

# Automated mode locking in nonlinear polarization rotation fiber lasers by detection of a discontinuous jump in the polarization state

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**Abstract:** A strategy to align a mode-locked fiber laser with nonlinear polarization rotation is presented. This strategy is based on measurements of the output polarization state. It is shown that, as the angle of a motorized polarization controller inside the cavity is swept, the laser eventually reaches a mode-locked regime and the values of the Stokes parameters undergo an abrupt change. The sensing of this sudden variation is thus used to detect the mode-locking condition and a feedback mechanism drives the alignment of the polarization controller to force mode locking.

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**OCIS codes:** (140.3510) Lasers, fiber; (140.4050) Mode-locked lasers; (060.4370) Nonlinear optics, fibers; (140.3500) Lasers, erbium; (120.5410) Polarimetry.

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## References and links

1. M. E. Fermann and I. Hartl, "Ultrafast fiber lasers," *Nat. Photonics* **7**(11), 868–874 (2013).
  2. Q. Hao and H. Zeng, "Cascaded Four-Wave Mixing in Nonlinear Yb-Doped Fiber Amplifiers," *IEEE J. Sel. Top. Quantum Electron.* **20**(5), 0900205 (2014).
  3. I. N. Duling III, C.-J. Chen, P. K. A. Wai, and C. R. Menyuk, "Operation of a nonlinear loop mirror in a laser cavity," *IEEE J. Quantum Electron.* **30**(1), 194–199 (1994).
  4. O. Shtyrina, M. Fedoruk, S. Turitsyn, R. Herda, and O. Okhotnikov, "Evolution and stability of pulse regimes in SESAM-mode-locked femtosecond fiber lasers," *J. Opt. Soc. Am. B* **26**(2), 346–352 (2009).
  5. S. Yamashita, Y. Inoue, S. Maruyama, Y. Murakami, H. Yaguchi, M. Jablonski, and S. Y. Set, "Saturable absorbers incorporating carbon nanotubes directly synthesized onto substrates and fibers and their application to mode-locked fiber lasers," *Opt. Lett.* **29**(14), 1581–1583 (2004).
  6. H. Zhang, D. Y. Tang, L. M. Zhao, Q. L. Bao, and K. P. Loh, "Large energy mode locking of an erbium-doped fiber laser with atomic layer graphene," *Opt. Express* **17**(20), 17630–17635 (2009).
  7. M. Hofer, M. E. Fermann, F. Haberl, M. H. Ober, and A. J. Schmidt, "Mode locking with cross-phase and self-phase modulation," *Opt. Lett.* **16**(7), 502–504 (1991).
  8. H. A. Haus, E. P. Ippen, and K. Tamura, "Additive-pulse modelocking in fiber lasers," *IEEE J. Quantum Electron.* **30**(1), 200–208 (1994).
  9. T. Hellwig, T. Walbaum, P. Groß, and C. Fallnich, "Automated characterization and alignment of passively mode-locked fiber lasers based on nonlinear polarization rotation," *Appl. Phys. B* **101**(3), 565–570 (2010).
  10. D. Radnatarov, S. Khripunov, S. Kobtsev, A. Ivanenko, and S. Kukarin, "Automatic electronic-controlled mode locking self-start in fibre lasers with non-linear polarisation evolution," *Opt. Express* **21**(18), 20626–20631 (2013).
  11. X. Shen, W. Li, M. Yan, and H. Zeng, "Electronic control of nonlinear-polarization-rotation mode locking in Yb-doped fiber lasers," *Opt. Lett.* **37**(16), 3426–3428 (2012).
  12. R. Ulrich and A. Simon, "Polarization optics of twisted single-mode fibers," *Appl. Opt.* **18**(13), 2241–2251 (1979).
  13. M. Olivier and M. Piché, "Origin of the bound states of pulses in the stretched-pulse fiber laser," *Opt. Express* **17**(2), 405–418 (2009).
  14. R. Ulrich, S. C. Rashleigh, and W. Eickhoff, "Bending-induced birefringence in single-mode fibers," *Opt. Lett.* **5**(6), 273–275 (1980).
  15. A. Gordon and B. Fischer, "Phase transition theory of pulse formation in passively mode-locked lasers with dispersion and Kerr nonlinearity," *Opt. Commun.* **223**(1-3), 151–156 (2003).
  16. G.-Z. Zhao, L.-L. Gui, X.-S. Xiao, and C.-X. Yang, "Magneto-optic crystal polarization controller assisted mode-locked fiber laser," *Chin. Phys. Lett.* **28**(3), 034203 (2011).
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## 1. Introduction

