Dual-comb generation in a single laser cavity for sensing applications

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Optical frequency combs (OFCs) have transformed the landscape of modern optical metrology by enabling precise measurements at optical frequencies referenced to primary time and frequency standards [1]. A pattern of sharp, equidistant comb lines spanning large optical bandwidths can now be used as a frequency ruler across different parts of the electromagnetic spectrum ranging from the ultraviolet (UV) to terahertz (THz). To resolve individual comb teeth, and access information encoded at optical frequencies, one can employ conventional interferometric or dispersive techniques. However, one of the most elegant ways involves a pair of OFCs that asynchronously probe each on a photodetector. No moving parts are required, as the technique purely relies on optical heterodyne detection. Wideband spectral information about the optical intensity and phase is available within micro to milliseconds from periodic electrical interferograms (IFGs). This emerging technique referred to as dual-comb spectroscopy (DCS) has been widely used in a range of applications like remote sensing, combustion diagnostics or fundamental physics [2].

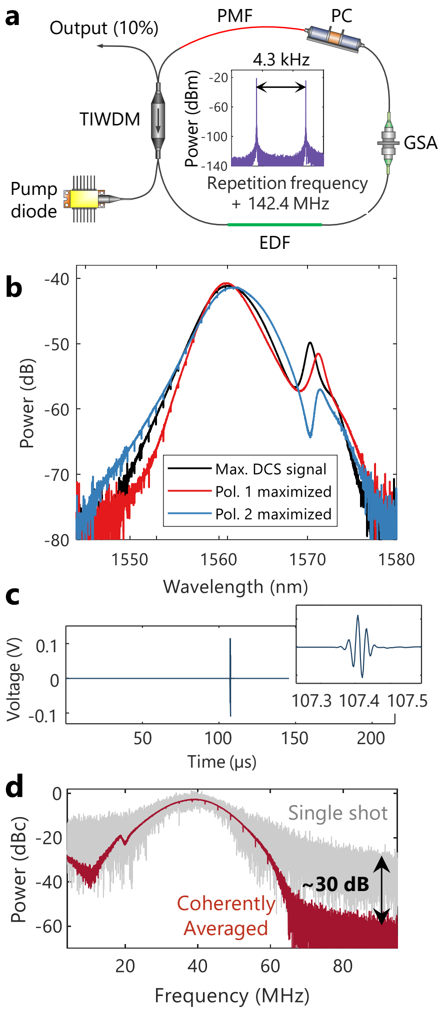

Fig. 1. (**a**) Experimental setup, (**b**) Optical spectra, (**c**) DCS interferogram, (**d**) Dual-comb spectra with HCN in the beam path in 230 μs and averaged (200 ms). See text for details.

Despite these advantages, experimental realization of DCS is still challenging. In a typical scenario, a pair of OFCs must be mutually stabilized using high-bandwidth electronic feedback loops exploiting nonlinear spectral broadening (*f*-2*f*) for retrieval of correction signals. The elegance, simplicity, and robustness for out-of-laboratory sensing is often compromised.

A remedy to this issue is dual-comb generation in a shared laser cavity. In DCS the most stringent requirement is the relative stability between the sources, which is natively provided by a pair of combs formed along the same beam path (due to common noise suppression). Among several dual-comb formation mechanisms, of particular attention is polarization multiplexing, which relies on simultaneous generation of optical pulses with orthogonal polarizations. This scheme has been adopted in our work [3].

Figure 1a shows the experimental setup comprising just a few fiber components (EDF – erbium-doped fiber, PC-polarization controller, TIWDM – hybrid component). The ring-type fiber oscillator that was mode-locked using a graphene saturable absorber (GSA) exhibits weak birefringence due to the presence of a short section of polarization-maintaining fiber (PMF). The laser supports self-starting dual-comb generation on orthogonal polarizations (Pol. 1 / Pol. 2, 5.4 nm 3-dB width, Fig. 1b) with excellent spectral overlap, and tunable repetition rates offset by 4.3 kHz (inset of Fig. 1a). When the oscillator output is guided through a polarization controller followed by a polarizing beam splitter, one can obtain a DCS IFG as shown in Fig. 1c. It is free of any spurious signals that typically plague other free-space DCS lasers. Using a dedicated phase correction algorithm [4], we coherently average thousands of DCS IFGs in post-processing to obtain mode resolved (~142 MHz / 1.16 pm) optical spectra over a 1.7 THz optical span. Fig. 1d already shows sharp absorption features of low-pressure hydrogen cyanide (HCN) detectable in the electrical spectrum even in free-running mode. Accurate and precise measurements of species with Lorentzian half-widths in the ~100 MHz regime are routinely possible.

The concept of polarization multiplexed dual-comb generation has also been recently adopted by the authors in a solid-state dual-comb laser based on a Yb:CNGS medium at a 1 µm wavelength [5]. Future work will focus on real-time correction of spectroscopic signals, and shifting the wavelengths to the mid-infrared or THz range through nonlinear frequency conversion. A mid-IR chip-based DCS system for molecular sensing is also investigated.

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