Characterization of mode-locking in an all-fiber, all normal dispersion ytterbium based fiber oscillator

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ABSTRACT

An ytterbium based all-fiber, all normal dispersion fiber oscillator with integrated SESAM can have several operation modes like mode-locked, Q-switched and noise-like. To know and to control the quality of the mode-locking is essential for the application of such laser oscillators, otherwise the whole laser setup can be damaged or the expected operation characteristics of the oscillator driven systems cannot be achieved. Usually the two-photon signal generated by the short pulses is used to indicate the mode-locked operation, however such detection can be misleading in certain cases and not always able to predict the forthcoming degradation or vanishing of mode-locking. The characterization method that we propose uses only the radio frequency spectrum of the oscillator output and can identify the different operation regimes of our laser setup. The optical spectra measured simultaneously with the RF signals proves the reliability of our method. With this kind of characterization stable mode-locking can be initiated and maintained during the laser operation. The method combined with the ability to align the polarization states automatically in the laser cavity leads to the possibility to record a polarization map where the stability domains can be identified and classified. With such map the region where the mode-locking is self starting and maintainable with minimal polarization alignment can be selected. The developed oscillator reported here with its compact setup and self alignment ability can be a reliable source with long term error free operation without the need of expensive monitoring tools.

Keywords: fiber laser, mode-locking, stabilization, ytterbium

1. INTRODUCTION

Passively mode-locked fiber oscillators are widely used sources where ultrashort pulses are required like in applications such as micromachining, supercontinuum generation, nonlinear microscopy, terahertz optics, etc. Although some setups are reported where the laser cavity contains only polarization maintaining (PM) components to improve environmental stability[1,2], non-PM setups are still popular as the required parts are less expensive and the achievable pulse duration can be shorter. For self starting and for stable operation all of the non-PM setups need to include polarization controllers otherwise the setups won't start, or can run in unwanted operation regimes such as continuous wave (CW), noise-like or Q-switched[3]. Although in-line polarization controllers are commercially available, not many setups are reported where these components are used for stabilization[4,5].

In this paper we report a method that can be reliably used to characterize the operation of our previously reported all-fiber, all normal dispersion ytterbium (Yb) based fiber oscillator[6]. As it turned out the measured radio- frequency spectrum of the laser output must be processed carefully to distinguish CW mode-locked operation from Q-switched mode-locking and to predict when the stable operation starts to degrade. By applying the method reported in this paper we are able to stabilize our setup with the help of the built in electronically tunable polarization controller. This characterization helps us to initiate and maintain mode-locking in our ring oscillator and might be used in similar setups as well. The remotely tunable polarization controller together with the mode-locking detection enable us to automatically record a polarization dependent operation map of the laser oscillator.

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2. EXPERIMENTAL SETUP

Our laser setup can be observed in Figure 1. The laser oscillator consists of the following fibers and fiber optic components. A highly doped ytterbium fiber (Yb) - used as the gain medium - is forward pumped by a 975 nm laser diode (LD) via a 980/1030 nm wavelength-division multiplexer (WDM). To realize the unidirectional cavity and to protect the doped fiber from unwanted reflections, a polarization independent isolator (ISO) is placed after the active media. The nonlinear properties of the optical fiber leads to spectral broadening that can be observed after a 10% output port (OUT 1) and to nonlinear polarization rotation that can be used for spectral filtering with the aid of an in-line polarization beam splitter (PBS). Before the filtering, the polarization of the center wavelength must be rotated with a polarization controller (PC 1) for the highest transmission. This polarization controller from General Photonics is electrically adjustable. The beam splitter is followed by a 10% output (OUT 3) where the pulse shape and optical spectrum is supposed to be the most appropriate for further processing. After the splitter a manual polarization controller is inserted. The last component in the ring is an optical circulator with one port spliced to a connectorized saturable absorber mirror (SAM) from Batop (absorptance 40%, relaxation time ~500 fs). This component is responsible for the initiation of the mode-locking.