Nowadays, low cost, reliability and robustness foster the use of passively mode-locked (ML) fiber lasers in many applications such as supercontinuum generation, terahertz wave generation, nonlinear microscopy, optical coherence tomography, spectroscopy, frequency combs and metrology [1, 2]. Different techniques exist to force these lasers to emit ultrashort pulses of light. For instance, nonlinear loop mirrors [3] and saturable absorbers such as SESAM [4], carbon nanotubes [5] and graphene [6] have been exploited. However, the most common and easiest to implement technique is based on nonlinear polarization rotation (NPR) inside the cavity [7, 8]. By inserting a polarizer in the cavity and controlling the polarization state of the signal with waveplates or equivalent systems, the cavity losses can become intensity-dependent and favor the emission of intense short pulses. A major drawback of this technique is the start-up procedure: when the laser is turned on, the alignment of the waveplates has to be adjusted to find the ML regimes. This step is usually performed manually using expensive equipment such as an optical spectrum analyzer or an autocorrelator. The polarization controller is manually rotated until the ML state is found. This state is usually stable for several hours unless the laser cavity is perturbed, in which case the alignment procedure has to be repeated. Automating this procedure to avoid this initial step represents a precious gain in reliability. To do so, an electronically adjustable polarization controller and a feedback loop based on an actual measurement of the signal discriminating ML are required. In recent years, different approaches have been proposed. Hellwig et al. [9] used piezoelectric squeezers as polarization controllers and a full analysis of the polarization state of the signal based on an all-fiber division-of-amplitude polarimeter for the feedback loop. Radnaratov et al. [10] used the RF spectrum as the feedback signal and a single liquid crystal plate to get ML. Shen et al. [11] used an electronic polarization controller based on piezoelectric squeezers and a feedback loop based on a smart control system using a photodiode and a high-speed counter.

In this paper, we propose a new strategy using measurements of the laser output polarization and compatible with an all-fiber scheme. This new strategy consists of a motorized polarization controller based on the twisting of an optical fiber clamped in a squeezer and a feedback loop used to adjust the polarization state in the cavity. We show that, as the angle of the controller is swept, the polarization state of the output varies continuously but, when the laser becomes ML, it undergoes an abrupt change. This change constitutes a promising opportunity to successfully automate the alignment procedure. This change is actually detected by measuring a single Stokes parameter. After introducing our laser cavity and experimental setup, this paper will discuss the fact that a single waveplate or polarization controller can be used to ML a fiber laser. Then, numerical and experimental results of the chosen Stokes parameter as a function of the angle of the polarization controller are presented. These results demonstrate the feasibility of using the discontinuous jump in the output polarization state to find ML in an erbium-doped fiber laser. Finally, based on these results, we discuss the automation of the process to reach the self-starting ML conditions in such a laser.

## 2. The laser cavity and characterization setup

In order to analyze the behavior of the output polarization state in a passively ML femtosecond fiber laser based on NPR, the experimental setup shown in Fig. 1 was used. This setup uses an unidirectional all-fiber ring laser with a total fiber length of 244 cm. The 68-cm highly-doped erbium fiber (OFS EDF-150) is pumped by two 800 mW laser diodes at 976 nm that are injected through wavelength-division multiplexers (WDMs) placed at both ends of the gain fiber. ML is initiated by the combined effect of the polarizer and the NPR in the cavity. A motorized all-fiber polarization controller (GiGa Concept Inc. GIG-2201-1300) controls the polarization state in the cavity. This controller clamps the fiber in a squeezer with

a fixed screw-adjusted pressure and then, with a step motor, controls the polarization by twisting the fiber between two fixed ends [12]. This system is equivalent to a waveplate with the retardation fixed by the pressure exerted by the screw on the fiber. Although for a given screw adjustment the controller does not cover the entire Poincaré sphere for a given input polarization, it allows sufficient control to ML the laser as discussed later. Different values of retardation could lead to ML as will be shown in section 3.1 but here we adjusted the pressure of the screw to correspond to a  $\lambda/3$  waveplate. The twisting angle is controlled dynamically via a USB-port module and a computer; this angle can be varied by steps of  $0.1125^\circ$ . The output signal is tapped through a 1% coupler to a General Photonics PolaDetect POD-101D polarimeter to analyze its polarization state. The 99% port provides the output signal for the laser user. In our case, we feed it to a pulse analyzer (optical spectrum analyzer, autocorrelator or fast photodiode) to check for ML and characterize the resulting pulses. As discussed later, the computer determines and applies the required angle correction to the polarization controller thus closing the feedback loop and automating the ML of the laser.

