Experimental investigation on evolution of a split multi-wavelength bright-dark pulse in a mode-locked thulium-doped fiber laser*

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We report the experimental observation of evolving phenomenon of a split multi-wavelength bright-dark pulse in the nonlinear amplifying loop mirror (NALM)-based mode-locked thulium-doped fiber laser (TDFL) with a figure-eight configuration. Bright-dark pulse with 10 wavelengths was successfully obtained at the pump power of 3 W. The time interval between the bright and dark pulses was discovered not only increasing linearly with the pump power but also approximately equaling to the reciprocal of modulation frequency of radio frequency (RF) spectrum. Moreover, we also observed that the spectrum of split multi-wavelength bright-dark pulse can further present up to 13 wavelengths.

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In the past decades, pulse fiber lasers have attracted extensive attention due to the variety of applications in material processing, optical communications, surgery, and remote sensing. Laser pulses can be divided into bright and dark pulses according to the bulge or dip of intensity in continuous wave background, and bright and dark pulses can be analyzed by the nonlinear Schrödinger equation (NLSE)[1] and the complex Ginzburg-Landau equation (CGLE)[2], which have been observed experimentally[3-6] and proved theoretically[7-9] in fiber lasers. As we all know, since bright pulses are easier to obtain than dark pulses, most of the reported pulse fiber lasers operate at the bright pulse regime. Compared with bright pulses, the dark pulses are more stable in the presence of noise and lower transmission loss in fibers, so they can be applied in telecommunication and precision measurement[10]. Besides bright or dark pulses, bright-bright, dark-dark, bright-dark or dark-bright pulses have been theoretically confirmed in fiber lasers owing to the interaction between the pulses[11,12]. Among these, bright-dark pulses have gradually gained in-depth exploration because they can be used to form security codes in secure communication systems. So far, bright-dark pulses have been experimentally observed in fiber lasers based on different mode-locked techniques, including nonlinear polarization rotation (NPR)[13], nonlinear amplifying loop mirror (NALM)[14], nonlinear optical loop mirror (NOLM) and material-based saturable absorbers (SAs)[15]. Generally, the spectra of bright-dark pulses generated by these mode-locked techniques are mostly typical wide-band unimodal spectra[15-18] and dual-wavelength spectra[13-15]. In addition to two types of above-mentioned spectra, the tripe-wavelength[19], quad-wavelength[20], and 33 wavelengths[21] also have been obtained in bright-dark pulse passively mode-locked fiber lasers.

To further explore the formation mechanism of bright-dark pulses, many researchers have focused on a new phenomenon that bright-dark pulse can be split in mode-locked fiber lasers[22-24]. A split bright-dark pulse with the typical wide-band unimodal spectrum was firstly demonstrated experimentally in a passively mode-locked erbium-doped fiber laser (EDFL) based on NPR technique by increasing pump power or adjusting polarization controller (PC)[22]. Subsequently, a split dual-wavelength bright-dark pulse was obtained in a thulium-doped fiber laser (TDFL) based on self-mode-locking technology by adjusting the pump power or PC[23]. The generation of a split dual-wavelength bright-dark pulse was also reported in a passively mode-locked EDFL with a large-angle tilted fiber grating (LA-TFG) by adjusting PC[24]. Nevertheless, to date, the detailed evolution characteristics of a split multi-wavelength bright-dark pulse have never been studied.

In this paper, the evolution of a split multi-wavelength bright-dark pulse is experimentally investigated in passively mode-locked TDFL based on NALM technique. The split multi-wavelength bright-dark pulse is obtained, and related time interval evolution is investigated between

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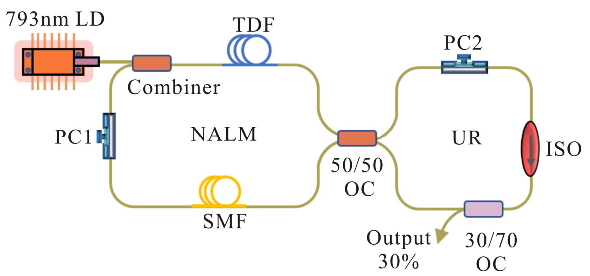
bright and dark pulses. The spectrum of split multi-wavelength bright-dark pulses can display up to 13 wavelengths. Moreover, the radio frequency (RF) spectrum appears a remarkable envelope modulation phenomenon, whose modulation frequency is approximately equivalent to the reciprocal of time interval between bright and dark pulses. Our works may contribute to a deeper insight into the coexistence and evolution of a multi-wavelength bright-dark pulse in passively mode-locked fiber lasers.

