Soliton mode locking fiber laser with an all-fiber polarization interference filter

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An erbium doped fiber ring laser achieving soliton mode locking by the use of an intra-cavity all-fiber polarization interference filter (AFPIF) has been demonstrated. To incorporate an AFPIF with relative narrow transmission bandwidth, the laser has produced clean soliton pulses of 1.2 ps duration at a repetition rate of 14.98 MHz with a polarization extinction ratio up to 25.7 dB. Moreover, we have demonstrated that the operating wavelength of the mode locking laser can be tuned over 20 nm range from 1545 to 1565 nm by thermally tuning the AFPIF cavity. © 2012 Optical Society of America

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Interest in mode locked fiber lasers has been growing rapidly over the last decade, similar to increasing demand of efficient ultra-short-pulse sources for applications in optical communications, metrology, biophotonics, and nanophotonics. The erbium doped fiber (EDF) has over 25 nm gain bandwidth and anomalous dispersion property in the 1550 nm region. This combination makes EDF based fiber lasers a good candidate to be developed into soliton pulse laser sources [1–4]. It is possible to obtain picosecond (ps) and femtosecond pulses based on EDF mode locking lasers. The soliton mode-locked laser was first reported by Mollenauer and Stolen in 1984 [1]. The stable soliton pulses were generated under the balance between nonlinearity and dispersion of the laser cavity. However, due to the perturbation induced by the discrete loss, gain, and dispersion properties, the pulses always shed into dispersive waves, which interfere with the soliton pulses generating sidebands superimposed on the pulse spectrum [2]. These sidebands become predominantly pronounced after the pulses propagate multiple cavity loop trips [2–4]. The strong sidebands on soliton pulses cause many disadvantages, such as limitation to the pulse duration, high noise and instability, and high energy loss on output pulses [3]. Therefore, it is necessary to sufficiently or totally eliminate the sidebands on a soliton pulse. So far, there are several efficient methods to suppress the sideband effects, such as using a short-length cavity [5]; a symmetric cavity structure separated by two polarizers [6]; a longer soliton period [7]; or a band-pass filter [8,9]. Among them, the band-pass filter is a simpler, efficient, and more direct method to suppress the sidebands. It has also been reported that to achieve sideband suppressing, by a bulk birefringence filter [6], the bulk components always need a collimation system that inevitably induces extra cavity loss and limits to the integration of the laser system. Recently, we have reported an all-fiber polarization interference filter (AFPIF) [10]. By using such an intra-cavity filter, we have demonstrated an all-fiber passively mode locking laser system capable of outputting soliton laser pulses. The utilization of an intra-cavity AFPIF can offer three unique advantages—suppressing sidebands of soliton pulses, generating pulses with high polarization extinction ratio (PER), and providing a simple and low-cost thermal tuning for operation wavelength over an entire EDF gain region.

The schematic of the passively mode-locked fiber soliton laser is shown in Fig. 1. The total cavity length is $\sim$14 m, consisting of a 3.5 m long EDF from Fibercore with 18 dB/m nominal absorption at 1530 nm and normal dispersion ~ -11 ps/nm/km, 9.5 m long standard telecom fiber (SM28) with anomalous dispersion $\sim +18$ ps/nm/km and 1 m long polarization maintaining fiber (PM1550 from Corning) with a dispersion similar to SM28. Thus, the net cavity group velocity dispersion is around -0.0137 ps^2. The 975 nm laser diode pump source that can provide up to 500 mW pump power is launched through a 980/1550 WDM. An AFPIF sandwiched between two PCs is used as a mode locking component. A 90∶10 optical coupler (OC) is employed to couple out the laser light (10% output and 90% feedback). The unidirectional operation is achieved by applying a polarization independence isolator in the cavity.

The AFPIF was formed by two 45° tilted fiber gratings (45°-TFGs) UV-laser inscribed in PM 1500 fiber separated by a section of PM fiber cavity. The detailed description on fabrication and functionality of AFPIF have been

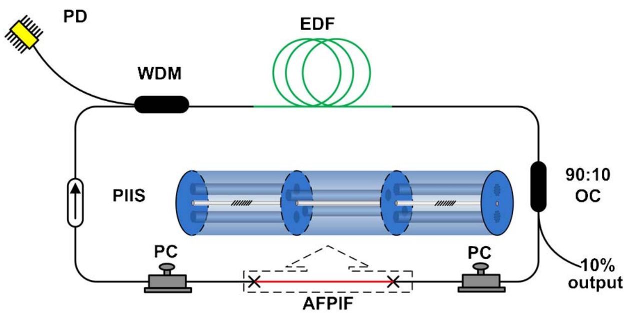

Fig. 1. (Color online) Configuration of a EDF based soliton pulse laser. PD, pump diode; PIIS, polarization independent isolator; EDF, erbium doped fiber; OC, optical coupler; PC, polarization controller; WDM, wavelength division multiplexer; the dashed line frame box and the inset showing an AFPIF.

