L-band mode-locked fiber laser delivering adjustable bright and dark pulses with erbium zirconia yttria aluminum co-doped fiber

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We demonstrate the generation of adjustable bright and dark pulses from Erbium Zirconia Yttria Aluminum co-doped fiber (Zr-EDF) incorporated fiber ring laser with net anomalous dispersion. The fiber enhances the birefringence and nonlinearity of the laser cavity to produce a mode-locked pulse train operating at a relatively low pump threshold of 70 mW. Domain-wall dark pulses repeated at the fundamental cavity frequency is observed by adjusting the intra-cavity polarization state. The pulse repetition rate was maintained at 14.1 MHz throughout the dark pulse operation. It operates at 1601 nm with the pulse energy of 14.2 pJ at pump power of 70 mW. Besides, the dark pulse operation was demonstrated at high stability with SNR of 33 dB.

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1. Introduction

Dark pulse operation of lasers has attracted considerable attention in recent years with respect to bright pulses because of their potential applications [1-4]. Dark pulses are defined as a train of intensity dips in the intensity of a continuous wave (CW) background of the laser emission. Numerical simulations have found that dark pulses are less sensitive to fiber loss and more stable in the presence of noise compared with bright pulses, which have potential applications in fiber based communication system [5-6]. To date, there have been many approaches for the generation of dark pulse trains. Most of these methods are based on external manipulation of laser light using pulse shaping techniques, such as direct modulation of CW light by means of a phase modulated fiber loop mirror [7] or a phase modulated Mach–Zehnder interferometer [8], and passive filtering of a mode locked bright pulse train with a fiber Bragg grating or a spatial mask [9].

The dark pulses can be occurred in both net anomalous and net normal dispersion regimes. Its formation can be classified into two mechanism; nonlinear Schrödinger equation (NLSE) [1, 10-11] and domain-wall (DW) [12-13] type dark pulses. For instance, in the previous work, Zhang et. al. [1] reported on the NLSE dark pulse emission of an all-normal dispersion erbium-doped fiber laser (EDFL) with a 150 m dispersion compensating fiber in cavity to provide a nonlinearity. NLSE type dark pulse exhibits single peak profile and its formation relies on the change of linear refractive index coefficient in the normal dispersion cavity. On the other hand, the fundamental concept of DW dark pulse is based on two or more lasers in different wavelengths oscillating and causing the topological defects in temporal domain. The generation of DW type dark pulse can be either in normal or anomalous dispersion cavity and the pulse exhibits multiple peak profile. In net anomalous dispersion regime, dark pulses are produced when two lasing beams originated from two-Eigen operation states of fiber lasers are coupled incoherently with each other [12]. Such two-Eigen operation states of lasers can be achieved by managing either the two orthogonal polarization states of the lasers or two separated wavelengths induced by intra-cavity birefringent filter [14]. The produced two light beams are coupled through the nonlinear effect of optical fibers, and the lasers typically require the pump threshold for formation of dark pulse to be around 100 mW [15-16]. In order to further enhance the cross-coupling effect between the two lasing beams and make the dark pulse generation easily, a medium with high nonlinearity is required.

In this paper, we report the experimental observation of bright and dark pulse generations in a dispersion managed Zr-EDFL cavity with net anomalous cavity GVD. The passively mode-locked operation of the fiber laser is achieved by employing the nonlinear polarization rotation technique. With the help of large Kerr nonlinearity in the Zr-EDF, mode-locking pulses are generated from the dispersion managed fiber laser at a relatively low pump threshold of 70 mW. The bright and dark pulses operating at the fundamental cavity frequency can be obtained by adjusting the polarization state of laser cavity. It was also experimentally found that the bright and dark pulses are formed mainly due to the cross coupling between two-Eigen operation states of fiber laser through the nonlinear effects of optical fibers. Compared to the previous work of ref. [1], an additional nonlinear fiber is not required in the proposed laser. The dark pulse is produced in net anomalous dispersion cavity and thus it is classified as a DW type.

2. Experimental setup

Fig. 1 shows the configuration of the proposed dispersion managed fiber laser. The fiber laser has a ring cavity of about 14.5m long consisting of a 980/1550 nm wavelength division multiplexer (WDM), Zr-EDF, polarization controller (PC), 10 dB coupler and a polarization dependent isolator (PDI). The laser cavity consists of three types of fibers: 3.0 m long Zr-EDF with a GVD parameter of about -56 ps^2/km, 3.0 m long WDM fiber with a GVD of -38 ps^2/km and 8.5 m long standard single-mode fiber (SMF) with a GVD of -21 ps^2/km. The net cavity dispersion was estimated to be -0.4605 ps^2 at 1600 nm wavelength. Apart from assuring unidirectional operation, the PDI also provides spectral filtering effect by combining with the intra-cavity birefringence. PC was used to adjust the polarization of light in the cavity and switched the operation of the mode-locked laser from bright to dark pulse regime. The gain medium, Zr-EDF was pumped by a 980 nm laser diode (LD) through a WDM. Since all of the fibers are fastened to an optical table to prevent any movement, the fiber laser operates in a stable passive mode-locking regime. The laser output is taken out via a 10 dB fiber coupler while allowing 90% of the light to oscillate in the ring cavity. The pump power and average output power were measured by a photodiode power meter. The monitoring of the output spectra and pulse trains was performed using an optical spectrum analyzer (OSA) with a minimum resolution of 0.02 nm and a 500 MHz digital phosphor oscilloscope.

