Symmetric Nonlinear Optical Loop Mirror Used as Saturable Absorber in Mode-Locked Fiber Laser

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Abstract: We investigate the operation of a power-symmetric NOLM, which relies on nonlinear polarization rotation. The device is made of a symmetrical coupler, highly twisted fiber and a QWR located asymmetrically in the loop (which can be rotated in a plane perpendicular to the fiber) and can be used in mode-locked fiber laser as saturable absorber.
OCIS codes: (060.3510) Lasers, fiber; (060.4370) Nonlinear optics, fibers; (060.2320) Fiber optics amplifiers and oscillators.

1. Introduction

The fiber nonlinear Sagnac interferometer, or Nonlinear Optical Loop Mirror (NOLM) [1], it's a simple device made of a coupler whose output ports are connected through a span of fiber, offers a versatile way to obtain a nonlinear transmission (or switching) characteristic through the optical Kerr effect, if a nonlinear phase shift difference appears between the two interfering beams. When a polarization controller is inserted in the loop, the bias of the switching characteristic can be adjusted to meet the requirements of a specific application. Most NOLM designs rely on self-phase modulation, which causes a differential nonlinear phase shift to accumulate only if a power imbalance exists between the beams propagating clockwise (CW) and counterclockwise (CCW) in the loop. As the power ratio between CW and CCW beams is generally imposed by construction (in general, through the fixed coupling ratio of the coupler), such designs offer few possibilities of adjustment, especially in terms of contrast or critical power (power difference between minimal and maximal transmissions, corresponding to a π nonlinear phase shift difference). In addition, when designing such a NOLM, a compromise often has to be found between high contrast, low critical power and low insertion loss, as in general the three criteria cannot be met simultaneously. A change occurred when it was realized that, thanks to the nonlinear polarization rotation (NPR) phenomenon, a polarization asymmetry between the CW and CCW beams can provide switching, even if powers are equal (case of a symmetrical coupler). A particularly promising NOLM structure, made of a symmetrical coupler, highly twisted fiber and a Quarter-Wave Retarder (QWR), and operating through NPR was proposed in [2]. In a previous publication, we proposed a complete theoretical description of the NOLM operation in the weakly nonlinear regime, which accounts for all possible input polarization states [3].

A passive mode-locked fiber laser is a simple and effective setup to generate ultrashort pulses. Many mode-locking techniques have been reported to implement a passive mode-locked laser including semiconductor saturable absorber, nonlinear amplifier loop mirror (NALM), NOLM and nonlinear polarization rotation with a polarizer. Configurations that include a NOLM or a NALM are called Figure-Eight fiber Lasers (F8L). The NOLM is usually formed by an asymmetrical coupler whose output ports are connected to form a loop. The nonlinear phase shift of these beams is due to the self-phase modulation effect. If a symmetrical coupler is used in the loop, the switching can be obtained through the dispersion effect or the dependence of the nonlinear phase shift on polarization. In this paper we make a review of our previous works, in which, we suggested the use of the NOLM with symmetrical coupler, highly twisted fiber and a QWR in the loop (to break the polarization symmetry [4]) to be used as saturable absorber. For low input power the NOLM transmission is adjustable as well as the slope of the nonlinear dependence by a simple rotation of the QWR. A symmetrical NOLM with a QWR was suggested and investigated also for mode locking in the F8L [5].

2. Simulations

The structure under discussion consists of a 50/50 coupler, a span of low linear birefringence, highly twisted fiber connecting the two output ports of the coupler, and a QWR inserted in the loop, close to the coupler. In such power-symmetric design, different nonlinear evolutions can only be obtained through the polarization difference generated by the QWR. The QWR can be rotated in a plane perpendicular to the fiber (angle α). The purpose of the strong twist applied to the fiber is to overcome its residual birefringence, which also depends on environmental conditions. Indeed, this twist generates high optical activity (circular birefringence) along the fiber, and also causes a rapid precession of its principal axes. Both effects tend to conserve the polarization ellipticity of each of the counterpropagating beams during propagation in the loop. This allows NPR to build up, and generate switching. Twist also makes the interferometer more robust against environmental perturbations. Fig. 1(a) presents the curves for different values of α for circular input polarization, and Fig. 1(b) shows the transmission obtained for different values of ψ (which defines the direction of the ellipse major axis) for linear input polarization [3].

