ISSN 1054-660X, Laser Physics, 2009, Vol. 19, No. 2, pp. 368–370.

All-Fiber Passive Mode-Locked Laser to Generate ps Pulses Based in a Symmetrical NOLM[1]

B. Ibarra-Escamilla[a, c], *, O. Pottiez[b], E. A. Kuzin[a], M. Duran-Sanchez[a], and J. W. Haus[c]

[a] *Instituto National de Astrofisica, Optica y Electrónica, Optics Department,*
Apdo. Postal 51 y 216, Puebla, Pue 72000, Mexico
[b] *Centro de Investigaciones en Optica, León, Gto 37150, Mexico*
[c] *Electro-Optics Program, The University of Dayton, Dayton, OH 45469, USA*
*e-mail: baldemar@inaoep.mx

Received July 4, 2008

Abstract—We experimentally investigate an all-fiber passively mode-locked laser generating ps pulses. The experimental setup is a figure eight fiber laser configuration, including a power-symmetric Nonlinear Optical Loop Mirror (NOLM) with highly twisted low-birefringence fiber in the loop. NOLM switching is achieved by polarization asymmetry between the counter-propagating beams in the loop. We used a Quarter-Wave Retarder in the loop to break the polarization symmetry. Using a polarizer beam-splitter cube as the NOLM output we got the best quality output pulses from the laser. At this output, we are monitoring the output pulse polarization component which is parallel to the input NOLM component. We achieved stable generation of ~25 ps pulses at the repetition frequency of 0.78 MHz with milliwatts average output power. The mode-locked laser ran in stable operation for hours.

PACS numbers: 42.81.-i, 42.55.Wd, 42.65.-k

DOI: 10.1134/S1054660X09020327

1. INTRODUCTION

All-fiber passive mode-locked lasers are versatile devices for ultrashort pulse generation. A variety of all-fiber configurations was proposed including the insertion of a Nonlinear Optical Loop Mirror (NOLM) or a Nonlinear Amplifier Loop Mirror (NALM) in a laser ring [1]. These kinds of devices are called Figure-Eight Lasers, F8L [2]. Up to now, the generation of pulses of several tens of picoseconds using this kind of devices did not receive a lot of attention. However the generation of high-peak-power picoseconds pulses from passively mode-locked laser can be useful for some applications, for example supercontinuum generation [3, 4]. The mechanisms of the supercontinuum generation are quite different for femto- and picosecond pulses.

The NOLM is usually formed by an asymmetric coupler whose output ports are connected to form a loop [5]. The power imbalance between the counter-propagating beams produces a difference in the nonlinear phase shift of these beams caused by self phase modulation [6]. This in turn results in an intensity dependent transmission of the NOLM required for passive mode locking. In that case the polarization of the beams does not contribute to switching. If now we use a symmetrical coupler in the loop, the switching can be obtained through the dependence of the nonlinear phase shift on polarization. The power dependence is obtained through a polarization asymmetry between the counter-propagating beams. Extensive theoretical and experimental studies have shown that this scheme allows stable operation and provides a simple way to adjust its characteristic [7–11]. The low-power NOLM transmission is adjustable between ~0% to 100% as well as the slope of the nonlinear dependence by a simple rotation of the QWR [11]. High twist reduces the fiber residual linear birefringence and makes it more robust to changes of environmental conditions. It was also shown that the twisted fiber has properties equivalent to those of an ideal isotropic fiber [12].

In this work we report on the experimental study of a F8L based on a power-balanced NOLM. The cavity of the laser includes a Fiber Bragg Grating (FBG) spectral filter that allows the generation of picosecond pulses. We used the flexibility of the nonlinear characteristic of the NOLM to find the setting for self-starting operation [13]. We used a polarizer beam-splitter cube (PBSQ) in the output NOLM to get the best quality pulses from the laser output. In this PBSQ output we are monitoring the output pulse polarization component which is parallel to the input NOLM component. We achieved stable generation of ~25 ps pulses at the repetition frequency of 0.78 MHz with milliwatts average output power.

