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 ($\Delta f_{\text{rep}}$), 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 $\Delta f_{\text{rep}}$, 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 $\Delta f_{\text{rep}}$. 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 ($f_{\text{ceo}}$) beat notes using a self-referencing technique in both directions simultaneously. Moreover, the two $f_{\text{ceo}}$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](image_url)

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