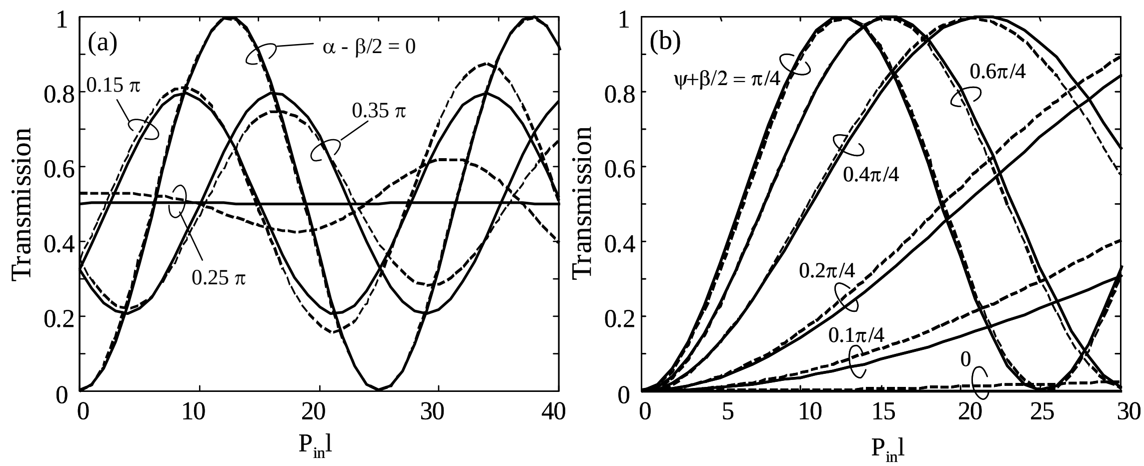

Fig. 1. NOLM transmission for (a) circular right and (b) linear input polarizations, for different values of the control parameter (α and ψ, respectively). In Fig. (b), $\alpha = \beta/2$.

3. Experimental setup and results

Recently, we experimentally investigated the conditions for the self-starting operation of a novel F8L based on a power-balanced NOLM with a twisted low-birefringence fiber and a QWR in the loop [5]. We demonstrated that the self-starting passive mode-locking operation of a F8L can be obtained through simple and clear adjustments using a symmetrical NOLM with highly twisted fiber in the loop. We demonstrated experimentally that self-starting modelocking critically depends on the precise adjustment of the NOLM. We determined experimentally the QWR angle (α in Fig. 1(a)) required for self-starting operation and have found that the self-starting operation is reproducible from day to day. The laser is capable of generating ~20 ps pulses at a repetition frequency of 0.78 MHz. We achieved stable generation of picosecond pulses with milliwatts of average output power. Fig. 2 shows the experimental setup of the F8L. The NOLM is formed by a 51/49 Coupler 1, a 220 m fiber length and a QWR. Before the pulse is transmitted in to the input NOLM segment, we used a QWR to adjust the clockwise propagating beam to be circularly polarized. Couplers 2 and 3 were used to monitor the optical power in the laser. After the pulse exits the NOLM we used a circulator with a fiber Bragg grating (FBG) with 1545 nm central wavelength, a 0.4 nm bandwidth and 100% of reflectivity. The principal idea behind the use of the FBG is to get a tunable mode-locked laser. P1 is a polarizer and optical isolator at the same time.

In other paper we experimentally demonstrated the wavelength tunability of a F8L formed by inserting a hi-bi fiber Sagnac loop into the cavity [6]. Our mode-locked laser (see Fig. 3) is based on a symmetrical NOLM with high-twist, low-birefringence fiber and a QWR in the loop. The signal at the NOLM output is amplified by 1 m of Erbium-doped fiber. The output pulses are wavelength tunable over a range from 1525 to 1555 nm. The filter transmission function can be changed by selecting the hi-bi fiber loop length. The wavelength of the transmission maximum is adjusted by changing the temperature of the hi-bi fiber. The mode-locking is achieved at a specific position of the QWR at pump powers higher than 50 mW. The FWHM of the autocorrelation trace is about 3.1 ps and the pulse spectrum has a FWHM width of 1.5 nm.

