Video Article

Automation of Mode Locking in a Nonlinear Polarization Rotation Fiber Laser through Output Polarization Measurements

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Abstract

When a laser is mode-locked, it emits a train of ultra-short pulses at a repetition rate determined by the laser cavity length. This article outlines a new and inexpensive procedure to force mode locking in a pre-adjusted nonlinear polarization rotation fiber laser. This procedure is based on the detection of a sudden change in the output polarization state when mode locking occurs. This change is used to command the alignment of the intra-cavity polarization controller in order to find mode-locking conditions. More specifically, the value of the first Stokes parameter varies when the angle of the polarization controller is swept and, moreover, it undergoes an abrupt variation when the laser enters the mode-locked state. Monitoring this abrupt variation provides a practical easy-to-detect signal that can be used to command the alignment of the polarization controller and drive the laser towards mode locking. This monitoring is achieved by feeding a small portion of the signal to a polarization analyzer measuring the first Stokes parameter. A sudden change in the read out of this parameter from the analyzer will occur when the laser enters the mode-locked state. At this moment, the required angle of the polarization controller is kept fixed. The alignment is completed. This procedure provides an alternate way to existing automating procedures that use equipment such as an optical spectrum analyzer, an RF spectrum analyzer, a photodiode connected to an electronic pulse-counter or a nonlinear detecting scheme based on two-photon absorption or second harmonic generation. It is suitable for lasers mode locked by nonlinear polarization rotation. It is relatively easy to implement, it requires inexpensive means, especially at a wavelength of 1550 nm, and it lowers the production and operation costs incurred in comparison to the above-mentioned techniques.

Video Link

The video component of this article can be found at https://www.jove.com/video/53679/

Introduction

The purpose of this article is to present an automation alignment procedure to get mode locking (ML) in nonlinear polarization rotation fiber lasers. This procedure is based on two essential steps: detecting the ML regime by measuring the polarization of the output signal of the laser and then setting-up a self-start control system to get to ML.

Fiber lasers have become an important tool in optics nowadays. They are an efficient source of coherent near-infrared light and they are now extending into the mid-infrared portion of the electromagnetic spectrum. Their low cost and ease of use have made them an attractive alternative to other sources of coherent light such as solid-state lasers. Fiber lasers can also provide ultrashort pulses (100 fsec or less) when a ML mechanism is inserted in the fiber cavity. There are many ways to design this ML mechanism such as nonlinear loop mirrors and saturable absorbers. One of these, widely used for its simplicity, is based on nonlinear polarization rotation (NPR) of the signal[1,2]. It uses the fact that the polarization ellipse of the signal undergoes a rotation proportional to its intensity as it propagates in the fibers of the laser cavity. By inserting a polarizer in the cavity, this NPR leads to intensity-dependent losses during a roundtrip of the signal.

The laser can then be forced to ML by controlling the polarization state. Effectively, the high-power portions of the signal will be subjected to lower losses (**Figure 1**) and this will eventually lead to the formation of ultrashort pulses of light when the laser is turned on and starts from a low-power noisy signal. However, the drawback of this method is that the polarization state controller (PSC) must be properly aligned to get ML. Usually, an operator finds the ML manually by varying the position of the PSC and analyzing the output signal of the laser with a fast photodiode, an optical spectrum analyzer or a nonlinear optical auto-correlator. As soon as the emission of pulses is detected, the operator stops varying the position of the PSC since the laser is ML. Obviously getting the laser to self-start automatically leads to an important gain in efficiency. This is especially true when the laser is subject to perturbations changing the alignment or the cavity configuration since the operator has to go through the alignment procedure again and again. In the last decade, different methods have been proposed to achieve this automation. Hellwig *et al.*[3] used piezo-electric squeezers to control polarization in combination with a full analysis of the polarization state of the signal with an all-fiber division-of-amplitude polarimeter to detect ML. Radnarotov *et al.*[4] used liquid-crystal plate PSCs with an analysis based on the RF spectrum to detect ML. Shen *et al.*[5] used piezo-electric squeezers to control polarization and a photodiode/high-speed counter system to detect ML.

More recently, a strategy based on an evolutionary algorithm was presented in which the detection is provided by a high-bandwidth photodiode in combination with an intensimetric second-order autocorrelator and an optical spectrum analyzer. The control is then performed with two electronically driven PSCs inside the cavity[6].

This article describes an innovative way of detecting ML and its application to an automation technique forcing the fiber laser to ML. The detection of ML of the laser is achieved by analyzing how the output polarization state of the signal varies as the angle of the PSC is swept. As will be shown, the transition to ML is associated with a sudden change in the polarization state detectable by measuring one of the Stokes parameters of the output signal. The fact that a pulse is more intense than a CW signal and will undergo a more important NPR explains this change. Since the output of the laser is immediately located before the polarizer in the cavity, the polarization state of a pulse at this location is different from the polarization state of a CW signal (**Figure 2**) and will be used to discriminate the ML state. Theoretical aspects of this procedure and its first experimental implementation were presented in Olivier *et al.*[7]. In this article, the emphasis will be on the technical aspects of the procedure, its limitations and its advantages.

This technique is relatively simple to implement and does not require sophisticated measuring instruments to detect the ML state and automate the alignment of the laser to get ML. A PSC adjustable externally through a programmable interface is required. Different PSCs could be used in principle: piezo-electric squeezers, liquid crystal, wave-plates rotated by a motor, magneto-optic crystals or a motorized all-fiber PSC based on squeezing and twisting the fiber[8]. In this article, the latter is used, an all-fiber motorized Yao-type PSC. To detect the polarization state an expensive commercial polarimeter can be used. However, since only the value of the first Stokes parameter is required, a polarizing beam splitter in combination with two photodiodes will be sufficient as shown in this article.

All these components are inexpensive for the widely used erbium-doped fiber lasers. A feedback loop based on this procedure can find ML in a few minutes. This response time is suitable for most applications of fiber lasers and is comparable to the other existing techniques. In fact, the response time is limited by the electronics used to analyze the polarization of the signal. Finally, although the procedure is applied here to a similariton[9] erbium-doped fiber laser, it could be used for any NPR based fiber laser as soon as the above mentioned equipment or its equivalent becomes available at the wavelength of interest.