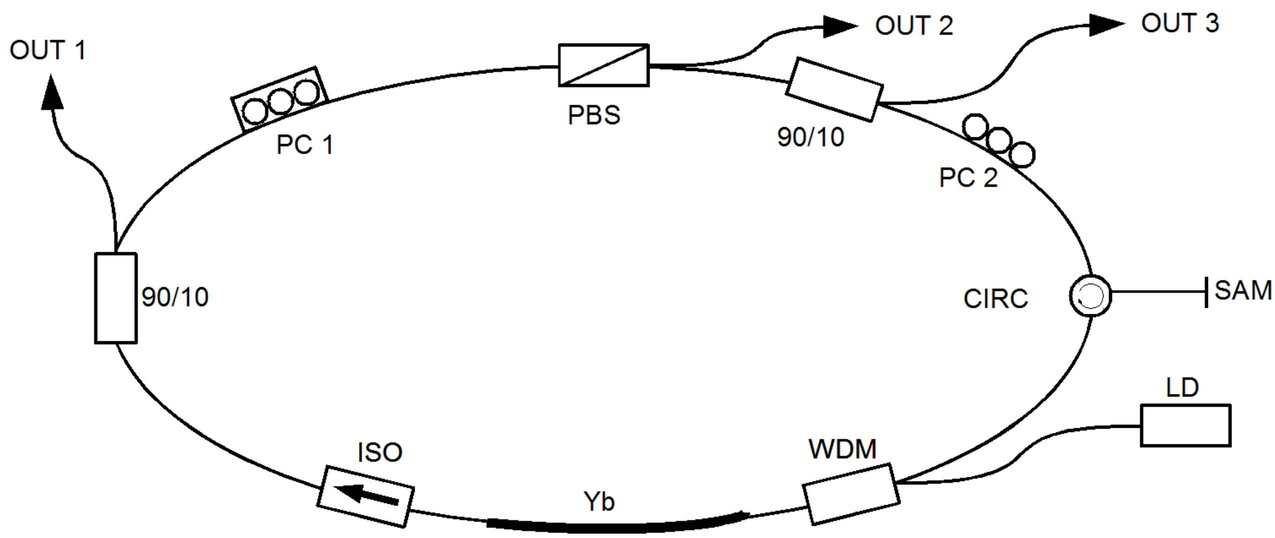

Figure 1. Experimental setup of the laser (LD: 975 nm laser diode; WDM: wavelength division multiplexer; Yb: Yb-doped fiber; ISO: isolator; 90/10: 90/10 splitter with 10% output coupling; PC1: General Photonics - PolaRITE III automatic polarization controller; PC2: manual polarization controller; PBS: polarization beam splitter; CIRC: circulator; SAM: saturable absorber mirror)

OUT 1 is monitored by an optical spectrometer (Spectral Products - SM540) and the output of the beam splitter (OUT 2) is directed to a fast photodiode (10 ns rise time). Over a certain pump power level stable mode-locking can be achieved with the alignment of the polarization controllers. The repetition rate of the system is around 15.47 MHz. Different polarization states result different operation modes like continuous wave operation, Q-switched mode-locking, noise-like pulses and CW mode-locking. The signal of the photodiode on OUT 1 is monitored by a digital oscilloscope with 50 MHz sampling frequency, 12 bit resolution and 65536 samples. The recorded samples were processed by a personal computer.

3. RESULTS

We implemented a characterization method based on the approach proposed by Csáti et al[5] and investigated the polarization dependent operation regimes of our oscillator. The recorded temporal signal of the photodiode was Fourier transformed to obtain the radiofrequency (RF) spectrum of the pulse train. The cumulated power, stored in a ±3 kHz band of the spectrum around the center frequency, was divided by the total spectral power of a broader ±250 kHz frequency range. This value we call quality factor (QF) indicates the stability of pulsing thus it is proportional to the quality of the mode-locking operation. The quality factor in function of the intracavity polarization state was recorded by adjusting the voltage of two of the three available polarization rotation channels of PC 1[7]. According to the manufacturer's datasheet, the π radian rotation voltage of the polarization controller was assumed to be 23.4 V at 1035 nm wavelength for each channel. A measured quality factor map in the approximated π/2 rotation range is presented in Figure 2 (left side). Operation regimes indicated by different quality levels can be visually classified, including two separate areas with QF values larger than 0.70 (dashed contour lines), where one can assume that the laser runs in mode-locked state.

