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Multiplexed ultrafast fiber laser emitting multi-state solitons

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Abstract: Ultrafast fiber lasers have been serving as an ideal playground for spreading the extensive industrial applications and exploring the optics nonlinear dynamics. Here, we report a bidirectional fiber laser scheme for validating the possibility of a multiplexed laser system, which is passively mode-locked by the nonlinear polarization rotation (NPR) technique. In particular, the proposed fiber laser consists of one main cavity and two counter-propagating branches with different dispersion distributions. Thus, different formation mechanisms are introduced into the lasing oscillator. Consequently, stable conventional solitons (CSs) and dissipative solitons (DSs) are respectively formed in the clockwise (CW) and counterclockwise (CCW) directions of the same lasing oscillator. Moreover, attributing to the strong birefringence filtering effect, the wavelength selection mechanism is induced. Through the proper management of intra-cavity birefringence, wideband wavelength tuning and switchable multi-wavelength operations are experimentally observed. The central wavelength of CS can be continuously tuned from 1560 nm to 1602 nm. Additionally, the evolution process of different multi-wavelength operations is also elucidated. Benefiting from this multiplexed laser scheme, bidirectional lasing oscillation, multi-state soliton emission, wavelength tuning and multi-wavelength operations are synchronously realized in a single laser cavity. To the best of our knowledge, it is the first time for such a multiplexed fiber laser has been reported. The results provide information for multifunctional ultrafast fiber laser system, which is potentially set for telecommunications, fiber sensing and optics signal processing, etc.

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1. Introduction

Ultrafast fiber lasers have attracted intensive researches for the extensive applications of telecommunications, optical storage, material machining, laser lithography, and biomedicine [1–5]. In the framework of the dissipative system, passively mode-locked fiber lasers have acted as an optimal playground for revealing the soliton dynamics [6]. With continuing energy supply, a mutual balance between nonlinearity, dispersion, self-amplitude modulation and spectral filtering effect plays a significant role in the formation of dissipative solitons (DSs), which is governed by the complex Ginzburg-Landau equation (CGLE) [7–10]. Due to the fertile physical mechanisms of pulse shaping in mode-locked fiber lasers, different lasing performances can be obtained with different cavity configurations. Traditionally, solitons in different dispersion regime have been extensively investigated previously [11–13]. However, the aforementioned investigations are mainly focus on a single type of soliton. Little attention has been paid to the multi-state soliton emission, and the applications of which have remained
untapped so far. In particular, D. Y. Tang et al. have numerically and experimentally demonstrated the coexistence and competition between different solitons-shaping mechanisms near zero group velocity dispersion (GVD), where different solitons could be formed depending on the laser operations [14]. Through setting up a switchable fiber laser with two lasing oscillators, Y. Cui and X. Liu have reported the formation of conventional soliton (CS) and DS in opposite propagating directions [15]. The observation of tunable CSs and noise-like pulses (NLPs) is also demonstrated by developing a bidirectional mode-locked fiber laser previously [16]. Whether the multi-state soliton emission could be achieved in a common laser cavity? How to realize the multi-state soliton emission? It is crucial to focus on these important issues.

Moreover, taking advantages of high efficiency, low thermal effect and ultrashort pulse width etc., mode-locked fiber lasers have been widely applied in industry [17]. Particularly, tunable and switchable multi-wavelength soliton fiber lasers play an increasing vital role in laser imaging, signal processing, fiber sensing and optic communications. Generally, active mode locking technique is considered as an effective approach to obtain high-repetition multi-wavelength operation. In order to satisfy the round-trip condition, dispersion-tuned cavity has been proposed for the synchronous mode locking of different wavelengths [18]. Nevertheless, intra-cavity modulators increase the insertion loss and the system complexity. As the improved schemes, passively mode-locked fiber lasers based on in-line bandpass filters like cascaded fiber Bragg gratings (FBGs) [19,20] are employed to provide an all-fiber solution. Furthermore, passively mode-locked fiber laser can support unequal round-trip frequencies. Consequently, stable multi-wavelength operation could be easily obtained in passively mode-locked fiber laser despite the cavity dispersion. Benefiting from the wavelength selection introduced by all-fiber filters such as chirped fiber Bragg grating (CFBG) [21,22], Sagnac fiber loop [23], Mach-Zehnder interferometer (MZI) [24] and artificial birefringence filter [25–28], wavelength tuning and multi-wavelength mode locking have been demonstrated in various wavebands, as well as dispersion regimes. Unlike physical filters, artificial birefringence filter could support simple configurations, which leads to less demand on cavity components. However, with the rapid development of modern manufacturing, traditional fiber laser schemes might gradually approach their bottlenecks. Thus, it is significant to develop a multiplexed ultrafast fiber laser, which is more compact and multifunctional.