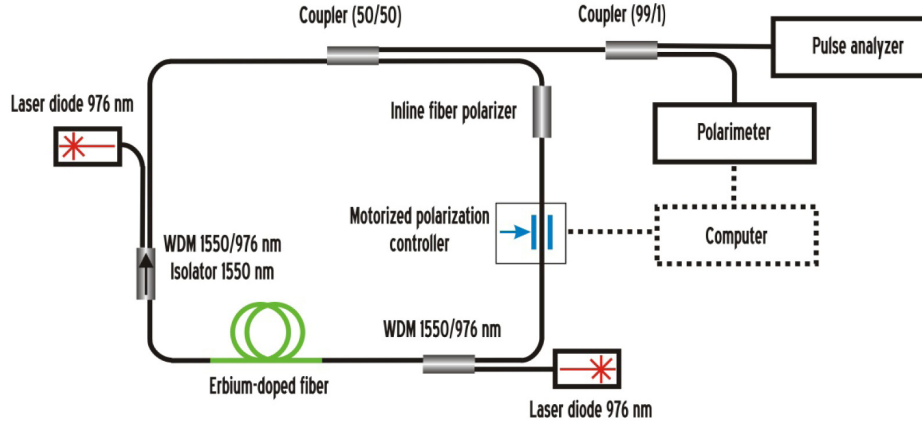


Fig. 1. The laser cavity and experimental setup.

### 3. Mode locking with a single waveplate

Mode locking by NPR is usually implemented via two or three waveplates in a cavity. A quarter-waveplate transforms the linear polarization exiting the polarizer into an elliptical polarization as required to get nonlinear polarization rotation. A half-wave plate is added to make sure that the intensity-dependent transmission at low powers increases, thus favoring pulse formation. Finally, another quarter-waveplate can be used to retrieve the linear polarization state and optimize the peak transmission through the polarizer. However, a single waveplate can also lead to ML as will be shown below. This is a noteworthy feature of the laser cavity presented above. It limits to one the number of adjustable free parameters to reach ML. Assuming the retardation of the waveplate and pump power were pre-adjusted in such a way to be able to get stable ML with a single pulse in the cavity, the only parameter to vary becomes the angle of the waveplate or, equivalently, the angle of the motorized polarization controller.

#### 3.1 The model for an ideal cavity

To demonstrate that a single waveplate can be used to ML, we follow the approach presented in [8]. We assume that the cavity does not have any birefringence, a characteristic called the “ideal” case in what follows. Note that for a short cavity such as the one presented in this paper the birefringence is small and so this condition is not too restrictive. The nonlinear transmission of the cavity is modeled by considering the evolution of a polarized CW signal represented by a Jones vector inside the cavity. The signal passes through a polarizer with its

axis along  $x$ , then through a waveplate with retardation  $\Gamma$  and angle  $\theta$  with respect to the polarizer's axis, then through a nonlinear optical fiber and finally comes back through the polarizer. The Jones matrix  $W$  representing the waveplate is

$$W(\Gamma, \theta) = \begin{bmatrix} \cos \frac{\Gamma}{2} - i \sin \frac{\Gamma}{2} \cos 2\theta & -i \sin \frac{\Gamma}{2} \sin 2\theta \\ -i \sin \frac{\Gamma}{2} \sin 2\theta & \cos \frac{\Gamma}{2} + i \sin \frac{\Gamma}{2} \cos 2\theta \end{bmatrix} \quad (1)$$