Protocol

1. Setting Up a Fiber ML Fiber Laser Including a Motorized PSC

1. Gather the following components: a single-mode erbium-doped fiber, a 980/1,550 nm wavelength division multiplexer (WDM), a 980/1,550 nm WDM-1,550 nm isolator hybrid component, a 50/50 fiber coupler, a fiber polarizer, a motorized PSC, two 980 nm laser pump diodes, a 99/1 fiber coupler and a manual inline PSC.
2. Cut the erbium-doped fiber and all the other fiber-pigtailed components to fit with the desired cavity design.
NOTE: The presented automation procedure is suitable for fiber lasers based on nonlinear polarization rotation. It should work for different operating regimes such as the soliton laser, the stretched-pulse laser, the dissipative soliton laser and the similariton laser. The latter regime is used in this experiment.
3. To build the laser cavity, use a fiber fusion splicer to join the cavity components in the order shown in the diagram (**Figure 3**). Before performing each fusion splice, clean the fibers ends with isopropyl alcohol and cleave them with a fiber cleaver.
NOTE: The internal components of the laser are, in clockwise order in the ring cavity, a motorized PSC, a 980/1,550 nm WDM, an erbium-doped fiber, a 980/1,550 nm WDM isolator hybrid component, a 50/50 output coupler and a fiber polarizer. The external components are a 99/1 fiber coupler and a manual inline PSC (as discussed in steps 1.7 and 1.8).
NOTE: A fiber segment of approximately 30 cm must be inserted in the motorized PSC before the splices are performed with the other components of the cavity. Although a standard single-mode fiber will work, the use of polyimide-coated fiber is recommended for this segment because it is more resistant to the pressure exerted by the screws of the controller and will thus last longer.
4. Join the pump laser diodes to the WDMs using the fusion splicer. Again, clean the fibers ends with isopropyl alcohol and cleave them with a fiber cleaver before performing each fusion splice.
5. Connect the laser diodes to their respective temperature controllers and current drivers.
6. Connect the intra-cavity motorized Yao-type fiber-squeezer PSC (**Figure 4**) to its driving module and then connect the driving module to the USB port of a computer.
NOTE: This port is identified by number "COM4" as shown in the "Device Manager" of the computer.
7. At the output of the laser, *i.e.* the 50/50 coupler's port not spliced yet, splice a 99/1 coupler.
NOTE: The 99% port is the usable output. The 1% port is used to monitor the polarization state in the automation procedure.
8. Insert a manual PSC along the fiber of the 1% port. To do so, remove the screws and open the PSC. Insert the fiber in the appropriate slot and then put the screws back into their holes and screw them in.
9. Splice an angle-polished fiber connector (APC) at the end of the 1% port fiber (after the manual PSC). Clean and cleave the fibers ends before performing the fusion splice.
10. Connect the 99% output to an optical spectrum analyzer (OSA) using a bare-fiber adaptor.
NOTE: As discussed later, the optical spectrum seen on the OSA will provide an alternate way of checking if the laser is ML.
11. Secure all the fibers and the components in the cavity properly with polyimide film tape.
NOTE: The fibers and components must be prevented from moving under any conditions such as when the table vibrates or fans blow air. The polyimide film tape is used in order to avoid damaging the fibers.
12. Tighten the pressure screws of the intra-cavity PSC until the fiber begins to be slightly squeezed.
13. Turn on the pump lasers diodes and adjust their currents to their maximum values as specified by the laser diode manufacturer.
14. Start the instrument communication interface. In the "Peripherals and Interface" column on the left, choose "COM4". Click on "Open VISA test panel". Click on "Input/Output". Then, in "Select or enter command" type "SM,500,3000\n" and click on the "Query" button. This commands the PSC to rotate by 3,000 steps of 0.1125° in the clockwise direction. While doing so, the PSC reaches a mechanical stop.
15. In the "Select or enter command" of the "COM4" test panel, type "SM,500,-10\n" and click on the "Query" button. The PSC then rotates approximately 1° counterclockwise. Check if ML is reached by looking at the optical spectrum on the OSA. ML is reached when the full-width

at half maximum of the optical spectrum is of the order of a few tens of nanometers (**Figure 5**). If ML is reached, keep the birefringence and the angle fixed and go to step 1.18.

16. If ML is not reached, repeat 1.15 until either ML or the maximum angle attainable with the PSC is reached.
17. If the maximum angle of the PSC is reached before ML occurs, increase the birefringence of the PSC by tightening the pressure screws slightly and repeat steps 1.14, 1.15 and 1.16 as many times as required to get ML.
18. Once ML is reached, decrease the pump powers to their minimum value allowing ML to self-start. To do so, reduce the pump powers until ML is lost. Then, bring them back slowly toward the smallest value that will make the ML reappear. Turn the pumps off and back on again and check if the laser mode locks by itself. Increase the pump powers slightly more to ensure the ML is stable and will self-start each time the laser is turned on.

2. Analyzing the Polarization of the Output Signal

1. Link the 1% tap to a commercial polarimeter.
2. Connect the polarimeter to the computer using a USB port.
3. In the "Select or enter command" of the "COM4" test panel, type "SM,500,3000\n" and click on the "Query" button.
4. Run the commercial polarimeter controlling software and start the polarization measurement by clicking on the "Start" button.
5. In the "Select or enter command" of the "COM4" test panel, type "SM,500,-10\n" and click on the "Query" button. Observe the polarization state on the polarimeter.
6. Repeat step 2.5 as many times as required to cover the whole range of angles allowed by the intra-cavity PSC. Observe that the polarization state varies very smoothly with the angle except at the specific angles where ML is reached as can be seen by watching simultaneously the width of the optical spectrum on the OSA.
7. Repeat steps 2.3 to 2.6 but this time, instead of just watching the polarization state, record the values of the Stokes parameters S_1, S_2 and S_3 as functions of the angle of the PSC (**Figure 6**). To see these values clearly, choose "Measurement-→Oscilloscope" in the menu of the software and look for the mean values of S_1, S_2 and S_3. Simultaneously watch the optical spectrum and record the angles for which the laser is ML.