Here, we proposed a multiplexed ultrafast fiber laser with a bidirectional main cavity and two counter-propagating branches. The two branches have different dispersion distributions so that CS and DS can be respectively delivered from clockwise (CW) and counterclockwise (CCW) propagating directions of the main cavity. Furthermore, benefiting from the birefringence filtering effect, the mechanism of wavelength management is introduced in our fiber laser. As a result, wideband wavelength tuning and switchable multi-wavelength operations of CS are experimentally obtained through appropriately adjusting the pump power and intra-cavity polarization state. The wavelength-switching process is also elucidated. Therefore, the proposed fiber laser could serve as a multifunctional platform for extending applications in high-speed communications, fiber sensing and optics signal processing. To the best of our knowledge, it is the first time for such a multiplexed fiber laser has been reported. Our investigation not only exploits the potential of single fiber laser system for industrial applications, but also paves a new way for exploring the optics nonlinear dynamics.

2. Fiber laser setup

The schematic diagram of the multiplexed fiber ring laser is illustrated in Fig. 1, which consists of a bidirectional main cavity and two counter-propagating branches. The main cavity is bidirectionally pumped by two 980 nm laser diodes (LDs) via two 980/1550 nm wavelength-division multiplexers (WDMs). A 2-m erbium-doped fiber (EDF, RightWave EDF80) with a $\beta_2$ of 0.061 ps$^2$/m is used as gain medium. Mode-locking operations are
realized by NPR technique, configured by a polarizer and three polarization controllers (PCs) respectively inserted in the main cavity and two branches. The output pulses are extracted by a 2 × 2 optical coupler (OC) with a 10% output ratio. The formations of CS and DS are respectively realized in two counter-propagating branches with different dispersion distributions. Two 3-port CIRs are employed to couple branches into main cavity and ensure the unidirectional operations in each branch. Particularly, PC2 and a 2-m dispersion compensation fiber (DCF, YOFC) with a $\beta_2$ of 0.203 ps$^2$/m are inserted in CCW branch, while PC3 and a segment of single mode fiber (SMF) are inserted in CW branch. The mode-locking states in CW/CCW directions can be controlled independently via adjusting PC1 and PC2/PC3. Pigtailed of all components are SMF with a $\beta_2$ of −0.022 ps$^2$/m. The total cavity length in CW and CCW directions are ~22.48 m and ~22.84 m, respectively corresponding to the net-dispersion of around −0.328 ps$^2$ and 0.114 ps$^2$ at 1550 nm. Here, considering that the inhomogeneous gain distribution might be induced by the difference of pump strength of the two LDs, we set the two pump LDs with almost same driven conditions for a better lasing performance. Thus, the pump powers injected from the two LDs are nearly equal so that total pump power is recorded by default. The optical spectrum and oscilloscope trace are respectively monitored via an optical spectrum analyzer (Yokogawa AQ6370D) and a 4-GHz oscilloscope (Tektronix CSA7404B) combined with a high-speed photodetector (Newport Mode#1414). A commercial autocorrelator (Femtochrome FR-103XL) is used to analyze the autocorrelation trace. The radio frequency (RF) spectrum are measured by a RF spectrum analyzer (Agilent E4447A).

