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Experimental study of the polarization asymmetrical NOLM with adjustable switch power

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ABSTRACT

This work presents a study of a nonlinear optical loop mirror (NOLM) based on polarization asymmetry. In contrast with the previously reported results where a quarter wave retarder was inserted to the loop to provide the polarization asymmetry, we used a wave retarder with variable retardation (VWR). We show that the use of the VWR allows easy adjustment of the switching power. We used in the experiment a NOLM made of 200-m length of standard SMF-28 fiber twisted at the rate of 6 turn/m to mitigate linear birefringence. As source of pulses we used a mode-locked ring fiber laser that generates 0.7-ps pulses. A change of nonlinear transmission up to 10 times at the same input power was found in the experiments. The experimental results were corroborated with numerical simulation. The adjustment of the NOLM transmission makes it attractive for applications in optical switching devices or mode-locked fiber lasers.

1. Introduction

The nonlinear fiber Sagnac interferometer known also as the nonlinear optical loop mirror (NOLM) which was first introduced by Doran and Wood [1], is commonly used nowadays in many applications, such as optical processing, see [2] and references therein, optical switching [3–5], wavelength demultiplexing [6], passive mode-locking [7,8], pedestal suppression and pulse compression [9], and regeneration of ultrafast data streams [10]. The NOLM consists of a coupler whose output ports are connected by a fiber. In order to operate, the counter-propagating beams inside the fiber loop have to accumulate different nonlinear phase shifts. Commonly, the difference in the nonlinear phase shift is achieved by using an asymmetrical coupler and hence different powers of the counter-propagating beams are obtained.

Birefringence in the loop strongly affects the NOLM operation. Without birefringence at low input power the NOLM has low transmission which grows with power. The birefringence can result in the inversion of transmission characteristics with high transmission at low input power and low transmission at high power [11]. Usually the birefringence in fiber with low birefringence has to be compensated by polarization controllers for appropriate operation of the NOLM. To operate in stable and predictable way the residual birefringence of the fiber can be mitigated by fiber twist. In twisted fiber the pulse propagates with stable polarization ellipticity. This opens the possibility to use polarization asymmetry of counter propagating pulses in the NOLM loop to accumulate the differential nonlinear phase shift. The NOLM with twisted fiber and quarter wave retarder (QWR) located near the coupler output port has shown a number of advantages [12–15]. The operation of the NOLM with polarization asymmetry is based on the dependence of the nonlinear phase shift on the ellipticity of the light. For circularly polarized input light, one of the counter propagating beams in the loop has a circular polarization while the other has a linear polarization after passing through the QWR. This is independently on the QWR angle. Linearly polarized light accumulates a nonlinear phase shift 1.5 times bigger than the circularly polarized light [16]. Therefore even with the symmetrical coupler the counter propagating beams accumulate a power-dependent phase difference. Low-power transmission depends on the angle of the QWR and can be adjusted in the range between 0 and 0.5 by rotation of the QWR. The possibility to change easily the low power transmission makes this NOLM useful for many applications, for instance, in all-optical regenerative systems [17] among others.

Substantially less investigated are the possibilities of the adjustment of the switch power which also provides the NOLM with polarization asymmetry. One of the possibilities is the use of

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linearly polarized input light. The rotation of the input linear polarization allows the adjustment of the nonlinear transmission [14,15]. However, the NOLM also allows another way to adjust nonlinear characteristics, which can be performed by changing the retardation of the birefringent element. For some applications it can be more desirable than changing the input polarization.

In the present work we theoretically and experimentally investigated the adjustment of the nonlinear properties of the NOLM by the change of the retardation of the birefringence element in the loop. We used a rotatable fiber squeezer as variable wavelength retarder (VWR), which makes possible to adjust both low power transmission and nonlinear transmission at high power. As pumping source we used 0.7 ps pulses generated by a fiber optical ring laser. The NOLM operation for short pulses is affected also by the fiber dispersion, which is also discussed in the paper.

2. Experimental setup

The experimental setup used to perform the characterization of the NOLM is shown in Fig. 1(a). We used a mode-locked fiber ring laser that emits pulses of 0.7 ps duration with 1545 nm central wavelength as a signal source. The pulses were amplified by an EDFA. The pulses from the amplifier output pass through a polarization controller (PC), a linear polarizer, and a QWR. Rotation of the QWR allows generating a stable polarization state with desired ellipticity; in this particular case left circularly polarized pulses were applied to the NOLM input. After this, the pulses were splitted by a 90/10 coupler where the 10% port was used to monitor the polarization and power of pulses at the input of the NOLM. The pulses at the NOLM input and output were measured by a photodetector with a bandwidth of 8 GHz and monitored by an oscilloscope with a bandwidth of 2 GHz. In this case we measured only the energy of the pulses considering that the detector response was proportional to the pulse energy.