2. EXPERIMENTAL RESULTS

The experimental setup is shown in Fig. 1. The NOLM is formed by a symmetrical Coupler, whose output ports were fusion-spliced with a 220 m loop of low-birefringence, highly twisted Corning SMF-28 fiber and a QWR1 was inserted in the loop to transform

---

[1] The article is published in the original.

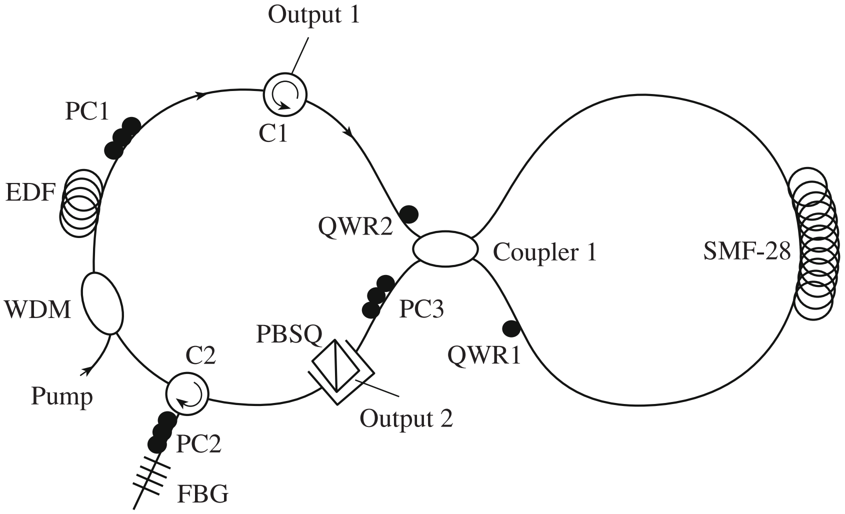

Fig. 1. Schematic of the setup used in the experiment.

the counter-clockwise beam (CCW) from circular to linear polarization. A twist rate of 7 turns/m was imposed to the fiber loop. Prior to the NOLM input, we inserted a QWR2 to polarize circularly the clockwise (CW) beam. We used a circulator (C2) to include a fiber Bragg grating (FBG) as filtering element in our system. The FBG central wavelength is 1548 nm with a 100% maximal reflection. For pumping we used a 980 nm laser with a 100 mW maximum output power. Pump power was injected into the system through a WDM coupler. The signal at the NOLM output was amplified by 10 m of Erbium-doped fiber (with an Erbium concentration of 1000 ppm) and passed through a polarization dependent circulator (C1), which was used actually as polarizer. The polarization controller (PC1) was adjusted to have maximal transmission from the C1. Circular polarization was realized at the NOLM input through the QWR2. We used a polarizer beam-splitter cube (PBSQ) as the NOLM output to get the best quality output pulses from the laser. The PC3 is adjusted to have minimal signal at the laser Output 2 at CW operation. That means at the same time that we adjusted the maximum transmission through the PBSQ to the circulator C1. In linear operation the NOLM operates as a half wave plate and therefore the output polarization is orthogonal to the input one. So at this adjustment the orthogonal polarization component at the NOLM output passes through the PBSQ and the parallel polarization component is monitoring at the Output 2. The parallel component is zero for low power; however it appears at high power. Through the QWR1 orientation it is possible to change the low-power transmission of the NOLM from a maximum to a minimum [8, 14], the corresponding dependence for the experimental setup discussed here is shown in Fig. 2. Adjusting the QWR1 at the position A, we get self-starting mode-locking pulses from a pump power higher than 70 mW. At this power multiple pulses are in the laser cavity. Autocorrelation function usually shows that the pulses have a long pedestal. However after adjusting the PC2, we were able to eliminate this pedestal. If we decrease the pump power down to 15 mW, only one high quality pulse remains in the cavity. Its autocorrelation function is shown in the Fig. 3. The FWHM of the autocorrelation trace is about 36 ps corresponding to a FWHM pulse duration $\Delta\tau = 25.45$ ps (if a Gaussian profile is assumed).