3. Experimental results and discussions

The formations of CS and DS are respectively supported by two branches, corresponding to CW and CCW propagating directions. However, these pulses still share one common main cavity including pump, gain, extraction and mode locking mechanism. The basic performance of the proposed bidirectional fiber laser is summarized in Figs. 2 and 3. In CW direction, CSs are realized with obvious Kelly sidebands in the spectrum. As shown in Fig. 2(a), the 3-dB bandwidth is 4.4 nm with a central wavelength of ~1596.7 nm. Its full width half maximum (FWHM) of autocorrelation trace is measured to be 997.3 fs, corresponding to ~646.4 fs pulse duration assuming temporal profile. Therefore, the time-bandwidth product (TBP) is calculated to be ~0.33, which is nearly transform-limited. Due to the pump hysteresis [29], single-pulse mode locking operation is obtained and still maintained by gradually reducing pump power to 32 mW. The average output power is ~183.7 μW, which corresponds to the
single-pulse energy of ~20 pJ. Moreover, the fundamental oscilloscope trace is depicted in Fig. 2(c) with a pulse separation of ~109 ns for one round-trip time. Figure 2(d) presents the RF spectrum in 5 kHz span with 1 Hz resolution bandwidth (RBW). The fundamental repetition rate is around 9.17 MHz, which agrees with the cavity length. The high signal to noise ratio (SNR) up to 60 dB manifests the stability of the mode-locked CSs.

![Fig. 2. Conventional solitons in clockwise direction (a) optical spectrum (b) autocorrelation trace (c) fundamental oscilloscope trace (d) fundamental RF spectrum in 5 kHz span, 1 Hz RBW (Inset: 1 GHz span, 1 kHz RBW).](image)

Besides, attributing to the net-positive dispersion in CCW direction, DSs are automatically formed by adjusting the pump power and polarization state. As the distinct rectangular optical spectrum shown in Fig. 3(a), the 3-dB bandwidth is about 11.8 nm with a central wavelength of ~1567.9 nm. The FWHM of the autocorrelation trace is 27.7 ps, corresponding to the pulse width of ~19.6 ps if the Gaussian profile fit is applied. The initial TBP is calculated to be 28.1, indicating the output pulses are strongly chirped and widening. Through cut-back method, the initial output DS can be dechirped naturally by SMF outside the cavity [7,30]. In the experiment, ~103.4 m SMF is used to dechirp the obtained DS and no remarkable spectral variation occurs during the compression. As depicted in Fig. 3(b), the red curve shows the autocorrelation trace of compressed pulses with a pulse duration of ~428.6 fs. After compression, the TBP is ~0.61, which is near to the transform-limited value of 0.441. Through carefully decreasing the pump power to 76 mW, the fundamental mode-locking operation is obtained. The average output power is ~950 μW, corresponding to the pulse energy of ~105.3 pJ. Figures 3(c) and 3(d) respectively illustrate the fundamental oscilloscope trace with a pulse separation of ~111 ns and the RF spectrum with a fundamental repetition rate of ~9.02 MHz. The high stability of DSs could be manifested by the SNR over 80 dB. Nevertheless, in order to support the emission of different soliton states, the configurations of two branches are partially different. As a result, when we switch different soliton states, the cavity parameters such as polarization state and pump power have to be readjusted at appropriate values for stable mode locking operations. Consequently, it might be difficult to obtain CS and DS at the same time in this bidirectional laser. However, with experimental setup optimizing, the laser performance could be further improved to...
simultaneously realize the generation of different soliton states. The issue deserves our further efforts for many practical applications.

Furthermore, broadband tunable mode-locked CSs are obtained in CW direction. Keeping the pump power fixed at 120 mW, the central wavelength can be tuned from 1560 nm to 1602 nm via appropriately rotating PC1 and PC2. As shown in Fig. 4(a), the optical spectrums tuned with a tuning step of ~3 nm and the whole tuning process is reversible. With the central wavelength tuning, small distortions are occurred. For clarity, we depict the variations of 3-dB bandwidth and pulse width in Figs. 4(b) and 4(c). As is well-known, wavelength tuning operation is realized because of the wavelength selection in the cavity. Here, the mechanism of wavelength selection can be explained due to the strong birefringence filtering effect. Benefiting from the intrinsic birefringence from fiber and polarization-dependent components in the cavity, an invisible artificial birefringence filter is induced to function as a physical comb filter [24,25]. This birefringence filter has linear wavelength-periodic bandpass, the related transmission of which is mainly governed by the phase delay resulted from intra-cavity birefringence, polarization axis bias, PCs and nonlinear effect [31,32]. As a result, the minima of the filter transmission can be varied by rotating PC paddles, which leads to the shift of mode locking waveband. In general, the period \( \Delta \lambda' \) of the artificial birefringence filter can be described by

