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A harmonically mode-locked dark soliton and bright–dark soliton pair ytterbium fiber laser

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Received 28 January 2016, revised 22 March 2016 Accepted for publication 1 April 2016 Published 6 May 2016

Abstract

We report on an experimental study of a dark soliton and bright–dark soliton pair, harmonically mode-locked, all normal dispersion (ANDi) ytterbium fiber laser with a long cavity length. Mode-locked output up to the fourth harmonic with respect to the fundamental repetition rate has been realized. To the best of our knowledge, this the first such demonstration so far in ANDi mode-locked ytterbium fiber lasers with a birefringence filter as spectral modulation component. The experimentally recorded mode-locked spectrum shows that the generation of a dark soliton is always accompanied by strong continuous-wave emission. Furthermore, by changing the pump power, the fundamental bright–dark soliton pair mode-locked operation can be evolved into the state of the second order bright soliton coexisting with the fundamental dark soliton. Additionally, bright–dark soliton pairs, which are symmetric relative to the vertical coordinate, can be interconverted by rotating waveplates in a fixed maximum pump power condition. The generation of the dark pulse is probably due to the large normal dispersion introduced in the ring cavity except for the nonlinearity.

Keywords: all normal dispersion, dark soliton mode-locking, harmonic mode-locking

(Some figures may appear in colour only in the online journal)

1. Introduction

With the development of laser technology, mode-locked fiber lasers have advanced from the stages of negative dispersion [1] and net positive dispersion [2, 3] to all normal dispersion (ANDi) fiber lasers [4]. In contrast to other laser oscillators, mode-locked ANDi ytterbium fiber lasers have been subject to significant progress in both power scaling and energy improvement [5, 6] and thus attracted greater attention. Apart from dissipative pulse shaping mechanism assisted modelocking, various novel experimental results have been reported in ANDi fiber lasers, such as multi-wavelength dissipative soliton generation [7] and dissipative soliton resonance modelocked operation [8, 9]. For the references cited above [1–9], all of these can be classified as bright soliton mode-locking in some sense. However, dark soliton mode-locked operation has also been realized in Er- and Yb-doped ANDi fiber lasers in the past few years [10, 11].

In contrast to the conventional bright soliton, a dark soliton is concomitant with an intensity dip in the uniform continuous-wave background and can form in the normal group velocity dispersion (GVD) regime of fibers [12]. For a dark soliton with normal GVD, due to reversed self-phase modulation (SPM), the combined effects of normal GVD and negative SPM make the dark pulse propagate with its original profile without any pulse broadening [13]. In this paper, we experimentally explore the generation of harmonically mode-locked dark pulses and bright–dark soliton pairs and the transformation between symmetric bright–dark soliton pairs in an ANDi ytterbium fiber laser with a birefringent plate as



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spectral modulation component. On the one hand this is of great significance for further fundamental studies of physical phenomena in ANDi fiber lasers and on the other hand it is of great value with respect to applications in the field of optical communication.

2. Experiment and discussion

The harmonically mode-locked dark soliton and bright–dark soliton pair ANDi ytterbium fiber laser is schematically shown in figure 1.

A pump laser with 611 mW maximum output power is used to pump the 40 cm long ytterbium doped gain fiber. A wavelength division multiplexer (WDM) ensures stable laser oscillation. A birefringent plate at Brewster's angle, located between the polarization beam splitter (PBS) and polarization-dependent isolator (PD-ISO), is introduced as a spectral modulation component with an 8 nm spectral bandwidth. Based on the dissipative mechanism and nonlinear polarization rotation (NPR) mode-locked technology, stable modelocked operation is possible and the PBS is used as an output port in the experimental set-up. For stable mode-locked operation, the fundamental repetition rate is approximately 976 kHz and the GVD introduced into the cavity is approximately 4.4 ps².



Figure 1. Schematic of the dark soliton related ANDi mode-locked fiber laser. LD: laser diode; WDM: wavelength division multiplexer; CO: fiber collimator; PBS: polarization beam splitter; BPF: birefringent filter; PD-ISO: polarization-dependent isolator.

In continuous-wave operation, the output wavelength is centered at 1035 nm. By adjusting the orientations of the waveplates, conventional bright soliton mode-locked operation can be realized, provided that the proper and the optimum pump power are both between 60 mW and 100 mW. As the pump power exceeds 100 mW, self-starting single bright soliton mode-locked operation is relatively difficult to achieve due to the accumulation of the nonlinear phase and the resulting pulse splitting. Figure 2 shows the corresponding single bright soliton mode-locked spectrum and the pulse train on an oscilloscope.