Figure 4 shows the output mode-locked pulse spectrum measured at Output 2, whose FWHM bandwidth is $\Delta\lambda = 0.15$ nm. This gives $\Delta\nu\Delta\tau = 0.478$ where $\Delta\nu$ is the FWHM of the frequency spectrum. This time-band-

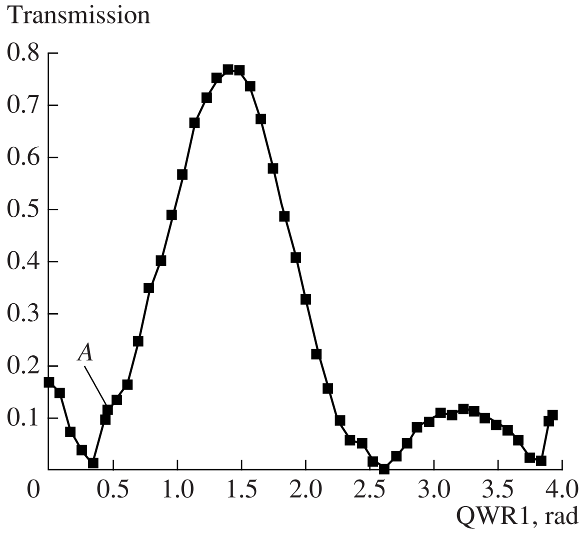

Fig. 2. Experimental low-power transmission dependence on the QWR1 angle when two maxima with different amplitudes are observed in a period of π rad.

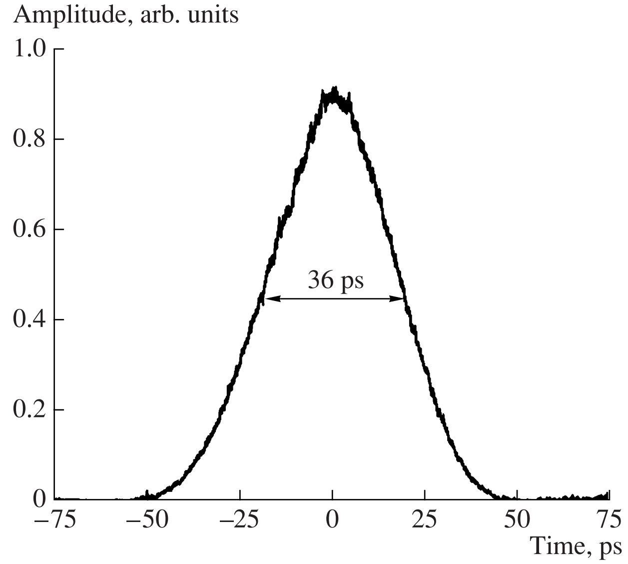

Fig. 3. Autocorrelation trace when a single output pulse is formed in the cavity.

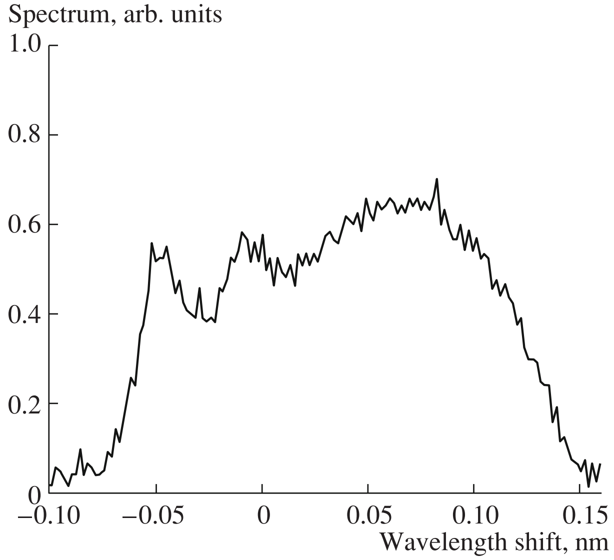

Fig. 4. Optical spectrum from the passively mode-locked fiber laser.

width product corresponds to nearly transform-limited Gaussian pulses.