The experimental setup is given in Fig.1. The used figure-eight cavity configuration includes an NALM and a unidirectional ring (UR). The UR and NALM are connected by a 50/50 fiber optical coupler (OC). In NALM module, a PC is used to control the linear phase bias and thus control the transmissivity of NALM. A 187-m-long single mode fiber (SMF28e, dispersion parameter of −0.067 9 ps^2/m) is used to introduce enough asymmetric nonlinear phase shift difference between the clockwise and counter-clockwise propagating light in the NALM, and a segment of 4.4 m dual-clad thulium-doped fiber (TDF, IXF-2CF-TM-O-10-130V1, IXFiber, dispersion parameter of −0.070 7 ps^2/m) with absorption coefficient of 5.6 dB/m at 789 nm is used to provide a gain amplification. The TDF is pumped by a 793 nm laser diode through a 793/2 000 nm (2+1)×1 pump combiner. In UR module, a polarization independent isolator (PI-ISO) is utilized to ensure the unidirectional operation, and the same PC is inserted into the UR to optimize the polarization state of the cavity. A 30/70 OC is used as the output coupler, where 70% power is feedback, and 30% power is output. The total cavity length of the laser is ~197 m corresponding to the estimated fundamental repetition rate of 1.041 MHz. The total net dispersion of cavity is estimated to be −13.39 ps^2 at 2 μm. In the experiment, the optical spectrum of the laser is monitored by an optical spectrum analyzer with a resolution of 0.02 nm (Omni-λ 750i, Zolix). The pulse waveforms and the RF spectra are measured by an InGaAs photodetector (ET-5000F, EOT) connected to a digital oscilloscope with a bandwidth of 1 GHz (WaveRunner610Zi, Lecroy) and an RF spectrum analyzer with a bandwidth of 3 GHz (FSL3, Rohde & Schwarz).



NALM: nonlinear amplifying loop mirror; UR: unidirectional ring; LD: laser diode; TDF: thulium-doped fiber; ISO: isolator; OC: optical coupler; SMF: single mode fiber; PC: polarization controller

Fig.1 Experimental setup of the TDFL

Fig.2 shows the laser output power increases linearly with the launched pump power after meeting the threshold. When the pump power is under 2.4 W, the laser operates in fluorescent state. As the launched power reaches the threshold, the TDFL operates in two regimes including continuous wave (CW) (2.4—3 W) and bright-dark pulse (3—8 W). Moreover, it can be seen that the average output power is 163.5 mW when the maximum pump power is 8 W. The slope efficiency of the TDFL in the experiment is ~2.93%. The main reason for the low slope is the mode field mismatch between the double-clad TDF and combiner fiber pigtail.

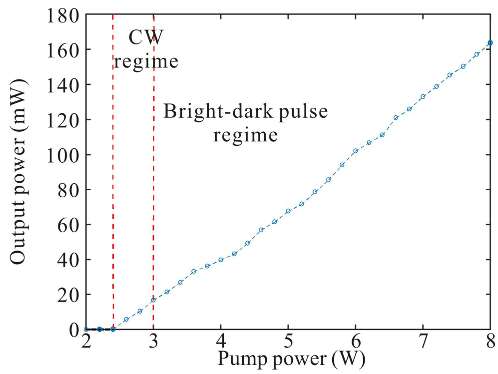


Fig.2 Average output power under different pump powers

Fig.3 shows the output characteristics of multi-wavelength bright-dark pulse at the pump power of 3 W.