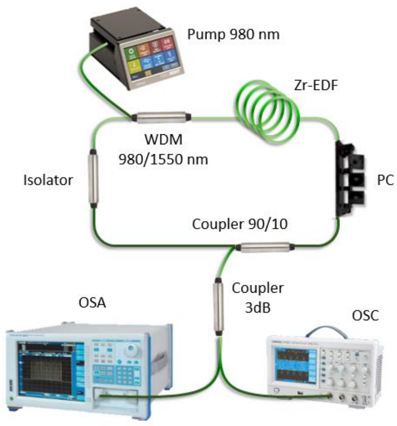

Fig. 1. Experimental setup

3. Results and discussion

Generally, the utilized Zr-EDF has a very large doping concentration, which caused lasing at near 1600 nm. The Erbium ion concentration of the Zr-EDF is estimated to be more than 5000 ppm. From this cavity, continuous wave lasing started at ~55 mW of pump power. This pump threshold is higher than that in a typical C-band fiber laser; this was associated with the much lower gain in the L-band. When the pump power continuously increased up to 70 mW, self-starting single pulse mode locking could be observed with an average output power of ~0.2 mW. The performance of the laser is maintained up to the pump power of 105 mW. The oscilloscope trace of the output pulse train is plotted in Fig. 2 (a). It shows that bright pulses are circulating in the cavity with a round-trip time of 70.9 ns which is corresponding to the cavity fundamental frequency of 14.1 MHz. The pulse repetition rate frequency was approximately defined by the cavity length of ~14.5 m.

By adjusting the polarization state of the oscillating light with a PC, dark pulses are found to circulate in the cavity repeated at the same frequency as shown in Fig. 2(b), indicating that the laser operating is shifted from the bright to the dark regime. Fig. 3 compares the typical measured output spectrum for both bright and dark pulse train. It shows a central wavelength at ~1601 nm and 3 dB bandwidth of 0.1 nm, falling in the L-band of the third telecommunication window. The output powers for both main laser and the secondary wavelength component are increased as indicated in the output optical spectrum of the dark pulse as shown in Fig. 3. Due to the significant output power for the secondary laser at around 1601.9 nm, we expect that the generation of dark pulse in the proposed cavity is based on dual wavelength DW, which was achieved under the optimum polarization orientation.

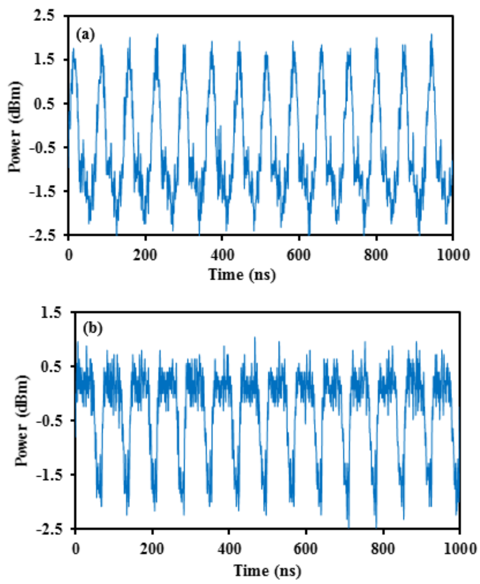

Fig. 2. Typical oscilloscope trace of the mode-locked Zr-EDFL when emitting (a) bright (b) dark pulse train at pump power of 70 mW

