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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 ps^2/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

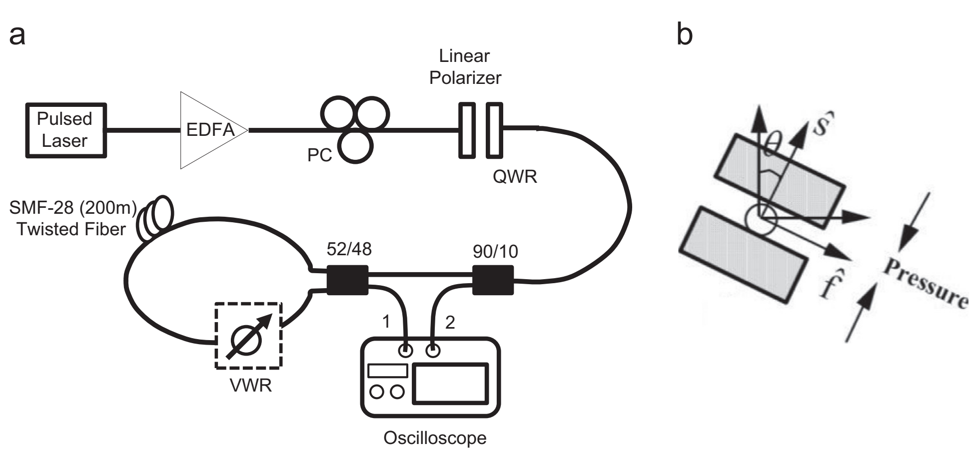

Fig. 1. (a) Experimental Setup; (b) the rotatable fiber squeezer used as VWR.

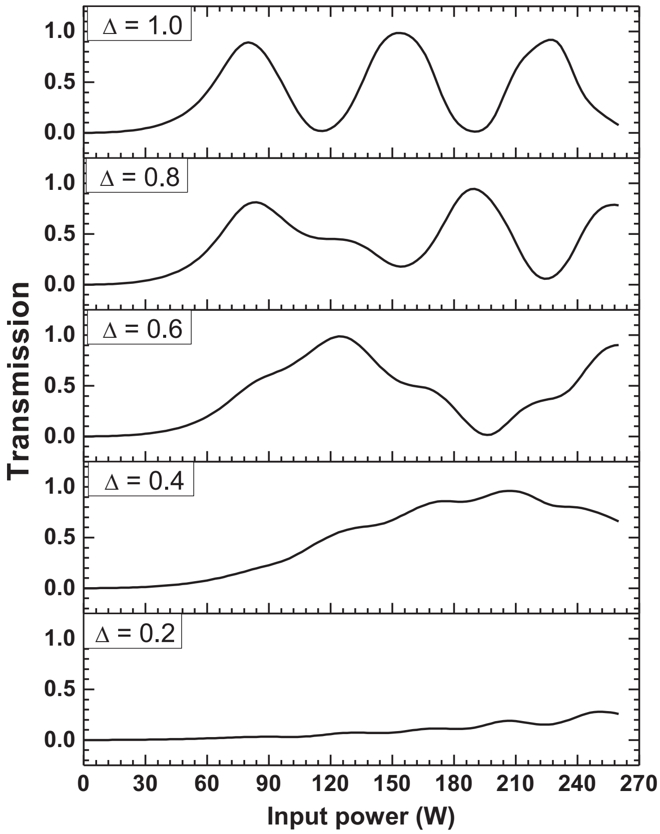

Fig. 2. Simulation of the NOLM transmission for different values of the VWR retardation.