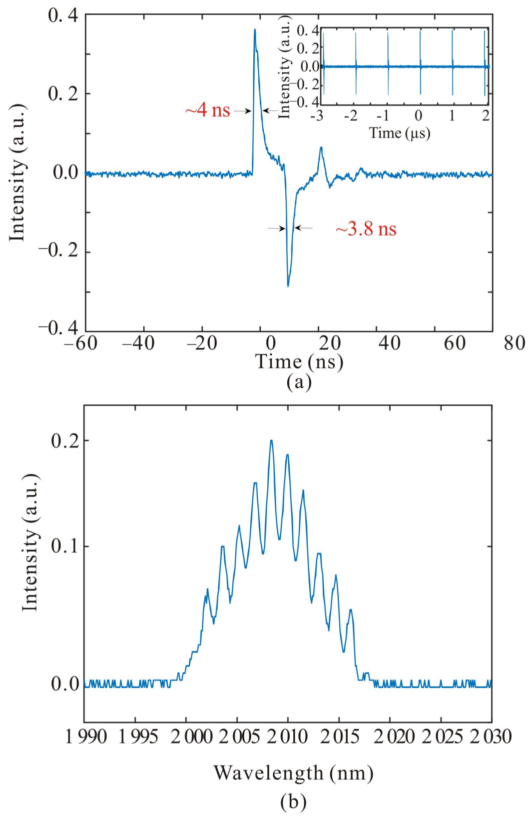
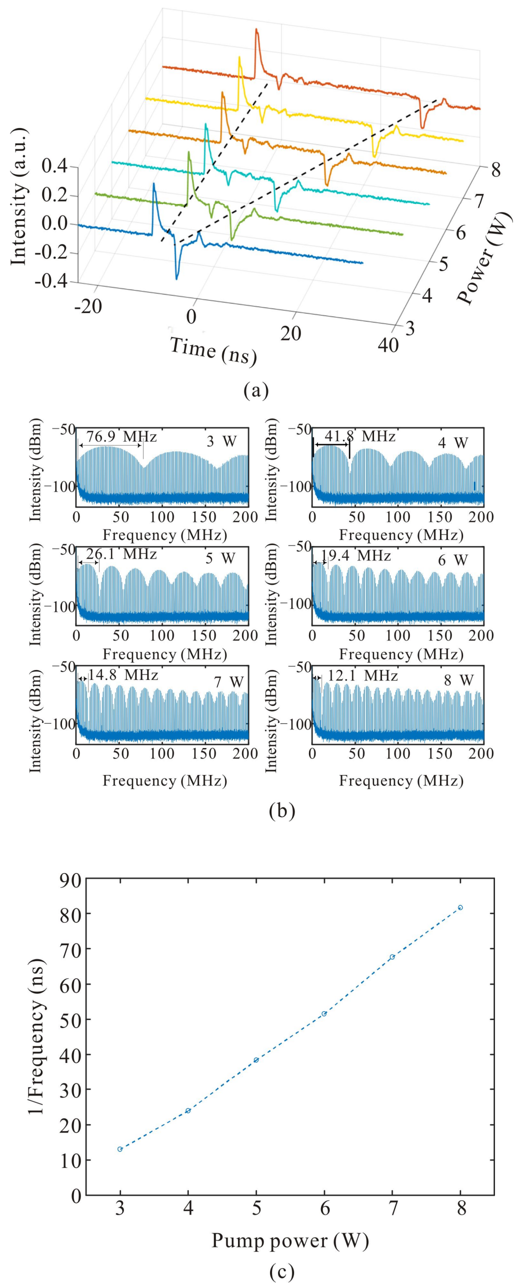


Fig.3 Characteristics of multi-wavelength bright-dark pulse at the pump power of 3 W: (a) Oscilloscope trace (Inset is the corresponding pulse train); (b) Optical spectrum

A stable multi-wavelength bright-dark pulse can be obtained by adjusting the pump power to 3 W. As can be seen in Fig.3(a), the duration of bright and dark pulses is 4 ns and 3.8 ns respectively at the pump power of 3 W. The pulse shapes and amplitudes of the bright pulse and dark pulses are slightly different. It can be found that there is also a bright pulse with low intensity to the right of the dark pulse, which is similar to the case in Ref.[25]. When the bright and dark pulses propagate together along the fiber, they shift their carrier frequencies to equalize their group velocities, and the generation of the pairs may be mainly attributed to the cross-phase modulation (XPM) between the bright and dark pulses[26]. In view of the characteristics illustrated in the inset of Fig.3(a), we argue that the interval between adjacent pulses is 0.96 μs, corresponding to the fundamental repetition rate of 1.041 MHz, which matches with the ~197 m cavity length. The optical spectrum shown in Fig.3(b) presents 10 wavelengths in the spectral range and the spectral bandwidth is 7.75 nm. The formation of the multi-wavelength may be attributed to the intensity-dependent loss induced by the NALM[27]. Moreover, the autocorrelation trace of the multi-wavelength bright-dark pulse is not observed by using the autocorrelator, which is similar to previous report[28]. The phenomenon may be caused by an inherent feature of bright-dark pulse in fiber laser.