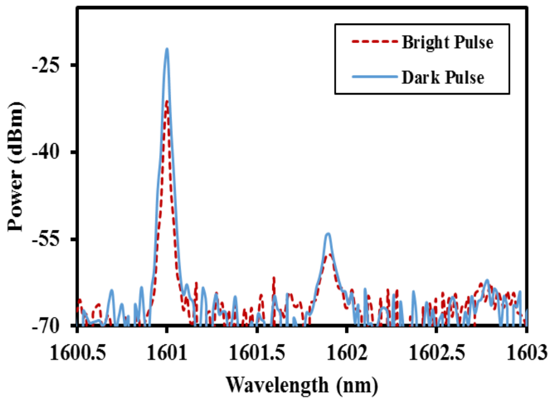

Fig. 3. Output spectra obtained during the bright and dark pulse generation

The incorporation of a PDI and the slightly residual polarization asymmetry of the used components in the cavity can cause the formation of a linear artificial birefringent filter. The existence of the artificial birefringent filter can result in the multi-wavelength within the effective laser gain bandwidth. At the optimized polarization rotation and sufficient pump power, the cross-phase coupling between the dual-wavelength emission is subsequently enhanced that could form the narrow intensity dip in the strong CW laser emission background as shown in Fig. 2(b). The pulse width is measured to be around 27.8 and 27.1 ns for the bright and dark pulse, respectively. The pulse energy of the dark pulse is estimated to be around 14.2 pJ at pump power of 70 mW. The long term stability of the laser is good since the pulse is stable for at least 24 hours. Fig. 4 shows the Radio Frequency (RF) spectrum of the dark pulse at the pump power of 70 mW. The signal to noise ratio (SNR) of the laser is around 33 dB, which indicates that the laser is operating in a stable condition. Even though there are two operating wavelengths in the cavity, only a single frequency component is observed, which confirms a typical DW operation whereby the mutual coupling of two wavelengths generates a single frequency component. In the experiment, the transformation of bright pulse into dark pulse can be reversed by adjusting the PC.

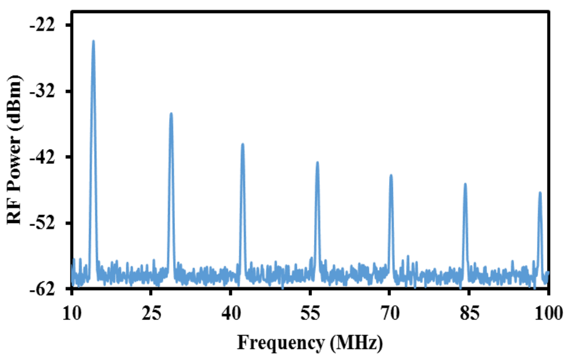

Fig. 4. DW dark pulse RF spectrum of the proposed laser at pump power of 70 mW

4. Conclusion

We have demonstrated the generation of bright and dark pulses from a Zr-EDF incorporated fiber ring laser for the first time. With the help of the high Erbium concentration and nonlinearity from the active fiber, bright and dark pulse emission could be observed at relatively low threshold pump strength (70 mW). The transformation of bright pulse into dark pulse can be obtained by adjusting the intra-cavity polarization state using a PC. DW dark pulses repeated at the cavity fundamental rate of 14.1 MHz was obtained with high SNR of 33 dB. It produces a pulse energy of 14.2 pJ at pump power of 70 mW.

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References

[1] H. Zhang, D. Y. Tang, L. M. Zhao, X. Wu, Phys. Rev. A **80**(4), 045803 (2009).
[2] J. Wu, F. Luo, Z. Yu, Q. Tao, Optoelectron. Adv. Mat. **2**(8), 466 (2008).
[3] A. Biswas, K. R. Khan, A. Rahman, A. Yildirim, T. Hayat, O. M. Aldossary, J. Optoelectron. Adv. M. **14**(7), 571 (2012).
[4] J. B. Schröder, S. Coen, T. Sylvestre, B. J. Eggleton, Opt. Express **18**(22), 22715 (2010).
[5] W. Zhao, E. Bourkoff, J. Opt. Soc. Am. B **9**(7), 1134 (1992).
[6] C. Milián, D. V. Skryabin, A. Ferrando, Opt. Lett. **34**(14), 2096 (2009).
[7] O. G. Okhotnikov, F. M. Araujo, Electron. Lett. **31**(25), 2197 (1995).
[8] M. Haelterman, P. Emplit, Electron. Lett. **29**(4), 356 (1993).
[9] H. Yin, W. Xu, A. Luo, Z. Luo, J. Liu, Opt. Commun. **283**, 4338 (2010).
[10] D. Y. Tang, L. Li, Y. F. Song, L. M. Zhao, H. Zhang, D. Y. Shen, Phys. Rev. A **88**, 013849 (2013).
[11] Z. C. Tiu, A. Zarei, S. J. Tan, H. Ahmad, S. W. Harun, Chin. Phys. Lett. **32**, 034203 (2015).
[12] H. Zhang, D. Tang, L. Zhao, X. Wu, Opt. Express **19**(4), 3525 (2011).
[13] L. Y. Wang, W. C. Xu, Z. C. Luo, W. J. Cao, A. P. Luo, J. L. Dong, H. Y. Wang, Opt. Commun. **285**(8), 2113 (2012).
[14] Q. Y. Ning, S. K. Wang, A. P. Luo, Z. B. Lin, Z. C. Luo, W. C. Xu, IEEE Photon. J. **4**(5), 1647 (2012).
[15] X. Wang, P. Zhou, X. Wang, H. Xiao, Z. Liu, Appl. Phys. Express **7**(2), 022704 (2014).
[16] J. Zhao, P. Yan, S. C. Ruan, Appl. Opt. **52**(35), 8465 (2013).

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