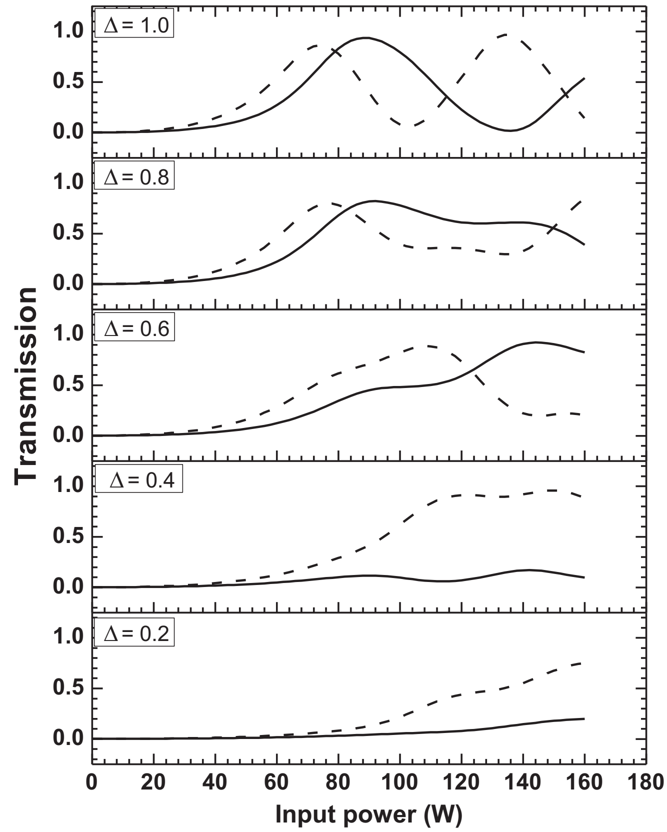

Fig. 3. NOLM transmission obtained by the simulation for different values of the retardation of the VWR; solid line when VWR is inserted close to the 0.48 port and dashed line when VWR is inserted close to the 0.52 port.

minima close to 0 can be reached. For $\Delta < 1$ the polarization of the clock-wise pulse is elliptical and the dependence becomes more complicated because of the nonlinear polarization rotation (NPR). The polarization angle of the elliptically polarized pulse is rotated because of NPR. The transmission of the NOLM depends on the polarization angle of counter and clockwise beams after traveling through the loop. However we can see that the decrease of the VWR retardation shifts the transmission maximum to higher input powers while the maxima keeps close to 1. For $\Delta = 0.6$ the maximum is equal to 0.98 at 124 W of input power; for $\Delta = 0.4$ the maximum is equal to 0.96 at 208 W of input power. These calculations show that the use of the VWR is effective for the adjustment of the switching power of the NOLM.

In our experiment we used a 48/52 coupler. We made calculations for this coupling ratio to compare with the experimental results and to understand the possible effect of slightly asymmetrical coupler. Fig. 3 shows the result for NOLM with VWR placed close to the 0.48 port (solid line) and the 0.52 port (dashed line), respectively. We can observe that for $\Delta = 1$ the effect of the coupler asymmetry is not strong. For $\alpha = 0.48$ the first maximum shifts from 80 W (symmetrical coupler case) to 88 W, while for $\alpha = 0.52$ the maximum shifts to 74 W. For $\Delta = 0.6$ the effect is more significant, for the 0.48 port the maximum shifts to 144 W and for the 0.52 port it shifts to 108 W. When the VWR was inserted close to the 0.52 port the clockwise beam showed higher nonlinear effect due to its higher power and also because the linear polarization has higher nonlinearity than the circular one. Therefore, the resulting nonlinear phase difference is a sum of both effects. If the VWR is inserted close to the 0.48 port, the clockwise beam has higher nonlinear contribution because of the polarization and lower contribution because of the lower power, the resulting nonlinear phase shift is the difference of both effects. Moreover, for some specific values of Δ the impact of the power and polarization imbalances may be equal and opposite and in this case the nonlinear transmission may be canceled. For $\Delta = 1$ the effect of the polarization prevails and power imbalance only shifts slightly the dependence. The strong effect of the coupler asymmetry can be seen in Fig. 3 for $\Delta = 0.4$ and $\Delta = 0.2$. At $\Delta = 0.4$ and VWR inserted close to 0.48 port the nonlinear transmission is nearly canceled.