Nonlinear propagation in the cavity fiber of length  $L$  and nonlinear Kerr coefficient  $\gamma$  is represented by the Jones matrix  $K$

$$K(\Delta\phi) = \begin{bmatrix} \cos \Delta\phi & -\sin \Delta\phi \\ \sin \Delta\phi & \cos \Delta\phi \end{bmatrix}, \quad (2)$$

where  $\Delta\phi(P) = \frac{\gamma L}{3} \sin \Gamma \sin(2\theta) P$  is the differential nonlinear phase shift cumulated

between the right-handed circular and left-handed circular polarized signals during the propagation in the fiber. Note that an overall common nonlinear phase shift is ignored in the context of this analysis because it has no influence on the nonlinear transmission of the cavity. In the definition of the nonlinear differential phase shift,  $P$  is the power of the linearly polarized signal just leaving the polarizer. Of course, at the beginning of its roundtrip the signal is polarized along the polarizer's axis and the same could be said at the end of the roundtrip after it went again through the polarizer. Consequently, we can compute the nonlinear transmission  $T$  by considering the ratio of the square of the  $x$ -components of the Jones vector at the output and input. It is given by

$$T(P) = \cos^2 \frac{\Gamma}{2} \cos^2 \Delta\phi + \sin^2 \frac{\Gamma}{2} \cos^2 (2\theta + \Delta\phi). \quad (3)$$

The transmission depends on the power through the differential nonlinear phase shift. We use Eq. (3) to analyze the ML of our cavity. Assuming the motorized polarization controller corresponds to a  $\lambda/3$  waveplate, we find that the angles  $\theta = \pm 1.093$  rad and  $\pm 2.052$  rad maximize the slope of the transmission at small powers. A representative value for the nonlinearity of the cavity is  $\gamma L = 5.0 \times 10^{-3} \text{ W}^{-1}$ . The transmission curves for five different angles close to 1.093 rad are shown in Fig. 2. All these curves have a positive slope at small power and could possibly lead to ML by favoring high powers. However, the value of the transmission at zero power is also an important parameter. If it is too high, a CW signal will see a net gain in the cavity and this situation can destabilize the laser and prevent the formation of a pulse. Using numerical simulations based on the vectorial nonlinear Schrödinger equation to propagate the signal in the fibers, we find that the laser can ML in the case  $\theta = 0.8$  rad as it will be discussed in section 4.

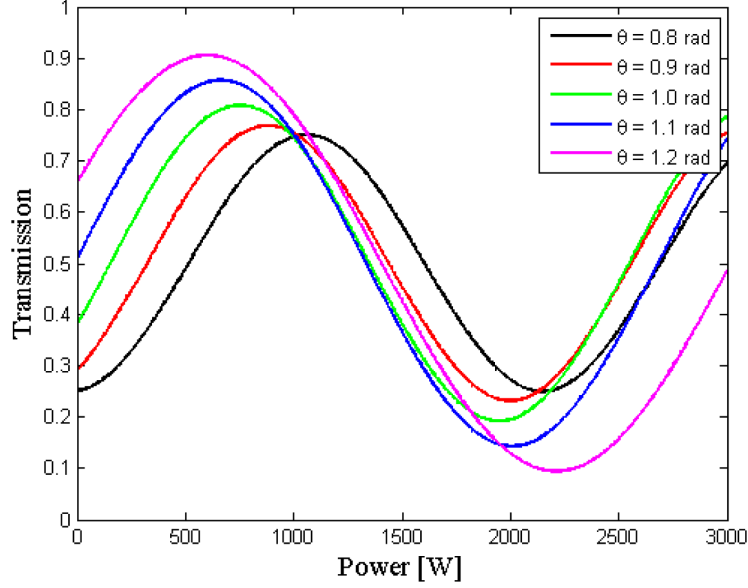


Fig. 2. Nonlinear transmission for different angles of the  $\lambda/3$  waveplate in the ideal case.

