Stabilize the Regeneratively Mode-Locked Fiber Laser based on a Polarization Maintained Dual-loop Structure

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Abstract: A novel stable regeneratively mode-locked fiber laser based on a polarization maintained dual-loop structure is proposed. Stable 10-GHz optical pulse train is successfully generated with a side-mode suppression ratio of 58.4 dB being simultaneously realized.

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1. Introduction

Active mode-locking is an attractive technique to generate ultra-short optical pulses with high quality for the future ultrahigh-speed optical communication application because of the production of a transform-limited, picosecond pulse train with a repetition rate of 10 GHz and higher [1, 2]. Among these, a regeneratively mode-locked fiber laser (RMLFL) realizes relative stable operation by achieving synchronization between the modulator driver and the laser through the regeneratively mode locking technique, where the modulated signal is derived from the detected intensity modulation of the pulse train itself [3]. However, it usually suffers from the instability of the state of polarization (SOP). To improve the stability, an all polarization maintain fiber based structure can be used [4], or a Fabry Perot laser diode is inserted in the ring [5]. In [6], an \( \sigma \)-type configuration with a Faraday rotating mirror (FRM) and a polarization beam splitter (PBS) to cancel the polarization fluctuation is realized based on the round trip propagation with 90° rotation by the FRM. On the other hand, an optoelectronic oscillator (OEO) in the optoelectronic loop is usually used to force the fiber laser into actively mode-locked operation [7]. However, the long cavity leads to many closely spaced modes in the oscillation signal, resulting in a poor side-mode suppression ratio (SMSR) and undesirable mode hopping, which make the system unstable. A length of unpumped erbium-doped fiber is inserted in the mode-locked laser loop to suppress the undesirable longitudinal modes near the lasing wavelength [7]. However, the SOP maintaining is not realized.

In this paper, a novel stable RMLFL scheme using a polarization maintained dual-loop structure is proposed and demonstrated. The polarization maintained dual-loop structure in the fiber laser loop is used to stabilize the SOP and suppress the side modes simultaneously. Stable 10-GHz transform limited pulse train is successfully generated and a SMSR as high as 58.4 dB is realized for the modulated output.

2. Principle

The schematic diagram of the proposed stable RMLFL is shown in Fig. 1. In the scheme, the output of the intensity modulator (IM) is followed by an optical coupler (OC, OC1) to form two feedback loops, i.e., the OEO and the regeneratively mode-locked fiber laser. In the OEO loop, the output of OC1 is connected by a photodetector (PD), filtered by an electrical bandpass filter (EBFP), amplified by an electrical amplifier (EA), and then finally sent to the RF port of the IM to form a positive feedback. The fiber laser ring shares the IM with the OEO, which acts as an optical mode-locking element. In the fiber laser loop, the other output of OC1 is followed by an optical filter (OF), an erbium-doped fiber amplifier (EDFA), a tunable optical delay-line (TODL) and a polarization maintained dual-loop structure. The EDFA is used to supply the gain of the loop. The TODL is used to adjust the cavity length.

The polarization maintained dual-loop structure is consisted of a PBS, two paths with one including a polarization state 90° rotation device, and a polarization maintained OC (OC2). The output of the TODL is splitted into two paths with orthogonal polarization states through the PBS. Then in the path including a polarization state 90° rotation device, the polarization state is rotated by 90° to be consistent with that in the other path. The polarization maintained OC2 is used to combine the two paths. In this way, the polarization state in the loop of the regeneratively mode-locked fiber laser is maintained to realize the stability of the optical pulse generation. In addition, the dual-loop structure effectively suppresses the side modes. Thus by using the polarization maintained dual-loop structure, the polarization state is maintained in the loop simultaneously with the effective suppression of the side modes, which both make the regeneratively mode-locked fiber laser system stable. Additionally, the structure is simple and robust to the environment variation.
3. Experimental Results and Discussions