3. Setting Up a Feedback Loop to Automate the Alignment of the PSC Using the Commercial Polarimeter Measurements

1. Turn off the computer.
2. Connect the serial port of the commercial polarimeter to the serial port "COM1" of the computer. Restart the computer and the polarimeter.
3. Start the graphical programming language interface (GPLI) that will allow the reading of the polarimeter via "COM1" and the control of the motorized PSC via "COM4".
4. In the GPLI, click on "Blank VI". Then, select "Window→Tile Left and Right".
   NOTE: The screen will then be divided in two parts. The block diagram is displayed on the right. It is used to create the script using different functions associated with different icons. The front panel is displayed on the left. It is used to display the commands and the measurements when the script is running.
5. In the block diagram window of the GPLI, develop a ML automation script to be used with the commercial polarimeter (see **Figure 7**).
   NOTE: This script reads S_1 from the polarimeter and uses its value to provide feedback and reach the proper alignment of the PSC angle leading to ML. The detection of ML is achieved by searching for a discontinuity in the variation of S_1 as the angle is varied.
   NOTE: The commands used to control the PSC via "COM4" are the same as the ones presented in steps 2.3 and 2.5. The command to read S_1 on the commercial polarimeter via "COM1" is "*SOP?\n".
6. Save the script by clicking on "File→Save" and then run it by clicking on the "→" button. The PSC is brought back to its mechanical stop, then it rotates by steps of approximately 1° until ML is reached, showing the value of S_1 as it evolves.

4. Building a Rudimentary Homemade Polarization Analyzer

1. Connect an oscilloscope to the computer using the GPIB interface.
2. Put a polarizing beam splitter cube (PBS) on an optics bench.
3. Set up three FC/APC fiber optics port collimators with the PBS (**Figure 8**).
   NOTE: One of the ports is the input. The other two are the outputs for the x- and y- polarization components of the signal.
4. Connect a fiber-pigtailed InGaAS PIN photodiode to the first output.
5. Connect the photodiode to a trans-impedance circuit (**Figure 9**).
6. Connect the electrical output of the circuit to channel 1 of the oscilloscope.
7. Turn on the trans-impedance circuit.
8. In the GPLI, read the average value of the voltage on channel 1 of the oscilloscope via the GPIB connection by using the commands "MEASU:IMM:SOU ch1;" to select channel 1 of the oscilloscope, "MEASU:IMM:TYPE mean;" to define the measurement to be an average voltage, "MEASU:IMM:VAL?" to get the value and finally "MEASU:IMM:UNI?" to obtain the units of the measurement. Save the script by clicking on "File→Save" and then run it by clicking on the "→" button.
9. Connect the 1% output of the laser at the input port of the PBS and turn the laser on at an arbitrary pump power. This sends a 1,550 nm optical signal to the input.
10. Measure the average voltage at the first output. Then, disconnect the fiber-pigtailed photodiode and replace it by a commercial power-meter. Measure the optical power at this output.
11. Repeat step 4.10 while varying the power of the input optical signal. The voltage should vary linearly with the optical power. Find the coefficients of this linear relation.
    NOTE: This relation will be used in step 4.20 to obtain P_x from the measured voltage.
12. Connect a second fiber-pigtailed InGaAS PIN photodiode to the second output of the PBS.

13. Connect the photodiode to a second trans-impedance circuit.
14. Connect the electrical output of the circuit to channel 2 of the oscilloscope.
15. Turn on the trans-impedance circuit.
16. In the GPLI, read the average value of the voltage on channel 2 of the oscilloscope via the GPIB connection by using the commands "MEASU:IMM:SOU ch2;" to select channel 2 of the oscilloscope, "MEASU:IMM:TYPE mean;" to define the measurement to be an average voltage, "MEASU:IMM:VAL?" to get the value and finally "MEASU:IMM:UNI?" to obtain the units of the measurement. Save the script by clicking on "File→Save" and then run it by clicking on the "→" button.
17. Turn the laser on at an arbitrary pump power.
18. Measure the average voltage at the second output. Then, disconnect the fiber-pigtailed photodiode and replace it by a commercial power-meter. Measure the optical power at this output.
19. Repeat step 4.18 while varying the power of the input optical signal. Ensure that the voltage varies linearly with the optical power.
NOTE: Find the coefficients of this linear relation. This relation will be used in step 4.20 to obtain P_y from the measured voltage.
20. After setting up the second detector to measure P_y, use the GPLI to compute the first Stokes parameter S_1 defined as $S_1 = (P_x-P_y)/(P_x+P_y)$. The homemade rudimentary polarization analyzer is now ready to use.

5. Replacing the Commercial Polarimeter by the Homemade Polarization Analyzer in the Automation Process

1. Connect the 1% output of the laser to the homemade polarization analyzer input (as was done in step 4.9).
2. Measure the first Stokes parameter S_1 as a function of the angle of the PSC (**Figure 10**) by repeating step 2.7 using the homemade polarization analyzer (instead of the commercial polarimeter). Observe the S_1 graph automatically updating at each step. Observe a discontinuous jump in the value of S_1 when ML occurs (this is the case while using the commercial polarimeter).
NOTE: Use a GPLI script to perform this task automatically. This script is based on a loop that varies the angle of the PSC by steps of 1° (using the command "SM,500,-10\n" sent to "COM4") and reads out the value of S_1 from the homemade polarization analyzer at each step.
3. Modify the script developed in 3.5 so that, instead of using the value given by the commercial polarimeter, it gets P_x and P_y from the homemade polarization analyzer and then computes $S_1 = (P_x-P_y)/ (P_x+P_y)$.
4. Use the new script based on the homemade polarization analyzer to ML the laser automatically in a way similar to step 3.6.