### 3.2 A cavity perturbed by a small birefringence

Even if in a real cavity we are able to find a ML condition such as the one described above, this condition might not last forever. For instance the configuration of the fiber segments forming the cavity might be slightly modified due to vibrations, change in the environmental temperature or small shocks to the frame of the laser. The waveplate or polarization controller can even be moved accidentally. Any such modification changes the state of the signal polarization inside the cavity and affects the ML condition. Consequently, the alignment of the waveplates must sometimes be readjusted to ML the laser when it is turned on or after a perturbation. In our cavity, a single waveplate is used. Since this waveplate does not allow covering all the polarization states, it cannot compensate for large external perturbations. However, for small perturbations, which is generally the case once the cavity has been built and secured properly, a single waveplate is enough to compensate and find the ML condition as it will be shown in the next section. To analyze this problem, we use the same approach as the one described in section 3.1 except that we introduce the perturbation as a new Jones matrix with retardation  $\varepsilon$  and angle  $\rho$  located before the nonlinear fiber. Assuming the parameters  $\varepsilon$  and  $\rho$  are small, we can try to compensate this new cavity birefringence by modifying the angle of the waveplate by a small value  $\delta\theta$ . Keeping terms to first order in  $\varepsilon$ ,  $\rho$  and  $\delta\theta$ , we find that the nonlinear transmission  $T'$  at small power becomes:

$$\begin{aligned}
 T'(P) \approx T(P) &+ \left[ \frac{1}{2} \varepsilon \sin \Gamma (\cos 2\theta + 1) - 2\delta\theta \sin^2 \frac{\Gamma}{2} \sin 4\theta \right] \\
 &+ \left\{ \varepsilon \left[ \frac{\gamma L}{6} \sin^4 \frac{\Gamma}{2} \sin^2 4\theta + \frac{1}{2} \sin \Gamma (\cos 2\theta + 1) \right] \right. \\
 &\left. - \delta\theta \left[ \frac{2\gamma L}{3} \sin \Gamma \sin^2 \frac{\Gamma}{2} \cos 2\theta \sin 4\theta + \frac{4\gamma L}{3} \sin \Gamma \sin^2 \frac{\Gamma}{2} \cos 4\theta \sin 2\theta \right] \right\} P.
 \end{aligned} \tag{4}$$

$T(P)$  is the nonlinear transmission in the ideal case at angle  $\theta$ . This equation shows that it is not possible, even to first order, to keep simultaneously the transmission at zero power (modified by the second term) and the slope of the transmission at zero power (modified by

the expression multiplying  $P$ ) unchanged by adjusting  $\delta\theta$ . Only one of the two parameters can be kept unchanged. For instance, suppose that we start from the ML situation with  $\theta = 0.8$  rad without perturbation. When the cavity is perturbed by birefringence  $\varepsilon$ , one can change the angle of the waveplate by a value  $\delta\theta$  such that the slope at zero power will remain the same. However, by doing so, the transmission at zero power will change. One could only hope that it will still be possible to ML the laser. We will see in the next section that it is indeed the case numerically and experimentally when the birefringence of the perturbation is kept small compared to the birefringence of the  $\lambda/3$  waveplate.

#### 4. Automated self-starting mode locking

##### 4.1 Forcing mode locking in NPR fiber lasers: a practical problem

When an NPR passively ML laser is turned on, it does not necessarily ML. The waveplate system must be adjusted such that the nonlinear transmission near zero power will increase with power and that the loss at low power will be sufficient to force the formation of a pulse. The detection of ML and adjustment of the waveplate could be done manually by observing the output signal on an optical spectrum analyzer, an optical autocorrelator and/or a fast photodiode but it could be a rather tedious task. To render this process automatic, which is effectively an important feature in a commercial system, a feedback control loop is required to detect when ML occurs. This section discusses how polarization measurements at the output of the laser could be used for the feedback loop. This strategy is simple and could be implemented at relatively low cost as will be seen later.

