Ultra-broadband Bidirectional Dual-Comb Fiber Laser with Carrier Envelope Offset Frequency Stabilization

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1. Introduction

Dual-comb spectroscopy techniques are superior to a conventional Fourier transform spectroscopy in terms of the acquisition time, sensitivity, and resolution. Owing to its excellent capabilities, it has been applied to several useful applications. The conventional dual-comb system employs two independent mode-locked lasers for the generation of two optical frequency combs (OFCs) with slightly different repetition rates (Δf_{rep}), and a complex servo system for high mutual coherence were needed. Despite the capabilities of dual-comb spectroscopy, the use of the dual-comb technique is still mainly restricted to experts for OFC. In recent years, a dual-comb laser, which emits two OFCs from a single laser cavity with a small Δf_{rep}, has attracted attention owing to its desirable properties such as passive mutual coherence. Recently, dual-wavelength [1], bidirectional [2, 3], and polarization-multiplexed [4] mode-locked Er-fiber lasers have demonstrated as dual-comb fiber lasers. In previous works [1, 2], the demonstrated spectral bandwidth of the dual-comb fiber laser was of the order of a few nanometers. Thus, it was difficult to expand the spectral bandwidth with high coherence by nonlinear spectral broadening.

In this study, we develop a bidirectional dual-comb fiber laser that generates two high-coherence ultra-broadband OFCs spanning more than one octave with Δf_{rep}. We use a combination of saturable absorbers (SAs) and nonlinear polarization rotation (NPR) for mode-locking mechanism, which facilitates the generation of low-phase-noise OFCs. Furthermore, we can successfully generate high-coherence ultra-broadband OFCs by nonlinear spectral broadening and high-signal-to-noise-ratio (SNR) of >30 dB carrier-envelope-offset frequency (f_{ceo}) beat notes using a self-referencing technique in both directions simultaneously. Moreover, the two f_{ceo}s can be stabilized with servo systems.

2. Experimental setup and results

Figure 1(a) shows a schematic of the developed bidirectional dual-comb fiber laser. It consists of a single-mode fiber and an Er-doped fiber amplifier (EDFA), which is bidirectionally pumped by a laser diode. The two output couplers are placed symmetrically in the laser cavity for the EDFA. The counter-propagating pulses are separated via two 3-dB couplers and two 3-port circulators, and they are launched into separate SA mirrors. We installed an inline polarization controller (PC) in the laser cavity to ensure

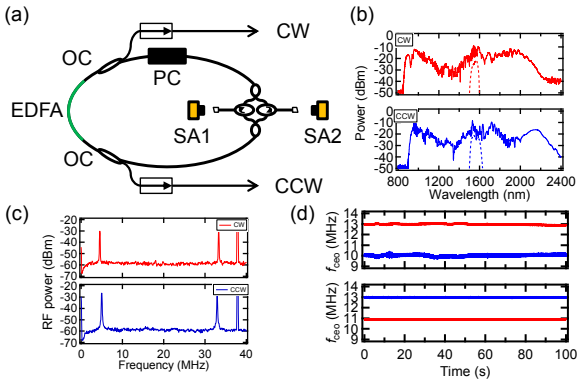

Fig.1 (a) Experimental setup. For both outputs, (b) optical spectra of supercontinuum with a HNLF, (c) f_{ceo} beat notes, and (d) temporal variation of both f_{ceo}s, upper: free-running case, lower: stabilized case.

mode-locking operation based on NPR. The two outputs from the oscillator are amplified and spectral broadened via extra-cavity EDFAs and HNLFs in both directions. As shown in Fig. 1(b), we generated a supercontinuum spanning more than one octave in both directions. From the two supercontinua, as shown in Fig. 1(c), we successfully detected f_{ceo} beat notes with the self-referencing scheme. The SNR is >30 dB at a resolution bandwidth of 100 kHz. The two f_{ceo} signals can be varied by a pump current (I), i.e., pump power, which is important for practical applications. The tuning rates (df/dI) are 0.39 and 0.86 MHz/mA for the clockwise (CW) and counter-clockwise (CCW) outputs, respectively. The f_{ceo} in CW is feedback to the pump current and the f_{ceo} in CCW is feedback to the extra-cavity Acousto-Optic modulator (AOM) via servo systems, respectively. As shown in Fig. 1(d), the two f_{ceo} signals are stabilized.

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