4. Conclusions

Considering a symmetrical NOLM as a saturable absorber we demonstrated different fiber laser configurations. Our basic configuration was a figure-eight fiber laser (F8L). We can designe F8L to generate tunable pulses with 20 ps and 3 ps.

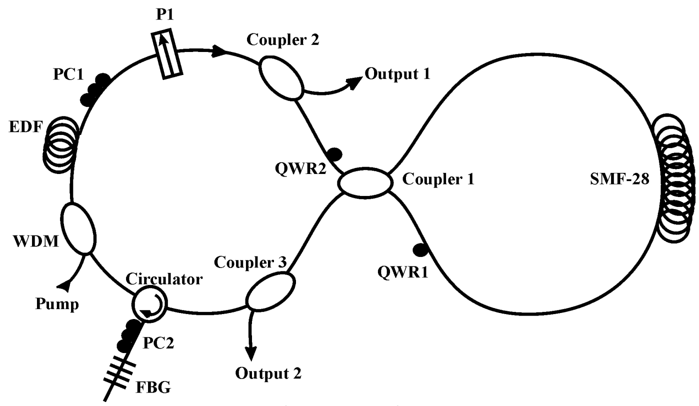

Fig. 2. Experimental setup of the tunable figure eight mode-locked laser.

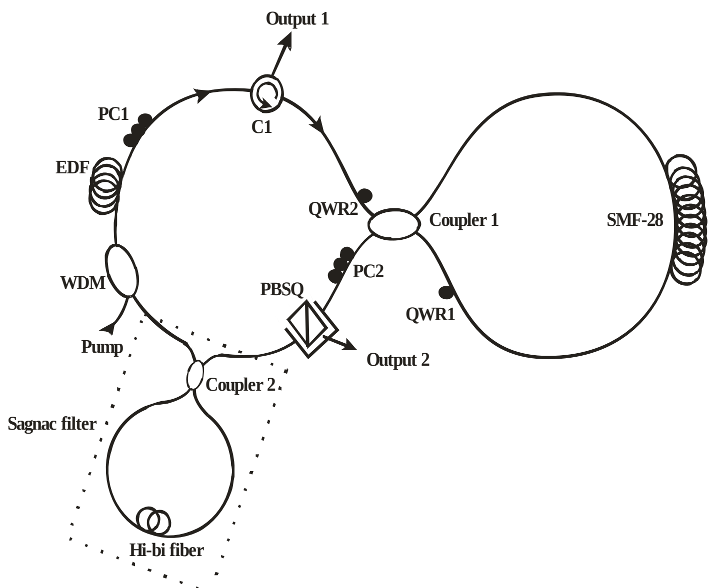

Fig. 3. Experimental setup of the tunable F8L with a Sagnac fiber filter.

REFERENCES

[1] N.J. Doran, and D. Wood, Opt. Lett. **13**, 56-58 (1988).

[2] E.A. Kuzin, N. Korneev, J.W. Haus, and B. Ibarra-Escamilla, J. Opt. Soc. Am. B **18**, 919-925 (2001).

[3] O. Pottiez, E. A. Kuzin, B. Ibarra-Escamilla, and F, Méndez-Martínez ”Theoretical investigation of the NOLM with highly twisted fibre and a λ/4 birefringence bias”, Optics Communications **254**, 152-167 (2005).

[4] B. Ibarra-Escamilla, E. A. Kuzin, P. Zaca-Morán, R. Grajales-Coutiño, F. Mendez-Martinez, O. Pottiez, R. Rojas-Laguna, J. W. Haus, "Experimental investigation of the nonlinear optical loop mirror with twisted fiber and birefringence bias,” Opt. Express **13**, 10760-10767 (2005).

[5] B. Ibarra-Escamilla, O. Pottiez, E. A. Kuzin, J. W. Haus, R. Grajales-Coutiño, and P. Zaca-Moran, “Experimental investigation of self-starting operation in a F8L based on a symmetrical NOLM”, Opt. Commun. **281,** 1226-1232 (2008).

[6] B. Ibarra-Escamilla, O. Pottiez, J. W. Haus, E. A. Kuzin, M. Bello-Jiménez, and A. Flores-Rosas, *“Wavelength-tunable picosecond pulses from a passively mode-locked figure-eight Erbium-doped fiber laser with a Sagnac fiber filter,”* Journal of the European Optical Society **3**, 08036 (2008).