3. CONCLUSIONS

In conclusion, we demonstrated the operation of a passively mode-locked F8L based on a power-symmetric NOLM with a highly twisted low-birefringence fiber and a QWR in the loop. With this architecture self-starting mode locking is observed for a specific QWR setting. We used a polarizer beam-splitter cube (PBSQ) in the output NOLM to get the best quality output pulses from the laser. At this output port we are monitoring the output pulse polarization component which is parallel to the input NOLM component. Without any further adjustment, we get in the cavity a single pulse with a long pedestal. If now we adjust the polarization controller before the FBG, it is possible to eliminate this pedestal and a packet of pulses appear in the cavity. When we decrease the pump power, the number of pulses is gradually decreased until only one single pulse remains in the cavity, for 15 mW pump power. The pulse repetition frequency is 0.78 MHz. The FWHM of the autocorrelation function is 36 ps, yielding ~25 ps near-transform-limited pulses. We believe that these ps pulses can be useful for investigating supercontinuum generation in optical fibers.

ACKNOWLEDGMENTS

B. Ibarra-Escamilla was supported by CONACyT grant 80451 for a sabbatical year. O. Pottiez was supported by CONACyT grant 53990.

REFERENCES

1. I. N. Duling III, Opt. Lett. **16**, 539 (1991).
2. I. N. Duling III and M. L. Dennis, *Compact Sources of Ultrashort Pulses* (Cambridge Univ., Cambridge, 1995).
3. K. Mori, H. Takara, and S. Kawanichi, J. Opt. Soc. Am. **18**, 1780 (2001).
4. S. Coen, A. H. L. Chau, R. Leonhardt, J. D. Harvey, J. C. Knight, W. J. Wadsworth, and P. St. J. Russel, Opt. Lett. **26**, 1356 (2001).
5. N. J. Doran, and D. Wood, Opt. Lett. **13,** 56 (1988).
6. G. P. Agrawal, *Applications of Nonlinear Fiber Optics* (Academic, San Diego, 2001).
7. O. Pottiez, E. A. Kuzin, B. Ibarra-Escamilla, and F. Mendez-Martinez, Opt. Commum. **229**, 147 (2004).
8. B. Ibarra-Escamilla, E. A. Kuzin, P. Zaca-Morán, R. Grajales-Coutiño, F. Mendez-Martinez, O. Pottiez, R. Rojas-Laguna, and J. W. Haus, Opt. Express **13**, 10760 (2005).
9. O. Pottiez, E. A. Kuzin, B. Ibarra-Escamilla, J. L. Camas-Anzueto, and F. Gutierrez-Zainos, Electron. Lett. **40**, 892 (2004).
10. O. Pottiez, E. A. Kuzin, B. Ibarra-Escamilla, J. T. Camas-Anzueto, and F. Gutierrez-Zainos, Opt. Express **12**, 3878 (2004).
11. B. Ibarra-Escamilla, E. A. Kuzin, O. Pottiez, J. W. Haus, F. Gutierrez-Zainos, R. Grajales-Coutiño, and P. Zaca-Moran, Opt. Commun. **242**, 191 (2004).
12. T. Tanemura, and K. Kikuchi, J. Lightwave Technol. **24**, 4108 (2006).
13. B. Ibarra-Escamilla, O. Pottiez, E. A. Kuzin, J. W. Haus, R. Grajales-Coutiño, and P. Zaca-Moran, Opt. Commun. **281,** 1226 (2008).
14. O. Pottiez, E. A. Kuzin, B. Ibarra-Escamilla, and F. Mendez-Martinez, Opt. Commum. **254**, 152 (2005).