisison (%)	23	47
Minimum nonlinear transmission (%)	21	14



(a)

(b)

Fig. 3. (a) Simulated nonlinear transmission for linearly birefringent (squares) and circularly birefringent (circles) fibers. (b) Shadow energy corresponding to the simulation in (a). The x axes in both (a) and (b) are signal launch polarizations. The signal polarization is parallel to control polarization at 0° and 180° but orthogonal to control polarization at 90°.

polarization. The signal is parallel to the control polarization at 0° and 180° but orthogonal to the control polarization at 90°. The discrepancy in peak transmissions between the simulation and the experimental results comes from assumption errors of fiber connection loss and stress-induced circular birefringence in twisted fiber, which are different from those of perfect CPF. It may also explain why the experimental limit on the polarization sensitivity is 0.5 dB instead of 0.3 dB, as predicted by the simulation for the CPF NOLM.

Additionally, simulations show that the limit on polarization sensitivity arises from the generation of shadow energy on the opposite state of polarization of the signal pulse.[9] The signal pulse's state of polarization is altered as the control pulse walks through the signal pulse. For example, the calculated shadow energy ($\lambda = 1535$ nm) as a percentage of the signal energy corresponding to the simulation in Fig. 3(a) is shown in Fig. 3(b). The change in the state of polarization affects the absolute phase of the signal pulse, resulting in a change in the transmission of the NOLM. The amount of energy transfer depends on the relative states of polarization between the control and the signal. When the control and the signal states of polarization are entirely parallel or orthogonal, the state of polarization of the signal is not changed. However, when the control polarization has a component that is parallel as well as a component that is orthogonal to the signal, the signal polarization is rotated. That is, a portion of the signal energy is moved from its original axis to the orthogonal axis. The exact quantity of this energy transfer is dependent on the walk-off time and the pulse power.

In summary, we have demonstrated a polarization-insensitive NOLM demultiplexer by twisting 550-m DS fiber to create circular birefringence and eliminate the fundamental cause of polarization sensitivity of the NOLM. By varying the twist rate, we reduce the polarization sensitivity from 5 dB for linearly birefringent fiber (nontwisted fiber) to 0.5 dB for fiber twisted at a rate of 8 turns/m (~24 turns/L_B). It is necessary to align the control-pulse polarization with one of the eigenmodes of the twisted fiber and to twist the fiber at a rate of more than 10 turns/beat length. The twisting makes the fiber approximately circularly polarized and gives it the minimum polarization sensitivity for the NOLM. Simulations verify the experimental behavior and predict that the polarization sensitivity will be at least 0.3 dB, owing to the nonlinear energy transfer between the orthogonal modes of the signal pulse. The nonlinear transmission of the NOLM with fiber twisted at a rate of 8 turns/m is 23% at a switching energy of 4 pJ/pulse. The difference in peak transmission between the nontwisted and the twisted fibers agrees with the expected nonlinear coefficient.

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References

1. K. J. Blow, N. J. Doran, and B. P. Nelson, Electron. Lett. **26,** 962 (1990).
2. K. Uchiyama, H. Takara, K. Kawanishi, T. Morioka, and M. Saruwatari, Electron. Lett. **28,** 1864 (1992).
3. H. Bülow and G. Veith, Electron. Lett. **29,** 589 (1993).
4. B.-E. Olsson and P. A. Andrekson, in *Optical Fiber Comunication Conference*, Vol. 2 of 1998 OSA Technical Digest Series (Optical Society of America, Washington, D.C., 1998), paper FA 7.
5. B.-E. Olsson and P. A. Andrekson, IEEE Photon. Technol. Lett. **9,** 764 (1997).
6. N. A. Whitaker, Jr., P. M. W. French, M. C. Gabriel, and H. Avramopoulos, IEEE Photon. Technol. Lett. **4,** 260 (1992).
7. C.-J. Chen, P. K. A. Wai, and C. R. Menyuk, Opt. Lett. **15,** 477 (1990).
8. R. Ulrich and A. Simon, Appl. Opt. **18,** 2241 (1979).
9. L. F. Mollenauer, J. P. Gordon, and F. Heismann, Opt. Lett. **20,** 2060 (1995).