Representative Results

NPR mode-locked fiber lasers are known to provide a large variety of pulsing regimes such as Q-switched pulses[10], coherent ML pulses, noise-like pulses, bound states of ML pulses, harmonic ML and complex structures of interacting ML pulses[11]. In the laser described here, after the birefringence of the PSC was fixed to be able to get ML, the pump power was adjusted to be relatively near the threshold of single-pulse ML. In doing so, the number of competing regimes was reduced to a minimum. At this pump power and depending on the angle of the PSC, the laser presented different regimes (**Figure 5**) but no multi-pulse regime. Noise-like pulses[12,13] were avoided due to the pre-adjustment of the cavity fibers that were kept fixed once a standard single ML pulse was found. In fact, the cavity design is probably important in that respect too but this aspect was not investigated thoroughly here. Consequently, the only remaining regimes were continuous-wave emission (CW), Q-switched emission and a stable ML with a single coherent pulse. In the continuous-wave (CW) and Q-switched regimes, narrow lines (1 nm or so, sometimes limited by the optical spectrum analyzer resolution) are seen. These spectra are to be compared with the wide spectrum of the ML regime with a full width at half maximum of the order of 30 nm or even more. On the fast photodiode, CW shows almost no variations, Q-switching shows a pulse train with a repetition rate of the order of a few microseconds (3.5 µsec here) and ML appears as a much faster pulse train with a repetition rate of a few tens of nanoseconds (12.2 nsec here) corresponding to the roundtrip time of the laser cavity. When an autocorrelation trace is used, only the ML regime shows the presence of pulses because the Q-switched regime generates pulses that have a much longer duration and a much lower peak power. The autocorrelation trace in the ML regime shows a single peak with a width of 156 fsec from which we deduced that only a single coherent ML pulse is present with a FWHM duration close to 100 fsec (110 fsec assuming a Gaussian pulse shape and 101 fsec assuming hyperbolic secant squared pulse shape).

The measurement of the Stokes parameters as a function of the angle of the intra-cavity PSC (**Figure 6**) yielded a typical result as expected in theory[7]. Notice that each Stokes parameter changes abruptly when ML is reached. Consequently, a measurement of only one of them, say S_1, is required to detect ML. Note that a discontinuity in the value of a given parameter that does not coincide with stable ML is sometimes observed. In fact, the laser could sometimes reach an unstable regime where it shifts really quickly between CW, Q-switched and ML regimes in a chaotic manner. In these situations, the values of the Stokes parameters might vary substantially in time. These variations appear as error bars on the graph. It can be seen that the variations are more important in some regions than others. However, in the stable ML regimes, the variations are really small. This suggests that the temporal variation of the Stokes parameters could be used as a complementary criterion to verify if ML is really reached or not after a discontinuous jump has been detected.

The previous analysis leads to the conclusion that the automation of the laser can be based on the search for a discontinuity of a given Stokes parameter. S_1 was chosen here. The variation of S_1 that is defined as a "discontinuity" is *a priori* arbitrary. Based on the measurements (**Figure 6**), it is found that S_1 usually varies by steps smaller than 0.1 as the angle is varied by 1°. The only exception is when ML is reached where it varies by 0.6. It was thus decided to fix the threshold of discontinuity to 0.3. The automation procedure presented here (**Figure 7**) is based on that condition. The laser must not be in a ML condition when the routine starts otherwise the routine will stop when the discontinuity leading from ML to CW will be found and the laser will end up emitting CW. This constraint is not problematic because the range of angles giving ML is small compared to the full range of the PSC. It is thus easy to position the PSC at an angle really far from ML when the routine is engaged. Here, the PSC was brought to its minimum angle where a mechanical stop prevents it from moving further. At this position, the laser was not ML. Under these conditions, the routine works really well. It finds ML within a few minutes. In this case, speed is mostly limited by the communication time required between the commercial polarimeter and the computer as the angle is swept.

When measured with the homemade polarization analyzer (**Figure 10**), the curve of S_1 as a function of the angle of the PSC is different from the curve measured with the commercial polarimeter (**Figure 6**). This is due to the fact that the x- and y- axes of both instruments do not necessarily coincide. However, the abrupt transition in S_1 when ML is reached is clearly seen in both cases. In fact, the behavior of S_1, S_2 and S_3 measured with the commercial polarimeter showed that the three parameters did not undergo the same discontinuity when ML was reached. It suggests that a change in the orientation of the polarizing beam splitter or, equivalently, the insertion of a manual PSC just before the polarization analyzer could help in making the transition more abrupt and easier to detect. In fact, this is exactly what happened here, the transition to ML is easier to see with the homemade polarization analyzer because the manual PSC was adjusted to make the transition appear more clearly. The automation procedure is then easier to achieve.

The automation with the homemade polarization analyzer works really well. ML is found within a few minutes. In fact, because the readings of the photodiode voltages are faster than the readings of the commercial polarimeter, the homemade polarization analyzer performs better.

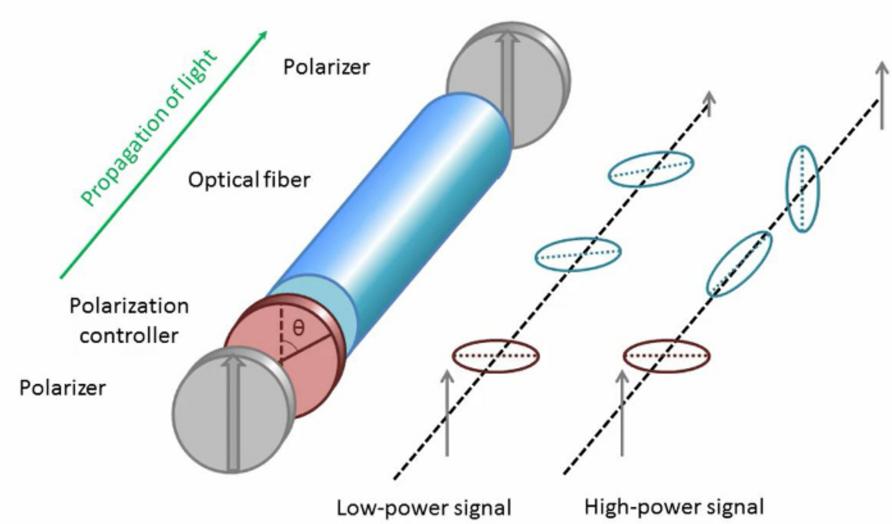

Figure 1: ML based on nonlinear polarization rotation. The signal is first linearly polarized by the polarizer and then transformed into an elliptic polarization state by the PSC. Due to the Kerr nonlinearity of the fiber in the laser cavity, the polarization ellipse undergoes a rotation of its main axis proportional to the signal's power. Since the polarizer at the end transmits only the vertical component of the polarization, the transmission will depend on the power of the signal and could favor the formation of a pulse from noise if the PSC angle is adjusted correctly. Please click here to view a larger version of this figure.