To further investigate the characteristics of the generated multi-wavelength bright-dark pulse, the evolutionary characteristics and RF spectrum at the fundamental frequency are measured, as shown in Fig.4. Fixing the PCs, a split multi-wavelength bright-dark pulse is generated when the pump power is gradually increased from 3 W to 8 W. In Fig.4(a), the dark pulse splits into two dark pulses. One is a high-intensity dark pulse, and the other is a low-intensity dark pulse. As the pump power increases, the high-intensity dark pulse gradually moves away from the bright pulse, and its intensity gradually decreases. Meanwhile, the intensity of the low-intensity dark pulse remains unchanged. This process is repeatable and reversible, which implies that the evolution of bright-dark pulse in our laser is precisely and solely controlled by the pump power. We can understand the origin of the splitting phenomenon of bright-dark pulse as follows. When the laser operates in large anomalous dispersion regime, the bright pulse can transmit stably. Under the influence of gain, the peak power and nonlinear effect increase, so that the dark pulse is broadened and split. Moreover, due to the intrinsic modulation instability caused by XPM, the higher laser gain induced by the increase in the launched pump power, which may disturb the balance between the laser parameters (dispersion, loss, gain, etc.) that maintain the stability of bright and dark pulses[23]. Therefore, at a higher pump power level, the splitting phenomenon of bright-dark pulse might occur. Note that the similar phenomenon of the split multi-wavelength bright-dark pulse can also be obtained by adjusting the settings of PCs. Thus, the polarization states of the laser modes in the cavity at high pump power may have significant effects on the pulse operation. It is found that the features of the bright-dark pulse sensitively depended on the cavity birefringence and pump power. Compared with Ref.[23] and Ref.[24], the split multi-wavelength bright-dark pulse observed in our experiment has a distinct evolutionary characteristic that time interval between the bright and dark pulses increases approximately linearly with increase of pump power. Fig.4(b) shows the RF spectral distribution with a resolution bandwidth (*RBW*) of 1 kHz and a span of 200 MHz under different pump powers. Interestingly, it can be clearly distinguished that there is a remarkable phenomenon of envelope modulation. The corresponding modulation frequency is approximately equivalent to the reciprocal of time interval between the bright and dark pulses. This modulation phenomenon is similar to that of the RF spectrum in dissipative soliton resonance (DSR) fiber lasers[29] due to the fact that the pulses are all broadened in the time domain. The reciprocal of modulation frequency varies with pump power, as shown in Fig.4(c). The reciprocal of the modulation frequency increases linearly with pump power, which means that the modulation frequency decreases linearly from 76.9 MHz to 12.1 MHz with the increase of pump power. Meanwhile, in order to evaluate the stability of the fiber laser, the RF spectrum is measured with an *RBW* of 300 Hz at the pump power of 8 W, as shown in Fig.4(d). The pulse repetition frequency is 1.041 MHz and the signal-to-noise ratio (*SNR*) is ~40 dB. The results indicate that the operation state of the split multi-wavelength bright-dark pulse is stable.