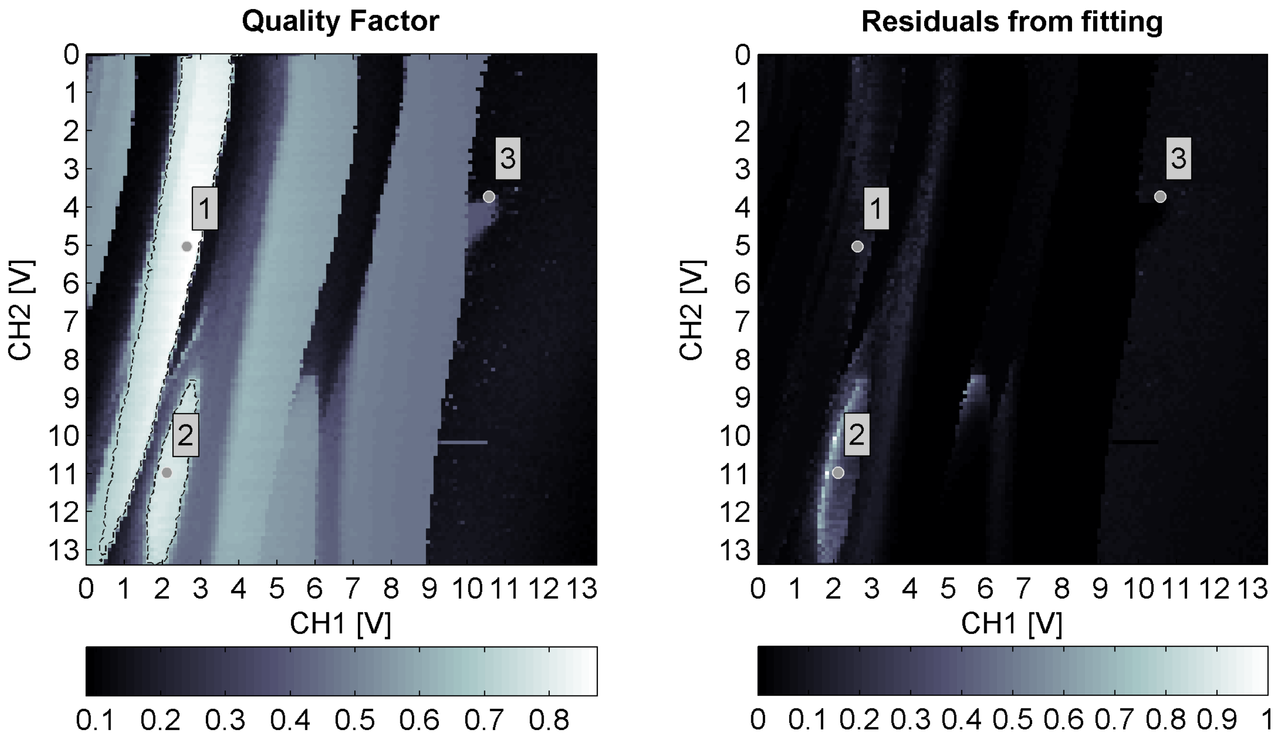

Figure 2. Recorded map of the quality factor (left) and the corresponding normalized residual values from the RF spectrum fitting (right).