An experiment based on the setup shown in Fig. 1 is demonstrated and analyzed. The IM (FTM7938EZ) has a 3-dB working bandwidth of 40 GHz; the PD has a 3-dB bandwidth of 10 GHz and a responsivity of 0.88 A/W; the gain of the EA is 40 dB with a working bandwidth of 8-18 GHz; the EBPF has a 3-dB bandwidth of 11.8 MHz centered at 10.664 GHz. The optical spectra are measured by an optical spectrum analyzer (OSA, AQ6370C) with resolution of 0.02 nm. A signal analyzer (ROHDE & SCHWARZ FSV-40) and a digital sampling oscilloscope (DSO, Agilent 86100C with module 86116C) are also engaged to observe the generated optical pulses and the microwave signals. The polarization state 90° rotation device in our experiment is realized by cascading two optical isolators, since an optical isolator rotates the polarization state by 45° based on the Faraday effect [8].

To demonstrate the stability improvement of the RMLFL by using the polarization maintained dual-loop structure, 10-GHz optical pulse trains are generated with and without the structure, respectively. For the condition without the polarization maintained dual-loop structure, a PC is inserted in the fiber laser loop before the IM. Fig. 2 (a) and (b) show the mode-locked laser output without and with the polarization maintained dual-loop structure, respectively. The amplitude jitters of the optical pulse due to the polarization variation in the loop are removed by using the polarization maintained dual-loop structure. The corresponding optical spectrum with the polarization maintained dual-loop structure is shown in Fig. 2 (c). As can be seen, the 3-dB spectral bandwidth is 0.18 nm. Considering the 19.8-ps FWHM (full width at half maximum) of the optical pulse shown in Fig. 2 (b), a time-bandwidth product of 0.45 is realized. A nearly Gaussian transform limited pulse is realized.

Fig. 3 (a) and (b) show the eye diagram and the electrical spectra of the 10.66-GHz microwave signal generated in the OEO loop with the polarization maintained dual-loop structure. As comparison, the eye diagram and the electrical spectra of generated microwave signal without the structure are shown in Fig. 3 (c) - (e). As can be seen, the polarization maintained dual-loop structure improves the eye diagram performance and reduces time jitters by stabilizing the polarization state in the fiber laser loop and suppressing the side modes. A SMSR of 58.4 dB is achieved with the use of polarization maintained dual-loop structure, as shown in Fig. 3 (a). Without the polarization maintained dual-loop structure, the SMSR is only around 37 dB, and mode hopping easily happens, with the spectra shown in Fig. 3 (d) and (e), which show the mode hopping between the frequency of 10.669 GHz and 10.665 GHz. Thus the polarization maintained dual-loop structure stabilizes the polarization state in the fiber laser cavity simultaneously with the great improvement of the SMSR for the modulated output.

Fig. 1. The schematic diagram of the RMLFL based on a polarization maintained dual-loop structure. IM: intensity modulator; OF: optical filter; EDFA: erbium-doped fiber amplifier; OC: optical coupler; TODL: tunable optical delay-line; PD: photodetector; EBPF: electronic bandpass filter; EA: electrical amplifier; PBS: polarization beam splitter; OI: optical isolator.
Fig. 3. (a) Eye diagram and (b) electrical spectrum of the 10.66-GHz microwave signal generated in the OEO loop with the polarization maintained dual-loop structure; (c) Eye diagram and (d) (e) the electrical spectra of the generated microwave signal without the polarization maintained dual-loop structure.

4. Conclusion

Stable pulse trains generation with greatly improved SMSR from a RMLFL by using a polarization maintained dual-loop structure is proposed and experimentally demonstrated. The polarization maintained dual-loop structure stabilizes the polarization state in the fiber laser loop and suppresses the side modes simultaneously. 10-GHz stable optical pulse train is successfully generated and a SMSR as high as 58.4 dB is realized for the modulated output. The proposed configuration can find applications in high-speed optical communication and optical signal processing.

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References