The variation of the output optical spectrum for the multi-wavelength bright-dark pulse is presented in Fig.5. The optical spectrum analyzer is used to measure the evolution of the laser output spectrum at different pumping powers, as shown in Fig.5(a). As the pump power increases from 3 W to 8 W, the optical spectrum shows a multi-wavelength operation within a broader spectral region and the spectral intensity increases gradually. In addition, the central wavelength of the spectrum does not change significantly. The slight broadening of the spectrum is due to the self-phase modulation (SPM) effect in the cavity. It is worth mentioning that the number of wavelengths increases from 10 to 13. This is due to the different gain values for different wavelengths, i.e. the result of the non-flat gain curve of the TDF, giving each laser wavelength a different laser threshold[30]. Since we don't have a suitable filter, we can't accurately filter on the wavelength. Therefore, the specific relationship between multi-wavelength and bright-dark pulses is not clear and needs further theoretical and experimental research. To evaluate the spectral stability of the multi-wavelength bright-dark pulse in the TDFL, the spectrum is measured every 10 min at the maximum pump power of 8 W. Fig.5(b) depicts the spectral stability within 1 h. The spectral fluctuation is small, inferring that the spectral stability is good in the long term. We also experimentally study the polarization characteristics of multi-wavelength bright-dark pulse by using a polarization beam splitter (PBS), and find that the spectra and time domain features are independent of two orthogonal polarization states. Thus, the bright-dark pulse can co-exist in any polarization state, similar to the result in Ref.[31] and Ref.[32].



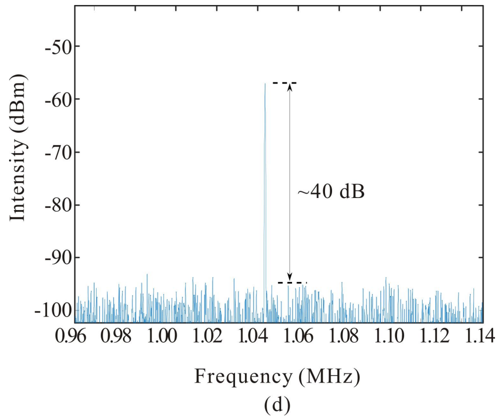


Fig.4 Properties of bright-dark pulse: (a) Evolution of the multi-wavelength bright-dark pulse under different pump powers; (b) RF spectra with a span range of 200 MHz under different pump powers; (c) Reciprocal of modulation frequency variation with pump power; (d) RF spectrum at the fundamental frequency

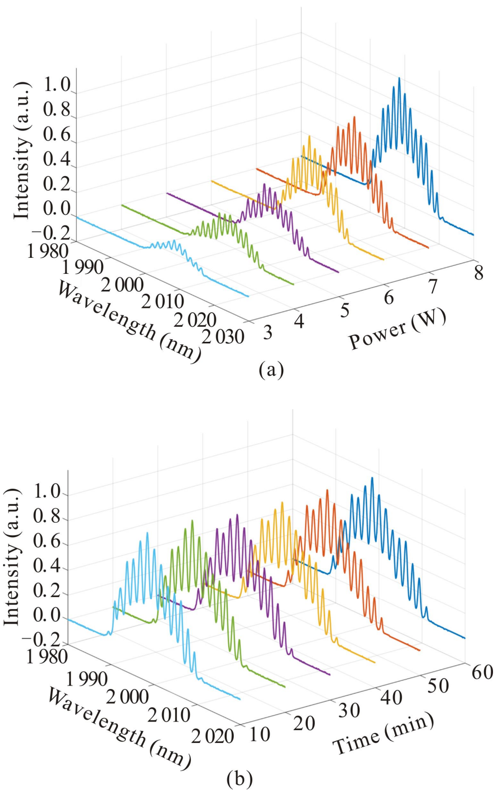


Fig.5 Variation of the output optical spectra: (a) Evolution of output spectrum with pump power; (b) Spectral stability within 1 h

In conclusion, we experimentally observed the evolving phenomenon of a split multi-wavelength bright-dark pulse in a mode-locked TDFL. The duration of bright and dark pulses is 4 ns and 3.8 ns, respectively. When the pump power is further increased from 3 W to 8 W, the dark pulse gradually moves away from the bright pulse by adjusting the pump power. Moreover, the same evolutionary phenomenon can also be observed by adjusting the PC. Simultaneously, the corresponding RF spectrum of the split multi-wavelength bright-dark pulse has a remarkable phenomenon of envelope modulation, and its modulation frequency is approximately equivalent to the reciprocal of time interval between the bright and dark pulses. These results can be useful for further theoretical studies on nonlinear dynamics of a multi-wavelength bright-dark pulse in passively mode-locked fiber lasers.

Statements and Declarations

The authors declare that there are no conflicts of interest related to this article.

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