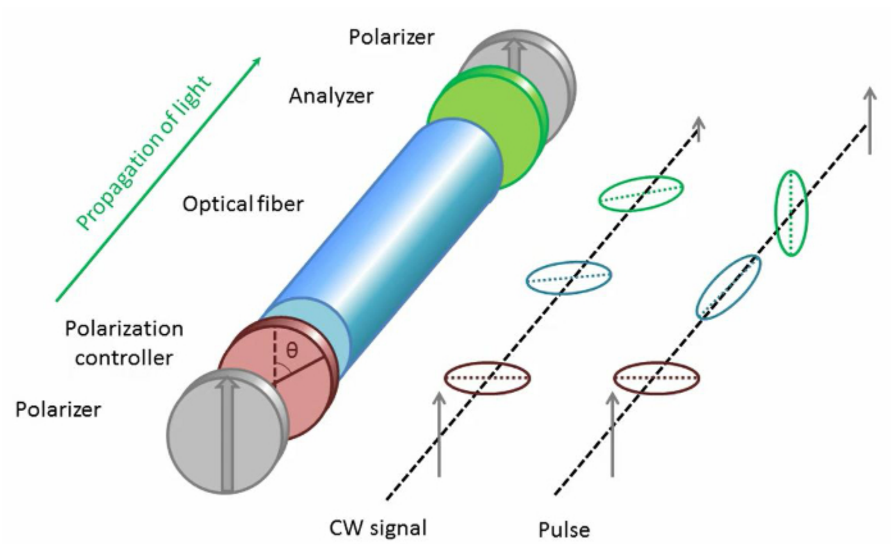

Figure 2: Position of the polarization analyzer. For a given average power, a pulse will have a peak power larger than a continuous wave (CW) signal and will undergo a larger nonlinear polarization rotation. By positioning the analyzer just before the polarizer, discrimination between the polarization states will allow detection of the presence of a pulse in the cavity. Please click here to view a larger version of this figure.

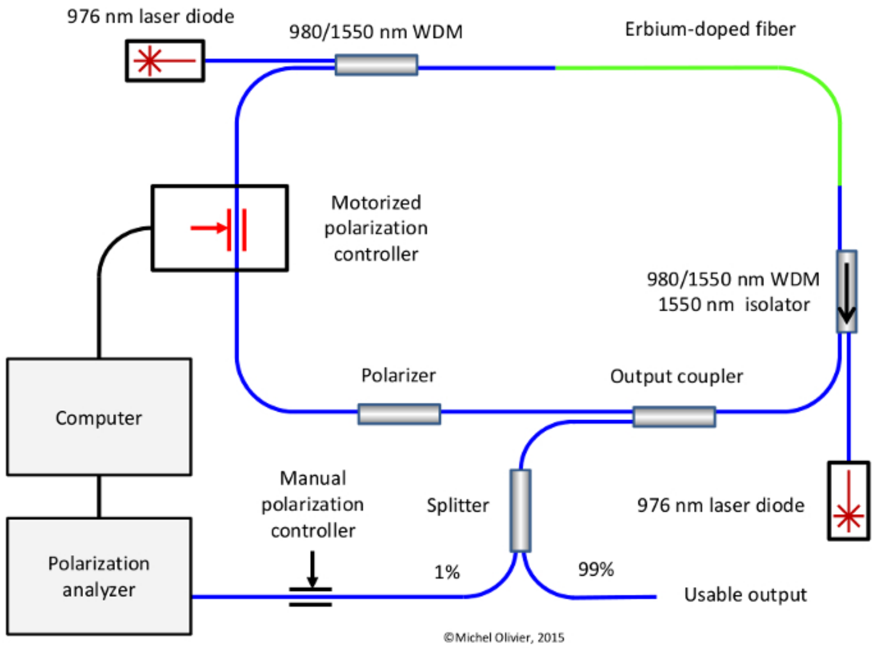

Figure 3: The fiber laser ring cavity. The laser must be a ring cavity including single-mode optical fibers (blue), a gain fiber (green), an isolator, a polarizer, a PSC adjustable through a computer interface. The output coupler must be located just before the polarizer. Finally, 1% of the output signal is tapped in order to monitor the state of polarization of the signal and 99% of the output signal remains available. The polarization analyzer provides feedback to a control loop programmed in a computer that adjusts the angle of the motorized PSC (light red) via an electric cable (black). Please click here to view a larger version of this figure.

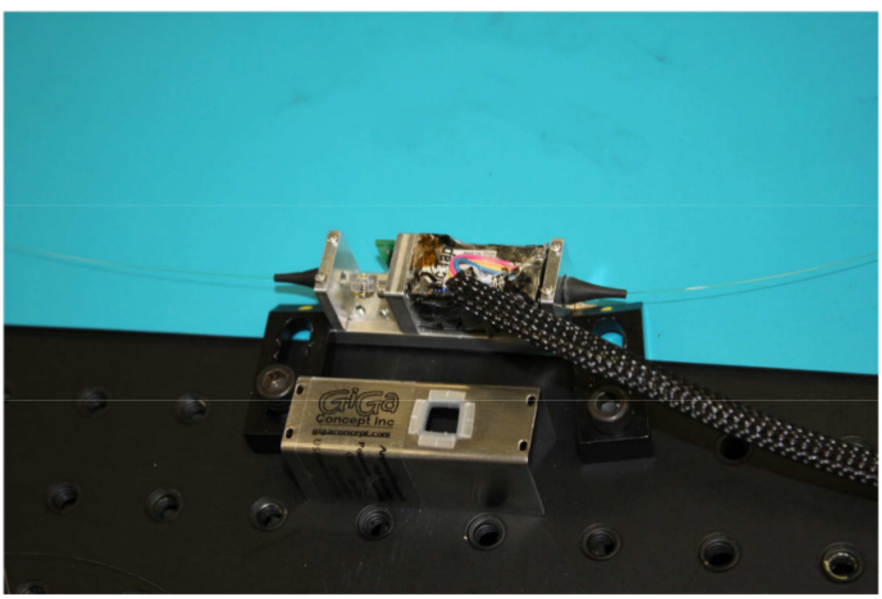

Figure 4: A motorized fiber-squeezer PSC. The birefringence of the PSC is fixed by the pressure of the screws on the left. The angle of the PSC is adjusted with the electronically controlled motor which is on the right. The electric cable connects the system to a computer interface. Please click here to view a larger version of this figure.