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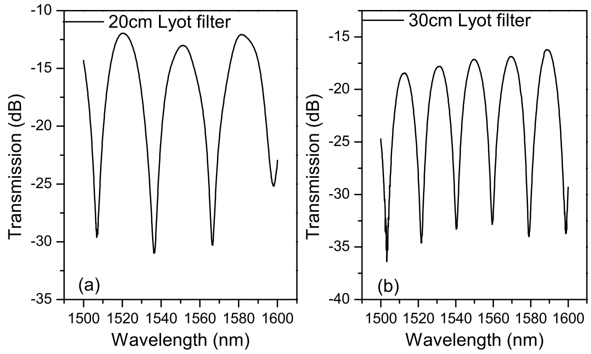

Fig. 2. Spectral responses of two AFPIFs with (a) 20 cm and (b) 30 cm PM fiber cavity giving 16 and 10 nm transmission bandwidth, respectively.

reported in [10]. Figures 2(a) and 2(b) show the spectral responses of two AFPIFs with 20 and 30 cm PM fiber cavity, respectively. From these figures, we can measure the transmission bandwidths of these two AFPIFs are around 16 and 10 nm in the 1550 nm region, respectively.

In the AFPIF based soliton fiber laser, the mode locking pulse is generated from the nonlinear polarization rotation. By adjusting the polarization controllers, the stable pulse can be generated when the pump power exceeds the threshold (>50 mW). In the evaluation, the pulse duration time was measured using an autocorrelator (INRAD Inc. Model 5-14B) and the pulse spectrum was captured by an optical spectrum analyzer (86142B, Agilent). After the evaluation in using AFPIF as the mode locking element, a 45°-TFG was connected into the cavity replacing the AFPIF for comparison. Figures 3(a)–(3c) plots the laser output spectra and pulse duration (inset) when using 45°-TFG and AFPIFs with 20 and 30 cm cavity as mode locking components, respectively. Although, soliton-like pulses with 1.6 ps duration time and 14.98 MHz repetition ratio can be generated from the laser using just a 45°-TFG as a mode locker [Fig. 3(d)], the pulse spectrum is showing 5 order sidebands at the shorter wavelength side and 7 orders at the longer wavelength side. In addition, we see that the ±1 order sidebands sited at ±9.4 nm from the center wavelength, on both sides, have comparable energy intensity to the main soliton pulse. These sidebands are highly undesirable because they usually induce noise, crosstalk, and instability to the laser system.

Unlike the broadband response from a 45°-TFG, an AFPIF offers a sinusoidal transmission filter function with finesse easily designed. By properly designing the transmission bandwidth of an AFPIF, the low level spectral features associated with the sidebands can be effectively suppressed. The two fabricated AFPIFs were applied in the laser system as mode locker, and the laser pulse spectra are shown in Figs. 3(b) and 3(c). It can be seen clearly from the figures that the sidebands have been suppressed to a good degree when the AFPIF, with a 20 cm long cavity is used, leaving only a first-order sideband, shown on the spectrum. However, when the AFPIF with a 30 cm cavity is used, the sidebands have been completely removed, giving a symmetrical and clean pulse as shown in Fig. 3(c).

The soliton pulse generated with a 30 cm long cavity AFPIF used as a mode locker was evaluated by using a high speed oscilloscope (352A Lecroy) and frequency spectrum analyzer (HP 8562A). Figure 4(a) shows the pulse train with around a 66 ns interval between two adjacent pulses. The radio frequency spectrum (RFS) of pulse is shown in Fig. 4(b). As shown clearly in Fig. 4(b), the RF spectra in the range of 0.1 MHz bandwidth has a 14.98 MHz fundamental cavity repetition rate which is in good agreement with pulse-pulse separation. The over 80 dB signal-to-noise ratio [see Fig. 4(b)] ensures the high stability of the mode locking status. Figure 4(c) shows the RF spectra in the range of 200 MHz bandwidth. Actually, in the experiment, the pulse from 45°-TFG based soliton laser also showed very high signal-to-noise ratio [11]. It was noticed in the experiment, when there was with an increase of the pump power, the shape of the pulse spectrum did not change but only the output pulse energy linearly increased with pump power, as shown in Fig. 4(d).

In addition to the sideband suppression function, the AFPIF also greatly improves the PER of output pulse.