In certain cases however, we found that the described approach is not accurate enough to distinguish noise-free mode-locked operation from mixed Q-switched and mode-locked pulses[8]. Since the optical spectrum of the generated beam gives valuable information about the operation mode of the oscillator, the optical spectrum at OUT 3 was measured for each polarization state and it was used as a reference. Three recorded RF and optical spectra belong to different polarization states on the QF map (indicated by numbered points) are depicted in Figure 3. Polarization state 1 enables CW mode-locked operation, while state 2 characterize a mixture of Q-switched and mode-locked pulse series. In case of state 3 only Q-switched pulses are propagating in the laser cavity. Although the operation modes of polarization state 1 and 2 can be distinguished from each other considering both the RF and optical spectra, the relative difference between the calculated QF values is less than 8%. Moreover, the two points were selected from the separated areas of the QF map that were classified as mode-locked regions by visual judgment.

Accuracy improvement of the characterization method is indispensable for constructing a reliable active control algorithm that guarantees a long-term operation stability. Therefore we fitted the recorded RF spectra with the following nonlinear probe function:

$$f(x) = \frac{1}{\frac{1}{P_1}\left|\sqrt{x - P_2}\right| + P_3} - \frac{1}{P_3}. \quad (1)$$

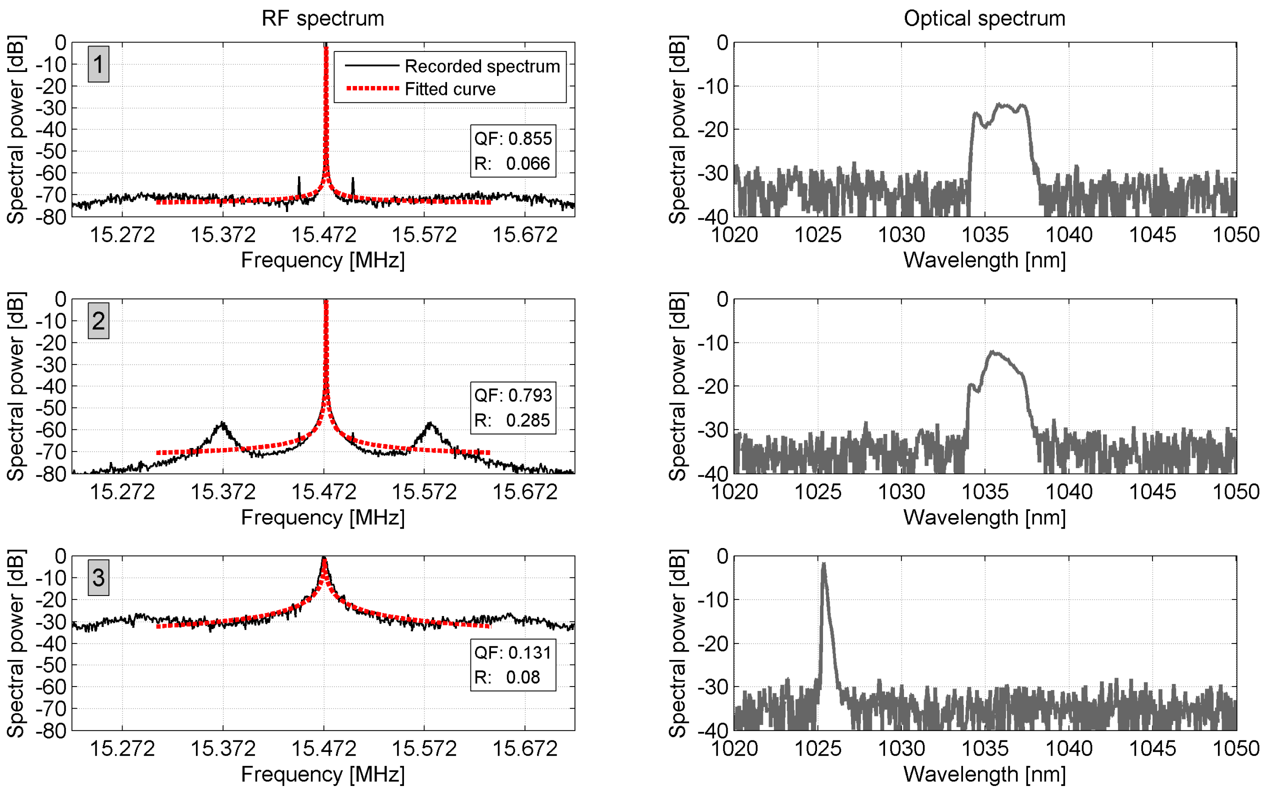

Figure 3. RF spectra and optical spectra measured at OUT 3 for different polarization states with the calculated quality factors (QF), the fitted characterization curves (dashed line) and the normalized residual values of curve fitting (R).