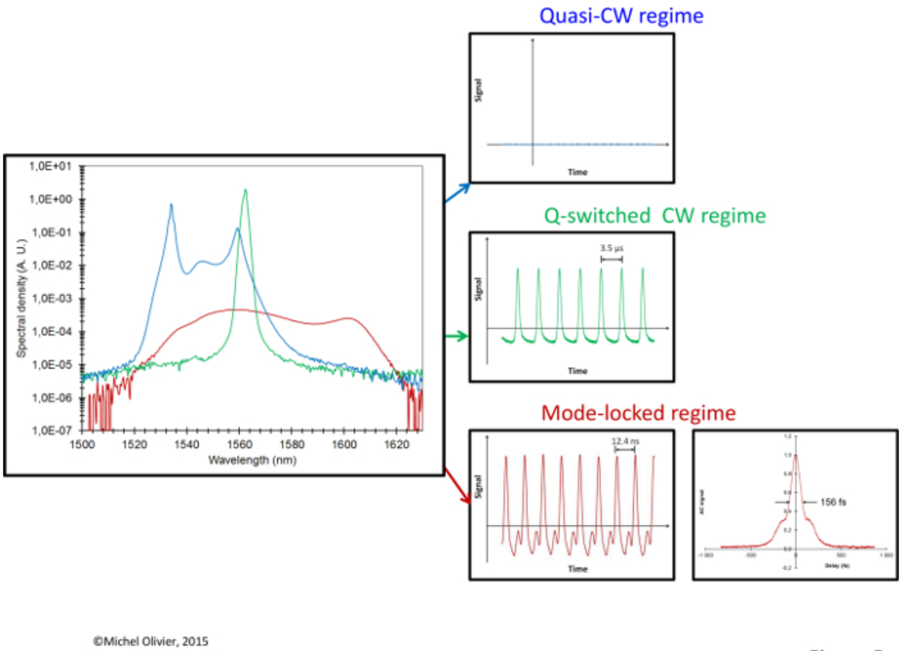

Figure 5: Detecting ML with an optical spectrum analyzer. Different regimes of the laser observed on the optical spectrum analyzer on the left, on a fast photodiode in the middle and on an autocorrelator on the right (when applicable): quasi-CW with multiple wavelengths (blue), Q-switched CW (green) and ML (red). The spectrum in the ML regime is much wider than the others and its dechirped autocorrelation trace shows a single peak with FWHM of 156 fsec and a relatively narrow pedestal. Please click here to view a larger version of this figure.

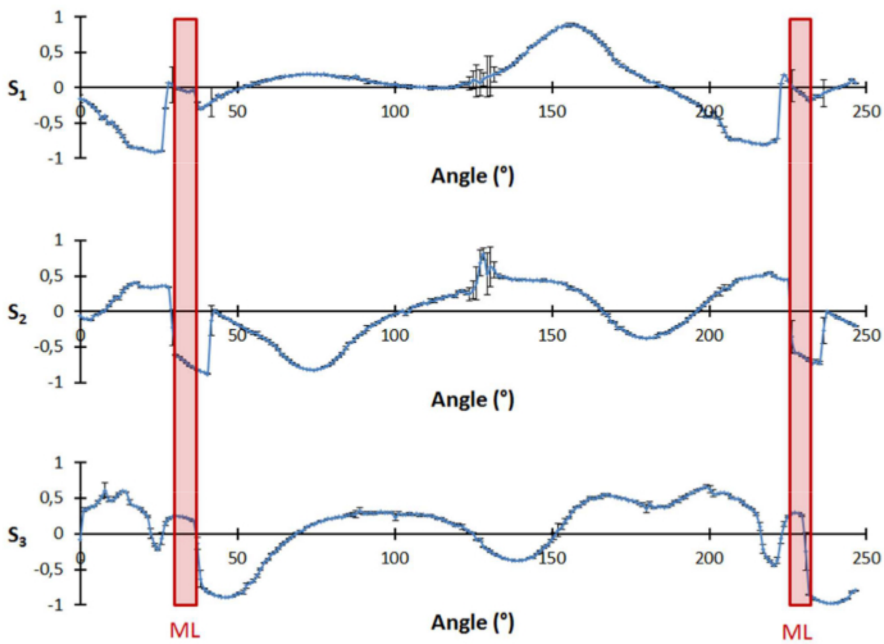

Figure 6: The value of the Stokes parameters as functions of the PSC angle and ML regions. The blue curves are the average value of each Stokes parameter over 5 measurements taken at intervals of 0.2 sec for a typical case. The error bars represent the standard deviation of the measurements and demonstrate the stability of the laser for a given PSC angle. As the angle of the PSC is varied, the values of the Stokes parameters change in a continuous fashion except when ML is reached (red areas on the figure). In this situation, their values undergo an abrupt variation that can be used to detect the ML. Please click here to view a larger version of this figure.