Fig. 4(a) and (b) show the result of the measurements of the NOLM transmission as a function of the pulses amplitude for the VWR inserted near the 0.52 port and the 0.48 port, respectively. We also plotted the NOLM nonlinear transmission for the case of $\Delta = 0$ to observe the effect of the power imbalance of the coupler. When the VWR is inserted near the 0.52 port the effect of the polarization imbalance adds to the effect of the power imbalance therefore the transmission grows with the increment of the VWR retardation. On the other hand, for the results shown in Fig. 4 (b) the polarization and power imbalances cause opposite nonlinear phase shifts. As a result at small retardations the transmission is less than for $\Delta = 0$. The transmission is 0 for any power at $\Delta = 0.375$. In this case the effects of power imbalance and polarization imbalance cancel out exactly. For retardation values higher than 0.375 the transmission starts to grow with the increment of the retardation. In the same figure we can note that a small increment of the low power transmission occurs, less than 5%. We attribute this to a slight misalignment of the VWR angle when the retardation is changed. The comparison of the Figs. 3 and 4 demonstrates the same principal features of the nonlinear dependencies. For a detailed comparison more exact characteristics of the pulse would be necessary. In particular the chirp is important. Moreover, we cannot measure the pulse power, however we can see that at $\Delta = 1$ the experimental transmission starts to grow abruptly approximately at 50 units of input pulse

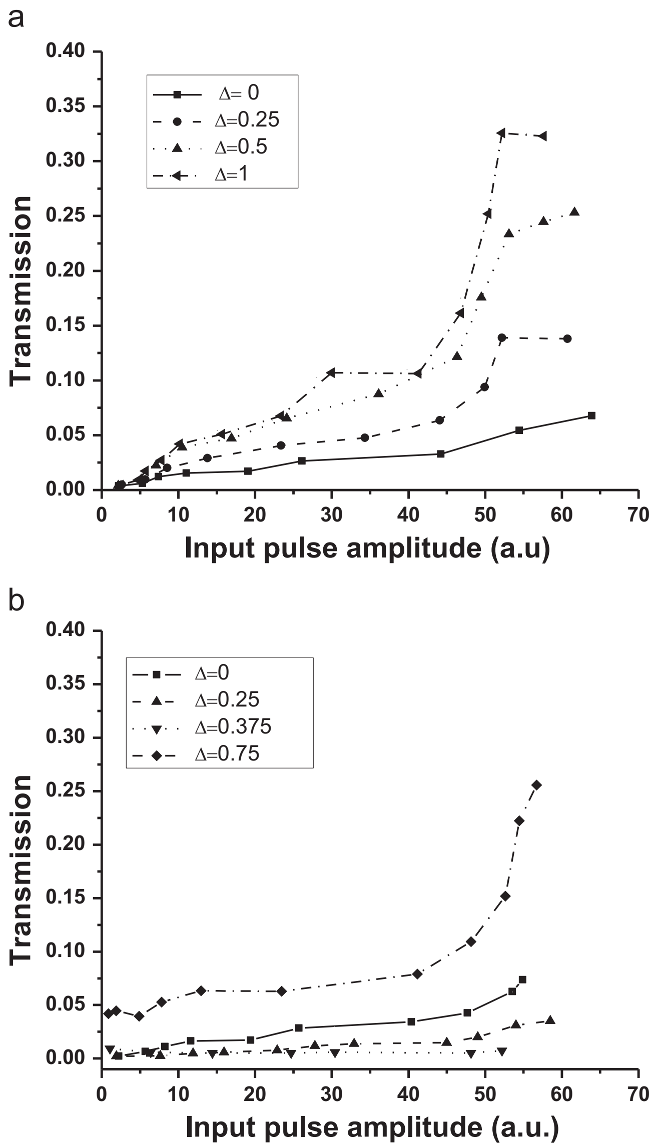

Fig. 4. NOLM transmission as a function of the amplitude for the VWR inserted (a) near the 0.52 port and (b) near the 0.48 port.