The fitted curves are plotted in Figure 3 by dashed lines. For each polarization state, the residual of the applied least square fitting method was determined to identify RF spectra that belong to the undesirable mixed Q-switched mode-locked pulses. These spectra typically have a narrow central peak, thus high quality factor but intense side lobes that significantly increase the residual value, like in case of polarization state 2. Normalized residual values (R) of the mapped polarization states are depicted in Figure 2 (right side). Comparing the QF and residual maps one can see that the area around polarization state 2 has significantly higher residual level that reveals the mixed Q-switched mode-locked or noiselike mode-locked operation regime. To accurately select a range of polarization states based only on the measured RF signal, where CW mode-locked operation is ensured, both the quality factor determination and the described fitting process are necessary. This method gives us the opportunity for an automated characterization of our setup and the prediction of the degradation of the mode-locking without the need of continuously monitoring the optical spectra.

Once an initial polarization state from the pre-measured operation map is selected, CW mode-locked operation can be maintained by continuously adjusting the voltage of the polarization controller's channels while keeping the initial QF value as high as possible. We developed a QF tracking algorithm to demonstrate the long-term operation stability of our setup. QF values were determined within a small range of the initial polarization state by scanning all the three channels of the polarization controller. The local maximum of these QF values was selected and the corresponding polarization state was set as the new initial state of the next iteration. A tracking step was performed approximately in every 10 seconds. The recorded QF local maximums and the applied voltages on the polarization rotation channels of a 17 hours long automatic operation control period can be seen in Figure 4.

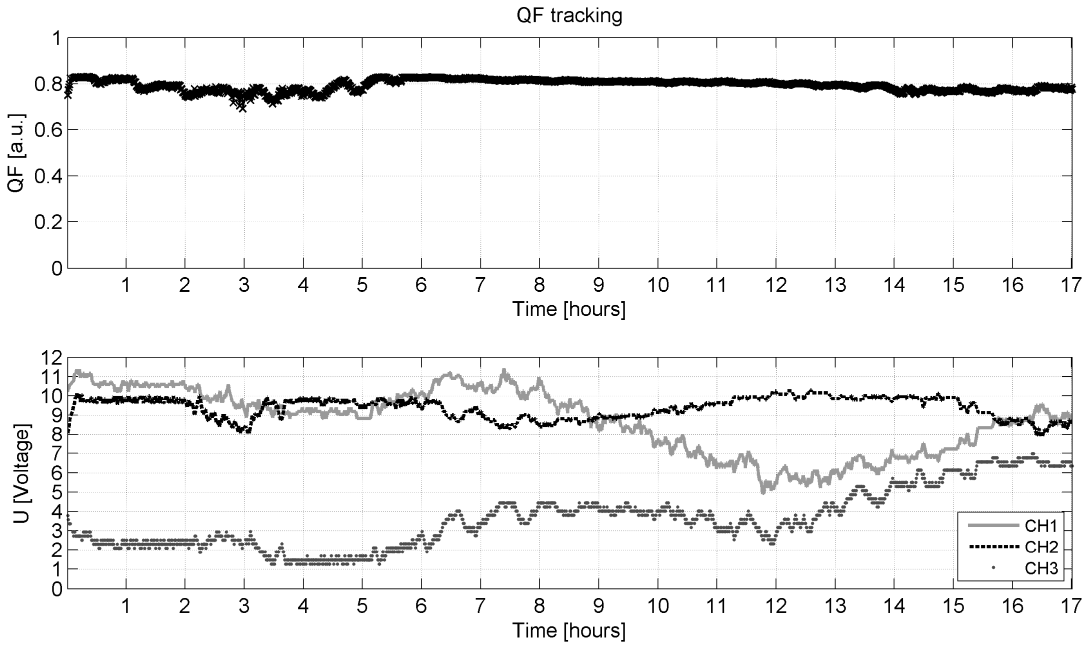

Figure 4. Recorded QF values and the corresponding polarization rotation voltages of a 17 hours long automatic operation control period.