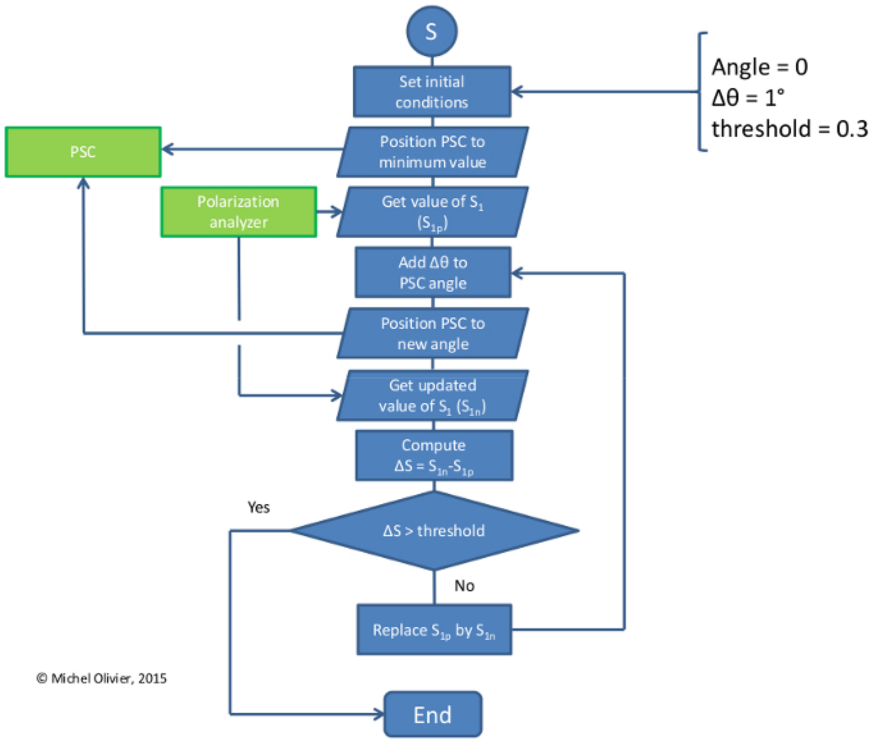

Figure 7: A routine to automatically align the PSC to get ML. This flowchart shows the simple routine used to automate the alignment of the polarization state controller (PSC) to get ML. Please click here to view a larger version of this figure.

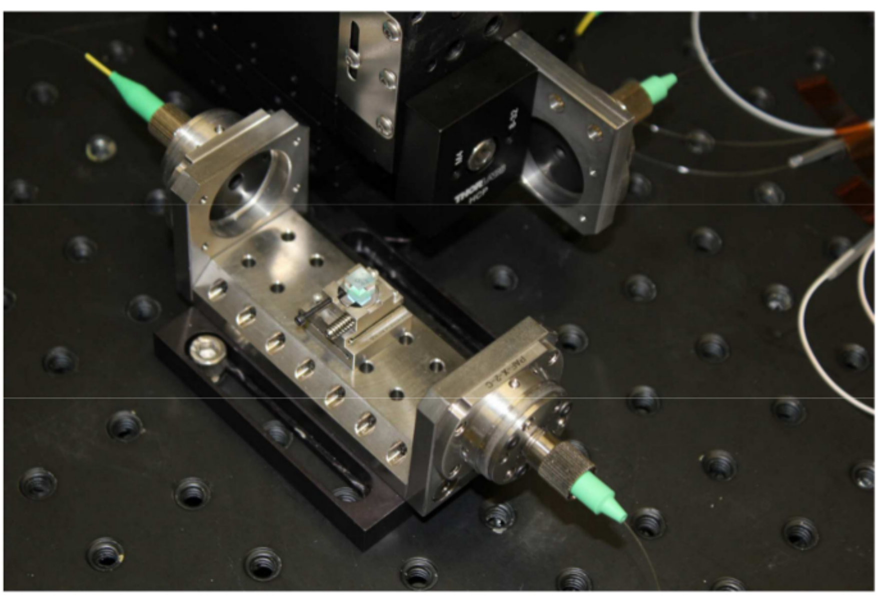

Figure 8: Homemade polarization analyzer measuring *S_1*. A free-space polarizing beam splitter splits the x- and y-polarization components of the signal. These components are sent separately to two photodiodes thus measuring the powers P_x and P_y in each polarization, allowing to compute the first Stokes parameter $S_1 = (P_x-P_y)/(P_x+P_y)$. Please click here to view a larger version of this figure.

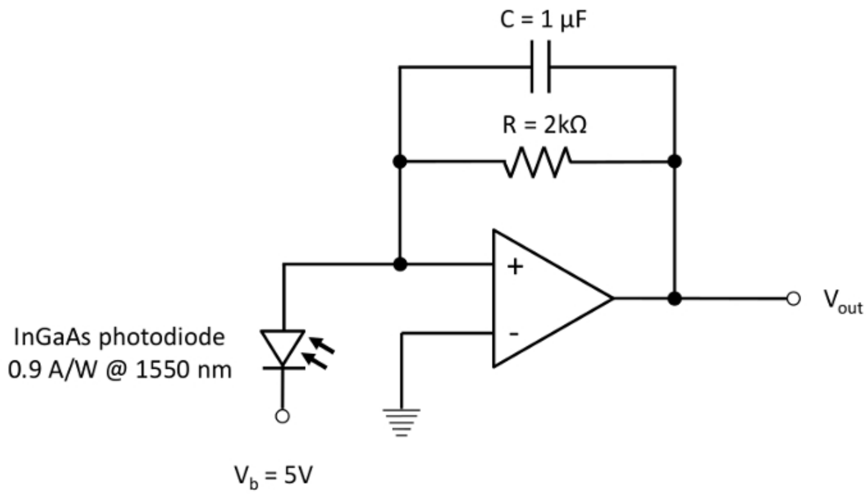

Figure 9: Trans-impedance amplifier circuit for each photodiode. The InGaAs photodiode detects the 1,550 nm signal. It is connected to an operational amplifier, a resistance and a capacitor. The role of the capacitor is to reduce the bandwidth of the circuit thus reducing the risk of getting an electrical oscillation from the circuit itself. The voltage value will be averaged out by the oscilloscope as the mean value will be read from it and transformed into an optical average power through calibration with a commercial optical power-meter. Please click here to view a larger version of this figure.