The NOLM is formed by a slightly imbalanced 52/48 coupler, whose output ports were fusion-spliced with a 200 m, low-birefringence, highly twisted (6 turns/m) single mode fiber (Corning SMF-28). The Newport polarization controller F-POL-IL was used as the VWR. It consists of a rotatable fiber squeezer (center section) and two stationary fiber holders (left and right). The center section of the fiber is sandwiched between two plates in the fiber squeezer. Turning the knob on the fiber squeezer clockwise applies pressure in this section of the fiber. Such pressure produces a linear birefringence in this portion of the fiber with the slow axis in the direction that pressure is applied (see Fig. 1(b)). The retardation between slow and fast axes can be varied between 0 and 2π. The VWR was placed near one of the output ports of the coupler. The rotation of the fiber squeezer changes the axes orientation. The rotation of the squeezer allows the adjustment of the transmission at low input power while the change of the retardation by the squeezing adjusts the switch power of the NOLM. We performed measurements with the VWR placed near both the 0.52 port and the 0.48 port to compare the results. The nonlinear transmission of the NOLM was calculated as the ratio between the detector responses at the output and input of the NOLM.

3. Results and discussion

Fig. 2 shows a set of the calculated dependencies of the NOLM transmission on the input pulse power for different values of the retardation of the VWR, from $\Delta = 0.2$ to $\Delta = 1$, where Δ is a fraction of $\pi/2$. The simulations were performed using Coupled Nonlinear Schrödinger Equations solved by the Split-Step Fourier method considering the optical Kerr effect and the 2nd order dispersion. We used a nonlinearity of the fiber equal to 1.6 $(\text{W-km})^{-1}$ and a 2nd-order dispersion equal to $-25\ \text{ps}^2/\text{km}$, which correspond to the SMF-28 fiber at 1545 nm. The FWHM pulse duration was taken equal to 1 ps. For the polarization asymmetrical NOLM the transmission at low power depends on the rotation of the retarder. We calculated the NOLM with a 50/50 coupler and set the VWR angle to have zero transmission at low power.

For $\Delta = 1$ the clockwise pulse is linearly polarized and counterclockwise is circularly polarized. Both pulses have equal power. In this case the nonlinearity for the clockwise pulse with linear polarization is 1.5 times higher than nonlinearity for the counterclockwise pulse. The first maximum equal to 0.89 at 80 W is followed by the minimum of 0.016 at 116 W of the input power and a second maximum at 154 W. So that the dependence is not periodic as it follows from the simplest consideration of the NOLM. The reason of such non periodical behavior is the effect of the dispersion in the fiber, owing to the fact that for 1 ps pulse, the dispersion length is 12.9 m that is much shorter than the NOLM length (200 m).

The soliton power for the 1-ps pulse in the SMF-28 fiber is 48 W and 72 W for linearly polarized pulse and circularly polarized pulse, respectively. At low input power the pulse dispersion strongly affects the transmission of the NOLM resulting in lower transmission than can be expected for pulses with the same power if there is no dispersion. For input powers close to 100 W (50 W in each direction in the loop) the pulses in both directions have power close to soliton power and propagate without significant broadening or compression. For higher power, compression plays an important role. The effect of the dispersion breaks the periodicity of the dependence; however several maxima close to 1 and

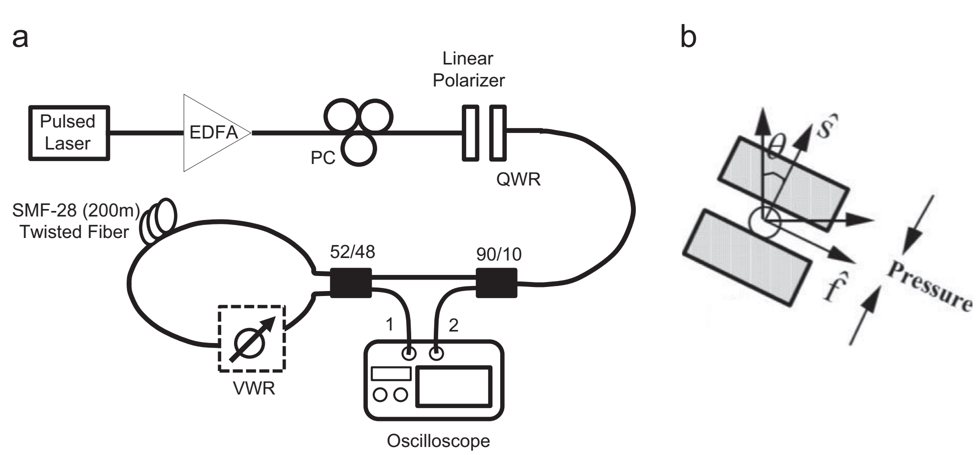

Fig. 1. (a) Experimental Setup; (b) the rotatable fiber squeezer used as VWR.