\[
\Delta \lambda' = \frac{\lambda_c^2}{LB}
\]

where \( \lambda_c \) is the central wavelength, \( L \) is the total cavity length and \( B \) stands for the strength of birefringence [27,28]. Additionally, fiber bending and doped fiber can further enhance the intra-cavity birefringence. Hence, the \( \Delta \lambda' \) could be controlled if the management of intra-cavity birefringence is strong enough. In fact, different from the physical saturable absorber (SA) like graphene and semiconductor saturable absorber mirror (SESAM), the tuning range of the NPR technique depends on combination of artificial birefringence filter and gain.
bandwidth, instead of the fabricated materials [33]. Thus, from our point of view, the 42-nm tuning scale might be the maximum tuning range limited by the efficient gain bandwidth.

Fig. 4. Wavelength tuning process of conventional solitons (a) optical spectrum ranging from 1560 nm to 1602 nm (b) variation of 3-dB spectrum bandwidth (c) variation of pulse width.

In addition, stable multi-wavelength mode locking operations are obtained. Figure 5 summaries the characteristics of the dual-wavelength CSSs at the pump power of 184 mW. The central wavelengths of the two partly overlapped spectra are 1573.4 nm and 1596.5 nm, which are respectively represented by \( \lambda_S \) and \( \lambda_L \). Thus, the wavelength separation is around 23.1 nm. The snapshot of the pulse trains is depicted in Fig. 5(b). Due to the different central wavelengths, the two pulses propagate at different group velocities. Therefore, the oscilloscope cannot synchronously trigger all the pulses but trace a random distribution. Here, we can denote the time difference \( \Delta t \) for one round-trip between \( \lambda_S \) and \( \lambda_L \) as

\[
\Delta t = LD\Delta\lambda = \Delta \left( \frac{1}{f} \right) = \frac{\Delta f}{f^2}
\]  

So that the repetition rate difference \( \Delta f \) can be calculated as

\[
\Delta f = \frac{\Delta t}{t^2} = \frac{LD\Delta\lambda}{t^2}
\]  

where \( L \) represents the total cavity length of 22.48 m in CW direction, \( D \) is the average group velocity dispersion (GVD) calculated as 11.22 ps/(km nm), \( \Delta \lambda \) is the wavelength separation, and \( t \) is the one round-trip time. Thus, the \( \Delta f \) is calculated to be 489 Hz, which agrees well with the measured value of 491 Hz as shown in Fig. 5(c). Furthermore, in order to verify the stability of the dual-wavelength mode locking operation, the intensity spectrum scanned for 150 min is plotted in Fig. 5(d). Particularly, the output optical spectrum is repeatedly scanned with an interval of 1 minute, the intensity distribution of which is defined by different colors. Apart from some slight perturbation of the sidebands, especially in the overlap region, the
intensity spectrum shows a good consistency, which indicates a relatively stable mode locking state.

![Fig. 5. Dual-wavelength mode-locked solitons (a) optical spectrum (b) oscilloscope trace (c) RF spectrum in 800 Hz span, 1 Hz RBW (d) optical intensity spectrum repeatedly scanned with 1-min interval for 150 min.](image)