##### 4.2 The behavior of the output polarization: numerical simulations

Numerical simulations of the laser shown in Fig. 1 were performed in order to investigate its behavior as the angle of the polarization controller is varied. The vectorial nonlinear Schrödinger equation was used to propagate the signal in the fibers as described in [13]. The erbium-doped fiber was assumed to have a 5 THz lorentzian spectral profile with homogeneous saturation, a small-signal gain coefficient  $g_0 = 4.0 \text{ m}^{-1}$  and a saturation energy  $E_{\text{sat}} = 0.5 \text{ nJ}$  in order to get a single pulse in the cavity. Group velocity dispersion coefficients and nonlinear coefficients of the fibers are  $\gamma = 1.4 \times 10^{-3} \text{ W}^{-1}\text{m}^{-1}$  and  $\beta_2 = -22 \text{ ps}^2/\text{km}$  for the SMF fiber and  $\gamma = 4.3 \times 10^{-3} \text{ W}^{-1}\text{m}^{-1}$  and  $\beta_2 = 59 \text{ ps}^2/\text{km}$  for the EDF fiber. The birefringence of the fibers in the cavity was neglected. For silica fibers with a cladding of  $125 \text{ }\mu\text{m}$  in a ring configuration with a radius of 30 cm and using the model described in [14], we estimate the retardation of the cavity to be 0.06 rad, which is obviously negligible compared to the  $\lambda/3$  waveplate or induced local perturbations. The polarization controller was assumed to be a  $\lambda/3$  waveplate (i.e.  $T = 2\pi/3$  rad) with angle  $\theta$  and was implemented by the Jones matrix given in Eq. (1). We also included a second waveplate with retardation  $\varepsilon$  and angle  $\rho$  at a discrete position in the cavity to represent the perturbative effect of a birefringence induced by environmental factors. Note that a real environmental perturbation such as an important bending or twisting of the fibers in the cavity would probably induce a distributed birefringence over some length of the fiber. However, the modeling of such a perturbation would complicate the calculations without changing the fundamental results obtained with the simpler model assumed here. Starting from noise and in the absence of perturbation, we found ML when  $\theta = 0.8$  rad. The resulting pulses have an energy of 0.74 nJ and a FWHM spectral width of 6.7 THz. We then performed several simulations keeping all the parameters fixed apart from the angle of the  $\lambda/3$  waveplate that was varied from 0 to  $\pi$  rad by steps of 0.02 rad and always starting from noise. At the output, we calculated the first Stokes parameter  $S_1 = (P_x - P_y) / (P_x + P_y)$  where  $P_x$  and  $P_y$  are the powers in the x and y polarization states, respectively.  $\langle S_1 \rangle$  represents the average value of  $S_1$  over the whole profile of the signal.

Figure 3 shows the results obtained for the ideal case and for the case of a perturbation placed after the erbium-doped fiber.

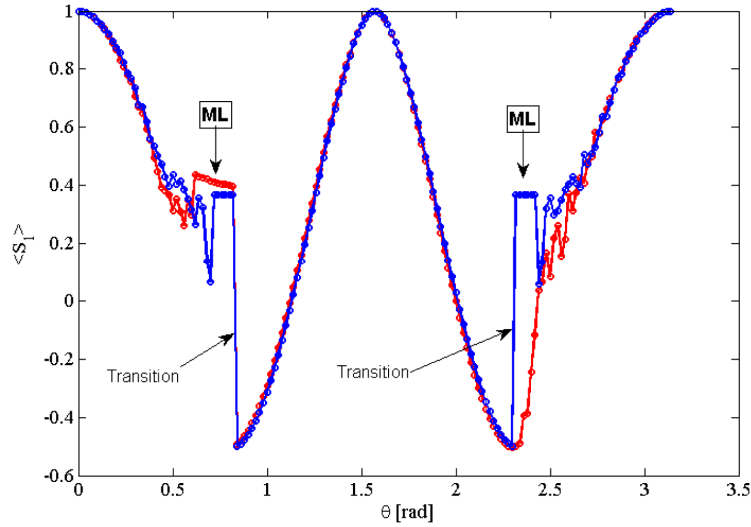


Fig. 3. Simulation results for the first Stokes parameter averaged over the output signal profile as a function of the angle of the  $\lambda/3$  waveplate in the ideal case (in blue) or with a perturbation  $\varepsilon = \rho = 0.5$  rad (in red). Stable mode locking is achieved in the regions labeled “ML”. There is no stable ML around  $\theta = 2.4$  rad for the perturbed case.