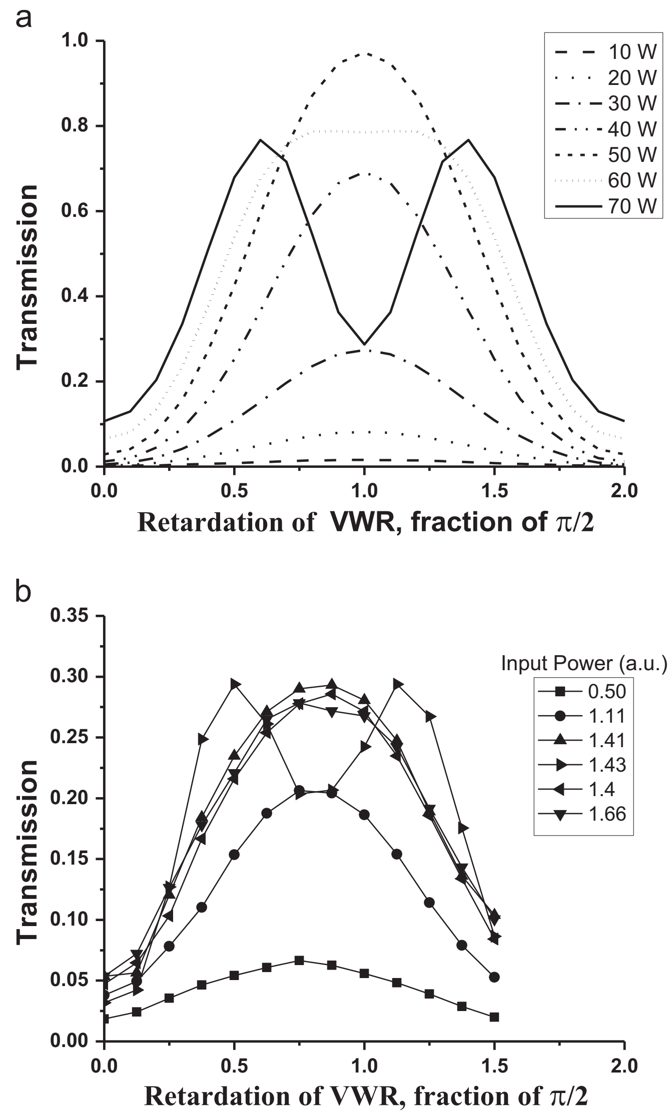

Fig. 5. Nonlinear transmission of the NOLM for different input pulse amplitudes, when VWR is inserted near the 0.52 port, (a) simulation results, (b) experimental results.

amplitude. The numerical simulations show an abrupt growth at approximately 50 W. So we can estimate roughly that 1 unit in the experimental dependencies is equal very approximately to 1 W.

The complexity of the measurements of the transmission dependence on the pulse power arises also from the fact that an increment of the pulse power results, at the same time, in a change of other pulse characteristics such as duration and chirp. These parameters, in turn, also affect the NOLM transmission. In order to observe clearly the effect of the VWR we measured the transmission in function of the retardation at constant pulse power.

Fig. 5 shows the nonlinear transmission of the NOLM as a function of the retardation of the VWR for different input pulse amplitudes when the VWR was inserted near the 0.52 port. Fig. 5(a) is a simulation and Fig. 5(b) shows experimental results. It can be observed in Fig. 5(a) that for the power of 70 W, the NOLM transmission has two maxima, one at $\Delta=0.59$ and another at $\Delta=1.39$, while at $\Delta=1$ it has a minimum. This is because at a retardation of $\pi/2$ the 70 W of input power is close to the switching power, or power required for the maximum transmission, see Fig. 3 (solid line). According to the results shown in Fig. 3 (solid line) for $\Delta=1$, when the power reaches the value of 70 W, the NOLM transmission decreases by approximately 25% with respect to the maximum. The simulations showed that the transmission can be changed for example from 0.012 at $\Delta=0$ to 0.69 at $\Delta=1$ in the case that input pulses with power of 40 W were selected. Fig. 5(b) shows the experimental results for different input pulse powers. The shapes of experimental and calculated dependencies are quite similar. When the pulse amplitude has a value of 1.43 (arbitrary units), the dependence has two maxima similarly to the simulated data at a pulse power of 70 W. The good agreement observed between Fig. 5(a) and (b) allowed us to conclude that our input pulse in the experiment was approximately 70 W. This value is in accordance with power estimation yielded from Fig. 4. Note that it is always difficult to measure the amplitude of the ps pulses and therefore the adjustable NOLM may provide a useful tool for this measurement.