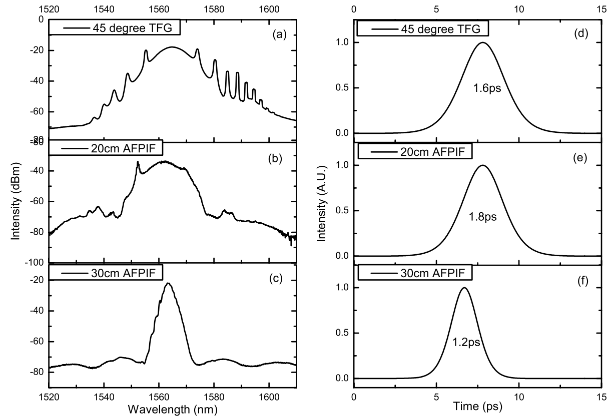

Fig. 3. Output spectra and autocorrelation of all-fiber EDF soliton lasers: (a) and (d) with just an intra-cavity 45°-TFG showing pronounced sidebands on the pulse spectrum, (b) and (e) with an intra-cavity AFPIF of 20 cm long PM fiber cavity, and (c) and (f) with an intra-cavity AFPIF of 30 cm long cavity.

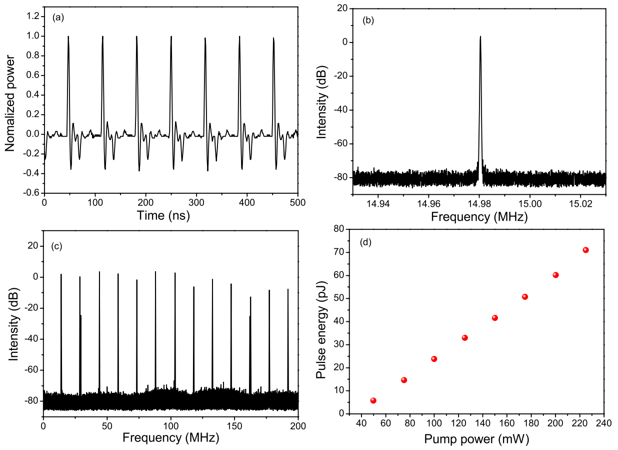

Fig. 4. (Color online) (a) Output pulse train observed on oscilloscope, (b) the RFS of mode-locked pulse train, (c) RF spectra in the range of 200 MHz bandwidth, and (d) the output pulse energy generated by using a 30 cm long cavity AFPIF versus the pump power.

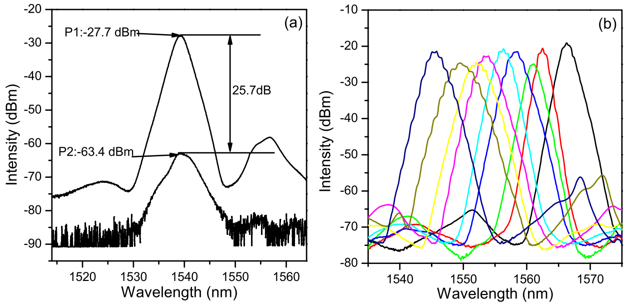

Fig. 5. (Color online) (a) PER of output pulse. (b) Output spectra of all fiber EDF soliton ring laser tuned by temperature.

We used the method reported in [11,12] to measure the PER. As shown in Fig. 5(a), the solid and dashed lines represent the max and min transmission for the output pulse with orthogonal polarization states. Thus, the PER of the output pulse from the AFPIF mode locking laser is the difference between the max and min transmission, and is around 25.7 dB. This value is comparable with the system reported in [13]. Thus, an AFPIF can ensure the laser is working at a single polarization status, which is desirable for many applications in signal transmission and sensing.

It has been reported in [14] that the 45°-TFG based mode locking fiber laser can generate the pulse at random operating wavelength, due to very broad polarization response of a 45°-TFG. In contrast, the utilization of an AFPIF as an intra-cavity polarization device can make sure the pulse is only generated at the wavelength locked by the passband of AFPIF, which offers another unique function for a soliton pulsed laser—operating wavelength tunability. We have previously demonstrated a wideband wavelength tuning of an AFPIF by simply heating up a section of the PM fiber cavity [15]. In this experiment, the passband of the AFPIF was thermally tuned covering almost the whole EDF gain region, and the mode locking status was achieved at the different central wavelength from 1545 nm to 1565 nm, as shown in Fig. 5(b).

In conclusion, we have presented a passively mode locking fiber laser with an intra-cavity AFPIF as a polarization functional device. By using an AFPIF with relatively narrow transmission bandwidth, the sidebands of laser pulse can be efficiently suppressed, improving the signal-to-noise ratio and stability of the soliton pulse laser. The AFPIF also ensures that the laser operates at single polarization status, giving high polarization extinction output. In addition, the AFPIF can offer wideband wavelength tunability. By thermally heating up the PM fiber cavity of the AFPIF, the laser operation can be tuned over almost the entire EDF gain range without any noticeable intensity change. Furthermore, by appropriate cavity design, the fiber laser incorporating an AFPIF may achieve all fiber normal dispersion mode locking and Raman fiber laser systems.

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