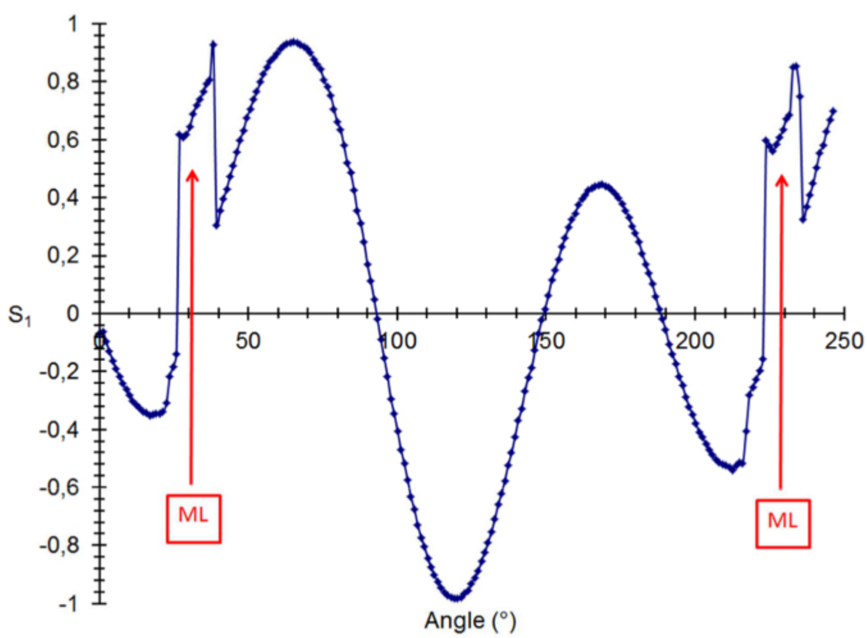

Figure 10: The value of the first Stokes parameter as a function of the PSC angle using the homemade polarization analyzer. The behavior of S_1 shows the typical abrupt transition at the angle where the laser reaches ML for a typical case. This was also seen with the commercial polarimeter. Please click here to view a larger version of this figure.

Discussion

It has been shown that it is possible to automate the ML of NPR fiber ring lasers by using a feedback loop based on output polarization measurements. To realize this task it is crucial to insert an adjustable PSC in the cavity. The output coupler of the cavity must be located just before the polarizer in order to see a difference between the polarization state of a CW signal and a pulse signal (**Figure 2**). The birefringence of the PSC must be pre-adjusted so that ML can be found and the pump power must be set near single pulse ML the threshold in order to get a single pulse in the cavity and minimize the number of competing regimes that can occur. This explains why the ML regime found automatically by sweeping the angle in a certain direction was always the same during the experiment. The parameter measured at the output to detect ML is S_1. This parameter changes continuously as the angle of the intra-cavity PSC is swept. The only exception to this is when ML is reached, the value of S_1 then undergoes a discontinuity. The possibility to make small angle increments is important here. If large increments are used it might become difficult to discriminate between a sudden jump and a "normal" variation. The small range of angles leading to ML might also be stepped over without noticing it. The small increment also ensures that the ML state is always the same because the system does not fall anywhere in the ML range but always detect the edge of this region where the pulses have always the same optical spectrum. This is the only obvious way of ensuring the repeatability of the procedure and the parameters of pulses generated.

Assuming the above critical points have been considered, it is possible to build a homemade polarization analyzer that provides a value of S_1 and allow the detection and automation of the ML. The setup proposed here was made up of a free-space polarizing beam splitter cube in combination with two photodiodes. An alternative would be to use a fiber-based polarization beam splitter. No alignment would be required and it would be an all-fiber setup. Note also that an oscilloscope was used to get the voltages of the photodiodes in order to communicate with it easily via a GPIB port. The use of an USB voltmeter or a homemade electronic circuit could reduce the cost of the apparatus.

The technique presented here is intended to work for NPR fiber mode-locked lasers. To apply it, one needs to work with a relatively stable cavity design that was pre-adjusted to be able to get ML. The fact that only a single parameter is varied to search for ML limits the generality of the technique. If the cavity is perturbed by, for instance, introducing a birefringence in the fibers, the system will be able to compensate and find ML when the perturbation is small. However, the PSC will not be able to compensate for a large modification of the birefringence of the cavity because its birefringence is fixed[7]. In that sense, this technique cannot be considered as general as the one presented in Hellwig *et al.*[3]. Also, the simple characterization of S_1 at the output used here in combination with the control of a unique PSC angle does not allow the exploration of all the possible regimes of emission of the laser as discussed by Andral *et al.*[6] for instance. Moreover, the ML detection technique presented here cannot discriminate between noise-like pulses[11], coherent ML pulses and multiple-pulses regimes. The pre-adjustment of the cavity fibers, the pump power and the PSC birefringence must thus be carefully done to ensure that single coherent ML pulses will form instead of noise-like pulses or multiple-pulses regimes.

As mentioned in the introduction, other ML mechanisms exist and some of them do not require alignment. They all have some pros and cons. ML based on nonlinear loop mirrors[14] requires an extra length of fiber inside the cavity and might not be suitable for high-repetition rate lasers[15]. ML based on saturable absorbers mirrors[16] requires the design of custom mirrors appropriate for the power and spectral characteristics of the laser under consideration. The NPR ML mechanism remains the most widely used because of its simplicity, its effectiveness and low-cost implementation.

The automation of its alignment makes NPR an even more interesting option because it can now be used in commercial systems without requiring the intervention of the user to ensure ML occurs. The technique to automate its alignment presented here is sufficient to get ML in normal conditions and is simple to implement. It requires a few low-cost components and no expensive instruments such as an optical spectrum analyzer or an RF-spectrum analyzer. The cavity design does not have to be modified since it relies on output polarization measurements. In fact, only a fraction of the output is tapped for monitoring and the remaining portion can be used for the ongoing application.

In other words, the laser does not need to be disconnected to proceed with the alignment procedure. Secondly, the required average power is so small that a 1% monitoring tap is sufficient. This is to be contrasted with ML detection techniques based on nonlinear processes such as second -harmonic generation or two-photon absorption that would require a significantly larger fraction for the monitoring to be efficient. Finally, since this technique requires only the first Stokes parameter S_1 to be measured, there is no need for a complete characterization of the polarization state and this renders the system much simpler and cheaper to design and build.

This technique is well-suited for commercial fiber lasers and, with that goal in mind, could be developed further to improve its performance. It will be interesting also to apply it to fiber lasers at different wavelengths. Here it was used in an erbium-doped fiber laser but it is easily transferable to ytterbium-doped fiber lasers since all the required equipment is readily available. It might become more challenging for lasers operating at non-conventional wavelengths but it is certainly feasible. More testing is required to verify its applicability to different dispersion regimes such as the soliton laser, the stretched-pulse laser, the similariton laser and the dissipative soliton laser.

Disclosures

The authors have nothing to disclose.

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