Increasing the pump power up to 200 mW, stable dark soliton mode-locked operation is realized by adjusting the orientations of the waveplates. Figure 3 shows the dark soliton mode-locked experimental results. In addition to the relevant mode-locked spectrum centered at 1047.8 nm, a continuous-wave spectrum also exists, in accordance with the reproducible experimental observations in dark soliton modelocked operation, as shown in figure 3(a). We conclude that the generation of the dark pulse related mode-locked operation in the experiment is a narrow spectral mode-locked state existing in the continuous-wave background, no matter whether it is dark soliton or bright-dark soliton pair harmonically mode-locked operation. For both types of operation, the spectra of both the continuous-wave and mode-locked laser coexist. However, the spectral intensity of the dark soliton is either lower or higher than that of continuous-wave operation. Figure 3(d) shows the linear increase in output power of the fundamental dark soliton mode-locking with increasing pump power. By increasing the pump power, the single dark soliton mode-locked output power boost from 84 mW to 328 mW while mode-locked operation turns out to be stable without any additional adjustment.

By rotating the orientations of the waveplates and the birefringence filter under the constant maximum pump power of 611 mW, the fundamental mode-locked dark soliton pulses gradually split into higher order harmonically mode-locked dark solitons and bright–dark soliton pairs as shown in figures 4 and 5. For the latter types of mode-locked operation, the characteristics of the output spectra are similar to those of the single dark soliton mode-locked pulses.



Figure 2. Single bright soliton mode-locked spectrum (a) and pulse train (b) measured from the output port of the PBS.



Figure 3. Fundamental dark soliton mode-locked results. (a) Measured mode-locked spectrum at the output port of the PBS. (b) RF spectrum with 1 kHz resolution. (c) Pulse train on an oscilloscope. (d) Pump power dependence of the output power. T_R stands for the cavity round-trip time period. The inset in (a) shows the output spectrum in continuous-wave operation.



Figure 4. Oscilloscope pulse trains corresponding to the second (a), third (b) and fourth (c) order harmonically mode-locked dark soliton operation.



Figure 5. (a) Fundamental bright–dark soliton pair mode-locked oscilloscope pulse train. (b), (c), and (d) show the second, third and fourth order harmonically mode-locked bright–dark soliton pair concomitant mode-locked pulse trains, respectively.

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Figure 6. Formation process of the second order harmonically modelocked bright soliton coexisting with the fundamental dark soliton pulse, triggered by increasing the pump power.

Increasing the pump power to 611 mW, the fundamental bright–dark soliton pair mode-locked operation, which corresponds to a pump power of less than 418 mW, gradually evolves into the second order bright soliton mode-locked operation coexiting with the fundamental dark soliton mode-

Figure 7. Measured spectrum at the output port of the PBS corresponding to the mode-locked state of figure 6.

locking and vice versa. To the best of our knowledge, the mentioned mode-locked operation is realized for the first time in an ANDi fiber laser. The formation process of the second order harmonically mode-locked bright soliton coexisting with the fundamental dark pulse resulting from bright–dark soliton pair mode-locked operation is shown in figure 6.



Figure 8. Evolution process between both different symmetrical bright–dark soliton pair mode-locked operation.

During the entire evolution, the mode-locked spectrum does not change, as shown in figure 7.

Figure 8 shows the evolution between both different bright–dark soliton pair mode-locked operations symmetrical relative to the vertical coordinate by accurately adjusting the waveplates under the pump power of 611 mW. The upper right bright soliton, as shown in figure 8(a), gradually moves backwards and combines with the following bottom left dark soliton, as shown in figures 8(b) and (c), and a final symmetric relative to the vertical coordinate bright–dark soliton pair mode-locked state occurs, as shown in figure 8(d). Namely, the state of the mode-locked bright–dark soliton can be tunable from the initial modes of the bottom left dark pulse and upper right bright pulse to that of the upper left bright pulse and bottom right dark pulse. The reversible tuning also works.

These new types of mode-locked operation demonstrated in an ANDi fiber laser with a birefringence filter as modulation component have remarkable value for both physical research and practical applications. Based on the experimental observations, we attribute the occurrence of dark pulse relevant mode-locked types of operation to the large amount of normal dispersion and accumulated nonlinearity.

3. Conclusion

In conclusion, various dark soliton related types of modelocked operation have been realized in a NPR based long cavity ANDi fiber laser with a birefringence filter as spectral modulation component. Single dark soliton mode-locked operation, harmonically mode-locked dark soliton and brightdark soliton pair operation, a second order harmonically mode-locked bright soliton coexisting with the fundamental dark pulse and interconversion between symmetric brightdark soliton pairs have been discussed in detail. The demonstration of various dark soliton related mode-locked operations can both improve the understanding of ANDi dissipative soliton mode-locking and motivate the exploration of novel experimental phenomena in order to promote the further development of fundamental science and laser technology.

Acknowledgments

This work is partly supported by the National Key Technology R&D Program of the Ministry of Science and Technology under Grant No. 2012BAC23B03, the National Key Basic Research Program of China under Grant No.2013CB922401 and National Natural Science Foundation of China under Grants No. 11474002.

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