The laser emits in CW regime or in unstable regimes everywhere except in the regions close to  $\theta = 0.7$  rad and  $\theta = 2.4$  rad that are labeled “ML”. Note that in the perturbed case, only the region near  $\theta = 0.7$  rad shows ML but this region is larger compared to the corresponding situation in the ideal case. The behavior of  $\langle S_1 \rangle$  varies quasi-continuously with  $\theta$  except when there is an abrupt transition near the ML regions as indicated in the figure. As discussed in [15], the transition from CW to ML could be interpreted thermodynamically as a phase transition during which the laser goes from a disordered state to an ordered one as the angle parameter, acting as an efficient temperature in the cavity, is varied. Here this transition could be interpreted as follows. When the laser is in the CW regime, the power of the signal inside the cavity remains low and the polarization of the signal is affected only by linear birefringence. Consequently, after it passed through the polarizer, its polarization is transformed by the polarization controller and remains approximately in this state up to the output coupler. However, when the laser is in the ML regime, the signal is a pulse that shows a much higher peak power than the CW signal. This pulse undergoes an important nonlinear polarization rotation in the cavity. Its polarization state is thus altered compared to the CW case when it reaches the output coupler. The transition in  $\langle S_1 \rangle$  is thus associated with this nonlinear contribution occurring when ML is reached. The pulses obtained throughout each ML region are almost identical and no multiple-pulse regime was obtained because, as mentioned earlier, the pump power was adjusted to the minimum value sustaining a single pulse when  $\theta = 0.8$  rad. In the region around  $\theta = 0.5$  rad, the curves show some oscillations. In fact, in these cases the laser is unstable and the value of  $\langle S_1 \rangle$  oscillates slightly in time also. In the ML region, the value of  $\langle S_1 \rangle$  is completely stable. Finally, the other Stokes parameters  $\langle S_2 \rangle$  and  $\langle S_3 \rangle$  (not shown here) behave similarly.

#### 4.3 The behavior of the output polarization: experimental analysis

A similar analysis was performed experimentally with the cavity represented in Fig. 1. ML was found a priori by properly adjusting the motorized polarization controller angle and its

retardation. The pump power was then adjusted to the threshold to obtain a single pulse in the cavity. We then get 0.64-nJ pulses with a FWHM spectral width of 45 nm and a repetition rate of 81 MHz. We note that, because the cavity is relatively short, ML is easily obtained and is robust to environmental perturbations. The angle of the polarization controller was then varied over its whole tuning range which corresponds to approximately 4.3 rad. In the first case, the cavity was left in the optimal conditions. Then, another manual polarization controller was inserted in the cavity to represent an adjustable birefringence in the cavity. When the birefringence of the second controller was too large, it was impossible to get ML just by varying the angle of the motorized controller. For small birefringence, it was possible to find ML. The behavior of  $S_I$ , averaged over 1s and noted  $\langle S_I \rangle$ , as a function of the angle of the motorized controller is shown in Fig. 4 for different situations.

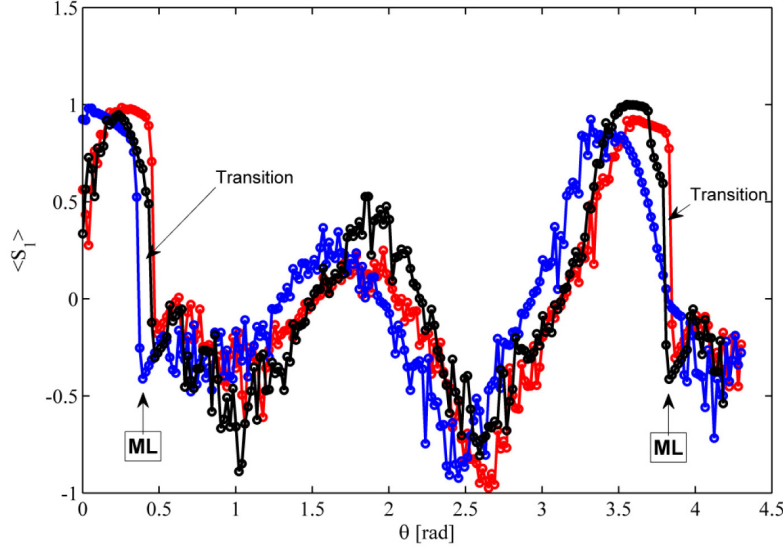


Fig. 4. Experimental results for the averaged first Stokes parameter obtained once steady state is reached (red: unperturbed case, blue: perturbation before EDF, black: perturbation after EDF). Stable mode locking is achieved in the “ML” regions except for the blue curve near  $\theta = 3.8$  rad.