As the plots show, the initial polarization rotation voltage had to be adjusted significantly during the whole tracking process to keep the QF value larger or equal to 0.7. Measured RF and optical spectra of the initial and final polarization states of the control period can be compared in Figure 5. The calculated quality factor is higher than 0.75 in both states due to the narrow central peak of the radio frequency spectrum. Sidelobes doesn't contain significant amount of spectral power thus the residual values of the curve fitting are negligible. The shape of the optical spectrum indicate CW mode-locked operation too. Since the traced QF value has not dropped below 0.7 during the control process, we can assume that the laser remained in the desired CW mode-locked operation area, though only the pump LD was temperature stabilized in the setup.

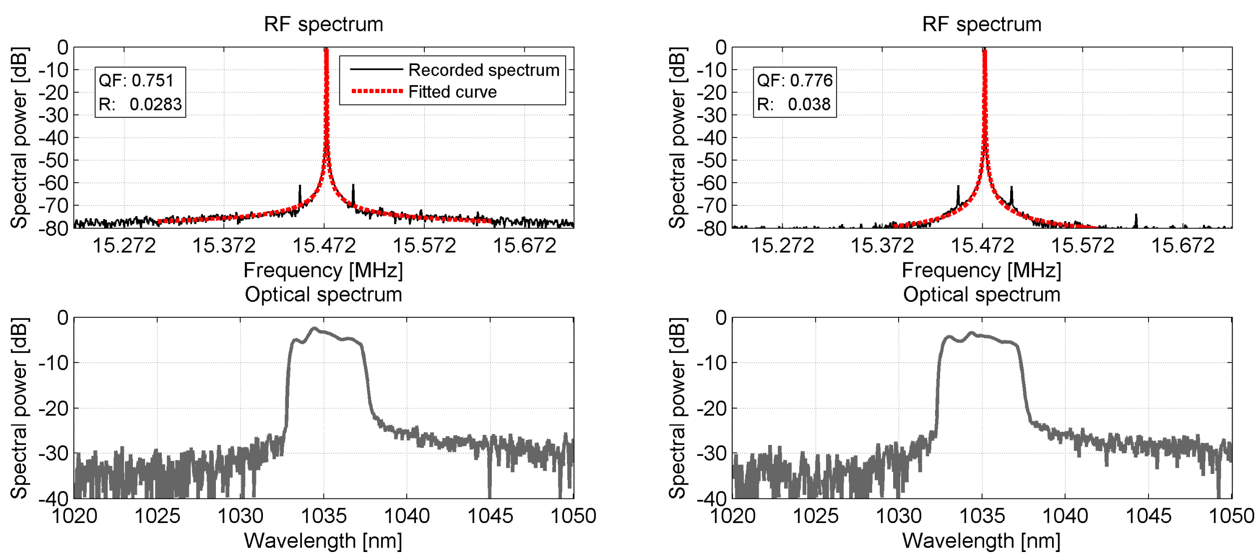

Figure 5. Measured RF and optical spectra of the initial (left) and final (right) polarization states of the control period.

4. CONCLUSIONS

We have demonstrated an operation mode characterization method based on the noise analysis of the power spectrum belongs to an all-fiber, all normal dispersion Yb based fiber oscillator. With this method one can investigate the polarization conditions of the mode-locking and predict the degradation of the stable operation. By scanning all the polarization states with the built in electronically tunable polarization controller, the regions where CW mode-locking can be initiated and maintained were located. Automatic control algorithm was developed and implemented to stabilize the long-term operation of our laser cavity.

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