From the dual-wavelength CS, the quadruple-wavelength operation is also observed. Increasing pump power to 206 mW, the quadruple-wavelength CSs are obtained via carefully rotating the PCs. As shown in Fig. 6(a), four peak wavelengths are respectively defined by $\lambda_{1,2,3,4}$, which are specifically around 1573 nm, 1581 nm, 1590 nm and 1596 nm. These spectral peaks of mode-locked wavelength components are characterized by several symmetrical sub-sidebands, which differs from the typical CW components even though they might be less obvious. Furthermore, RF spectrum is also measured to manifest the experimental results. Figure 6(b) depict the corresponding RF signals. The differences of the repetition rate between adjacent wavelengths are respectively $\sim$160 Hz, $\sim$190 Hz and $\sim$150 Hz, which are accordant with the wavelength separations of $\sim$7.5 nm, $\sim$9.0 nm and $\sim$7.0 nm according to aforementioned analysis. Nevertheless, owing to the serious mode competition, this quadruple-wavelength mode locking state is quite unstable. With environmental perturbations, the mode-locked wavelength components are easily evolved into continue waves (CWs). Except for the Kelly sidebands formed by the interference between dispersive waves and solitary pulses, another kind of sidebands occurred in optical spectrum of the picosecond pulse components. The formation of these sub-sidebands might be original from the modulation instability (MI) [34,35]. Unlike Kelly sidebands, MI induced sidebands almost symmetrically locate around the source wave and tend to form in the dispersion-managed cavity with net-negative dispersion [36].
Then, the evolution of different multi-wavelength operation is experimentally investigated for elucidating the formation mechanism of the multi-wavelength CSs. Figure 7 illustrates the switching process from single-wavelength to triple-wavelength mode locking states. By carefully rotating paddles of the PCs, the peak wavelengths gradually shift towards long waveband side. Alone with the red shift of the peak wavelengths, the mode-locked CSs are synchronously switched from single- to triple- and back to single-wavelength mode locking states. Particularly, after the generation of triple-wavelength CSs, the mode locking operation becomes relatively unstable and then automatically evolved into a transition state. If continue to rotate the paddles, the transition state will suddenly regress to another state of triple-wavelength CSs. The whole switching process is reversible when the paddles are rotated following the opposite direction. Here, the four switchable peak wavelengths are approximately equal with the aforementioned $\lambda_1$ to $\lambda_4$ of ~1573 nm, ~1581 nm, ~1590 nm and ~1596 nm, respectively. Hence, their relationship can be revealed by

$$\frac{1}{\lambda_1} + \frac{1}{\lambda_4} = \frac{1}{\lambda_2} + \frac{1}{\lambda_3}$$

Therefore, the formation mechanism of the switchable multi-wavelength operations could be partially attribute to the four-wave mixing (FWM) effect [37]. As a result, with the transmission of birefringence filter tuning, FWM induced energy exchange occurs between different wavebands, which contributes to the mode locking of new wavelength components as well as the suppression of previous wavelength.
Fig. 7. Optical spectrums of different multi-wavelength mode-locking operations along with the wavelength switching process.

Although tunable and multi-wavelength CSs are obtained in the experiment, no similar phenomena about DS are observed with adequate adjustments of polarization state and pump power. In the framework of dissipative system, with continuous energy flow, pulse shaping by spectral filtering effect plays a crucial role in the formation of DS [38]. Here, the formation of DS is realized by NPR technique, which however also contributes to the cavity birefringence filtering effect. Attributing to the instinct cavity birefringence, a birefringent filter is induced to support the wavelength tuning operation. Governed by phase delay introduced by cavity birefringence, the related filtering transmission could be tuned via appropriate management of intra-cavity polarization state. However, it might be difficult to experimentally satisfy all the requirements of pulse shaping and wavelength tuning operation at the same time. Consequently, wavelength tuning operations of DS might be very difficult in the proposed bidirectional fiber laser. Nevertheless, it is notable that the wavelength tuning performance could be further improved with optimization of cavity configuration. Recently, tunable and multi-wavelength DSs are demonstrated in a hybrid mode-locked fiber laser [39], which provides a feasible solution regarding to the above issue. Through introducing extra mode locking mechanism such as physical SA, it might be more convenient to obtain tunable and multi-wavelength DS.

4. Summary

In summary, we propose a multiplexed ultrafast fiber laser realizing the multi-state soliton emission, as well as wideband wavelength tuning and switchable multi-wavelength operation. The proposed fiber laser consists a bidirectional main cavity and two counter-propagating branches with different dispersion distributions. Therefore, distinct formation mechanisms are introduced into two propagating directions of the laser cavity. As a result, CS and DS can be respectively formed in CW and CCW directions, which might be very convenient for practical applications. Furthermore, owing to the strong birefringence filtering effect, the
wavelength selection mechanism is induced in our fiber laser. Though properly setting up the pump power and polarization state, tunable and switchable multi-wavelength CSs are experimentally obtained. Particularly, the central wavelength of CS can be continuously tuned from 1560 nm to 1602 nm with small distortions. Associated with the birefringence related transmission variation and the energy exchange induced by FWM, the evolution process of switchable multi-wavelength operation is also observed. The multiplexed fiber laser could benefit many applications including photonic component characterization and wavelength-division-multiplexing system, which paves a promising way for a multifunctional and compact laser system.

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