In all three cases, it was possible to get ML. Each time ML was found, the value of  $\langle S_I \rangle$  changed abruptly from one angular position of the controller to the next one. The  $\langle S_I \rangle$  variation was larger than 0.5 in each case. These results are qualitatively in agreement with the behavior obtained in the simulations presented in the previous section. A major difference to note is that the value of  $\langle S_I \rangle$  does not change abruptly on both sides of the ML regions as was seen in the simulations. This is due to the fact that experimentally the angle was swept continuously from 0 (where we made sure the laser was not ML) toward larger values. However, the laser was not restarted each time the angle was changed as was done in the simulations. Hence, after the first abrupt transition, the laser was ML. As the angle was increased, it remained ML over a certain range. Eventually, ML was lost as the laser entered in a transition regime where the value of  $\langle S_I \rangle$  was not completely stable and the behavior of the laser showed chaotic oscillations. In this region, the laser would not ML from noise. The fact that a pulse already existed in the cavity explains this chaotic behavior. Further increase of the angle would then bring the laser back to CW emission. By sweeping from large toward small angles, the abrupt transition would be seen from the right. Note that when the ML regime was reached, the value of  $\langle S_I \rangle$  was fixed, its variation was almost unnoticeable on the polarimeter. At the angle where the transition occurs, the pulses obtained were always identical to the reference pulse discussed at the beginning of this section. Note that they kept

approximately the same characteristics over the whole ML range. The same global behavior was observed for the other Stokes parameters  $\langle S_2 \rangle$  and  $\langle S_3 \rangle$ .

#### 4.4 Automation

These results suggest a really simple method to automate the alignment of passively ML fiber lasers based on NPR. The angle of the polarization controller has to be varied while a measurement of  $\langle S_I \rangle$  at the output of the laser is done. Making sure the initial angular position of the controller does not lead to ML, an abrupt variation in  $\langle S_I \rangle$  is eventually found during the sweeping process (a variation larger than some predetermined threshold value). At this angle, we know that the laser is ML. The angle of the controller must then be kept fixed and the alignment is achieved. To make sure that ML is reached, a monitoring of  $\langle S_I \rangle$  could be done continuously. In the ML regime, the variance of  $\langle S_I \rangle$  over time should be really small. A noticeable variation indicates that the laser was perturbed and realignment might be needed. We tested this automated alignment procedure. The output value of  $\langle S_I \rangle$  at the 1% tap was measured with the polarimeter and sent to a Labview routine that controlled the polarization controller as shown in Fig. 1. The threshold value was fixed at 0.5. For reasonable perturbations, such as moving one of the cavity fibers laterally by a few centimeters which is enough to lose ML if the laser is in that state, the routine reached ML from an arbitrary initial angular position within a few minutes. We note that the method would be relatively straightforward to implement without a commercial polarimeter. One could replace it by a fiber polarization beamsplitter combined with two photodiodes to measure the powers in the x and y polarization states. This setup could be done at relatively low cost, would be pretty robust and would not need any readjustment once implemented. The value of  $\langle S_I \rangle$  can then be computed easily as described in section 4.2. The procedure could certainly be adapted to be used with other polarization controllers adjustable by any type of electronic or mechanized technique such as motorized waveplates, piezoelectric squeezers [9, 11], liquid crystals [10] or magneto-optic crystals [16]. It could also be implemented for fiber lasers emitting in different spectral regions.

#### 4. Conclusion

A simple and robust strategy to automatically align passively ML fiber lasers based on NPR was presented. The technique is based on the fact that the polarization state at the output of the laser changes abruptly when the angle of the polarization controller reaches an angular position that leads to stable ML. Consequently, the alignment procedure is performed by sweeping the value of the angular position of the polarization controller from a position where the laser is not ML until a sudden variation in one of the Stokes parameter,  $\langle S_I \rangle$  for instance, is detected. This ensures that the laser has reached the ML state. This technique was implemented in a fiber laser with a single polarization controller and it worked well. It provides an alternative to others types of automatic feedback loops based, for instance, on complete polarization characterization, two-photon absorption, RF spectrum or pulse counting measurements.

#### Acknowledgments

The authors thank Éric Girard at GiGa Concept Inc. for his technical support, Jean Filion and Simon Duval for their collaboration and Pr. Réal Vallée for the loan of the polarimeter. Financial support was provided by the Fonds de recherche du Québec - Nature et technologies (FRQNT), the Natural Sciences and Engineering Research Council of Canada (NSERC) and Canada Summer Jobs.