Fig. 6(a) and (b) show the simulation and experimental results for the case when the VWR was inserted close to the 0.48 port. An important feature is that at low Δ the transmission decreases or is flat when Δ increases and reaches a minimum at approximately $\Delta=0.25$ in simulations. This occurs because the nonlinear phase shift due to power imbalance is subtracted from the phase shift

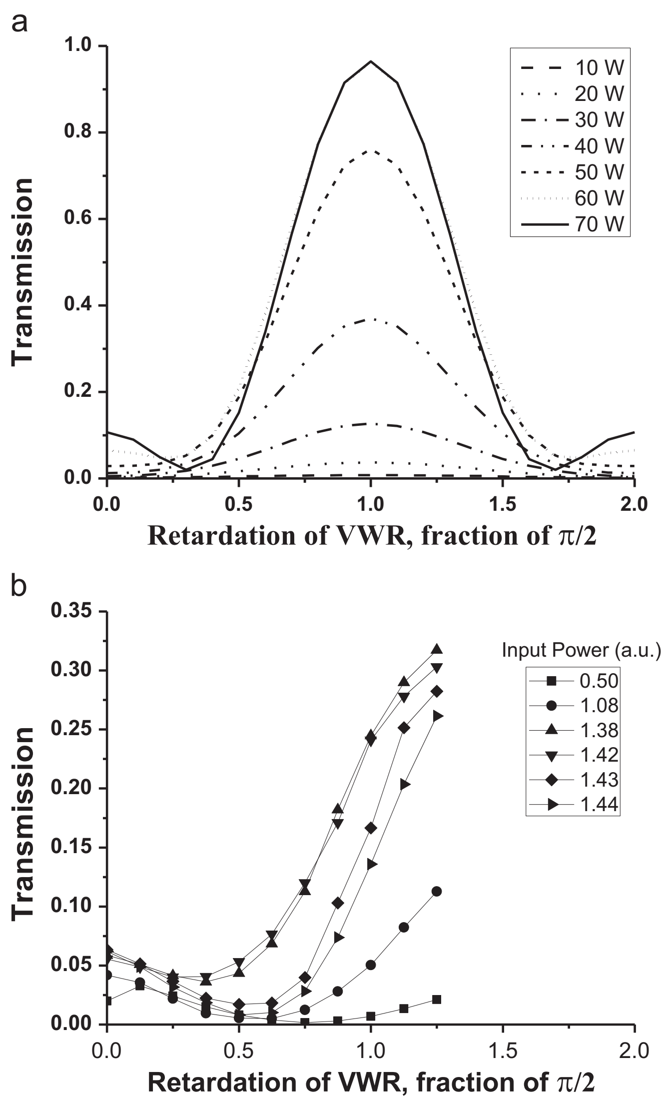

Fig. 6. Nonlinear transmission of the NOLM for different input pulse amplitudes, when VWR is inserted near the 0.48 port, (a) simulation results, (b) experimental results.

due to polarization imbalance until the latter eventually becomes dominant. Experimental results also show the decrease of the transmission for small Δ and the increase of the transmission for $\Delta > 0.5$. It has to be noted that the maxima of the transmission, or the local minimum at 70 W in Fig. 5(a) in simulations are observed at $\Delta = 1$, however in the experiment the maxima/minima are shifted. It may occur because of imprecise calibration of the VWR. We observed that the VWR is not very stable. The calibration of the VWR was performed in a range from 0 to a value around 1.5 $\pi/2$, which was the range that could cover the rotatable fiber squeezer. Therefore, all the experimental data are found in such range. In Fig. 5(b), nearly all the simulated range was covered experimentally as is shown in Fig. 5(a), while in Fig. 6(b), the range covered experimentally was only a portion of the simulated range. However there may be a more fundamental reason for the shift. Our preliminary simulation shows that the shift may also occur because the polarization of the input pulse is not exactly circular.

4. Conclusions

We have shown by experimental and numerical studies that the switch power of the NOLM based on polarization asymmetry can be effectively adjusted by changing the retardation of the VWR placed in the loop of the NOLM. The change of nonlinear transmission up to 10 times at the same input power was found in the experiments. At the same time the rotation of the VWR allows the adjustment of the low power transmission. These possibilities make the polarization asymmetrical NOLM with the VWR a versatile device for applications with very simple adjustment of the nonlinear characteristics.

Acknowledgments

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