High-resolution dual-comb spectroscopy with a free-running all-fiber laser

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Abstract: We use a 1.56 µm computationally-corrected polarization-multiplexed dual-comb laser in free-running mode to measure hydrogen cyanide at 10 Torr. The source with a repetition rate of 142.4 MHz requires only 0.35 W of electrical power. © 2019 The Author(s)
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Dual-comb spectroscopy (DCS) has proven its usefulness as a valuable tool in science and industry thanks to the unrivaled speed, precision, and moving parts free operation. The traditional DCS implementation requires two mutually coherent lasers attained by either mutually phase locking or referencing each source to an optical standard, yet these strategies may seem unfeasible for implementation in out-of-laboratory conditions, where simplicity, robustness, and compact size are favored. A straightforward way to ensure the critical requirement of mutual coherence between two repetition-rate detuned combs is to generate them in a single cavity, thus making any frequency fluctuations common in nature. A surge of activity in this field resulted in a number of shared-cavity dual-comb lasers based on waveguide lasers [1], and all-fiber dual-wavelength [2], bidirectional [3] and polarization-multiplexed [4] model-locked lasers, of which the most favored are the latter without free space optics.

A majority of the previous demonstrations of molecular DSC using single-cavity dual-comb lasers involved spectroscopic measurements of absorbers with gigahertz linewidths at relatively high pressures, where residual fluctuations between combs smeared out the down-converted lines radio frequency spectrum without distorting the line shape of broadband absorbers. Consequently, the mode-resolved capabilities of such lasers for gas sensing have not been fully exploited except for Hébert et al. [1], who proposed to employ computational phase and timing correction to perform a mode-resolved measurement of hydrogen cyanide at a pressure of 100 Torr with a resolution of 822.4 MHz, albeit the system relied on free-space optical elements limiting its portability and robustness.

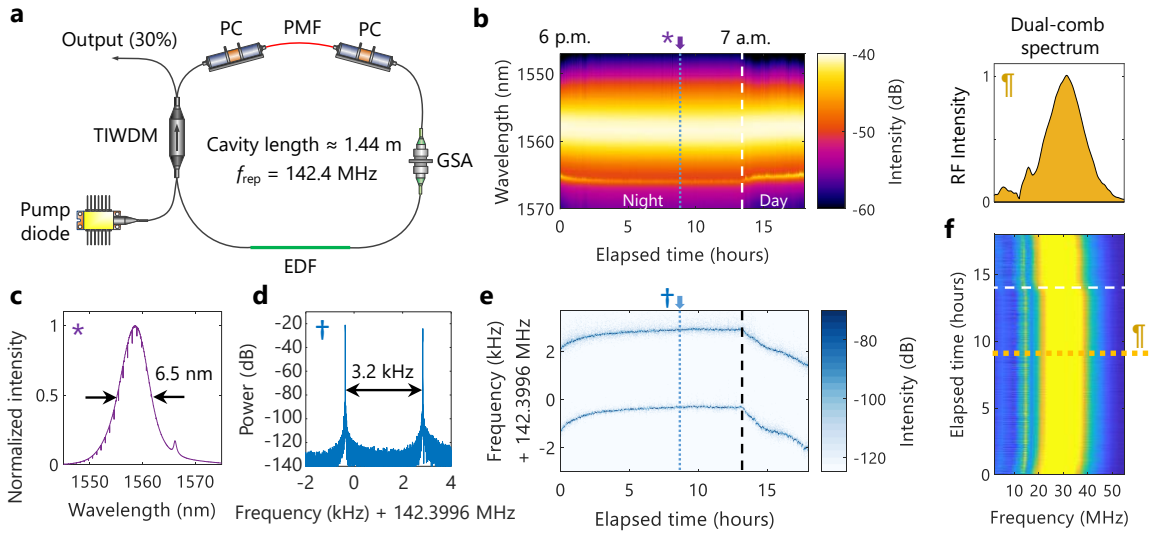

Fig. 1. Schematic of the polarization-multiplexed dual-comb all-fiber laser together with characterization in the optical and radio frequency (RF) domain. (a) Experimental configuration, TIWDM – tap coupler/isolator/WDM hybrid device, PC – polarization controller, GSA – graphene saturable absorber, PMF – polarization maintaining fiber, EDF – erbium doped fiber. (b) Optical spectrogram measured over 18 hours of uninterrupted free-running operation. After 13 hours, a gradual drift can be observed due to a change in ambient temperature caused by the heating system and mechanical perturbations. (c) Slice of the spectrogram after 9 hours of operation (position indicated with an asterisk in the spectrogram). The narrow lines are due to HCN absorption in the absorption cell connected at the output. (d) Corresponding RF spectrum. (e) RF amplitude spectrogram taken simultaneously with (b). (f) Dual-comb spectrogram calculated from apodized dual-comb interferograms and plotted together with an analogous slice after 9 hours. The soliton shape with a sideband corresponds well with the optical spectrum in (c).

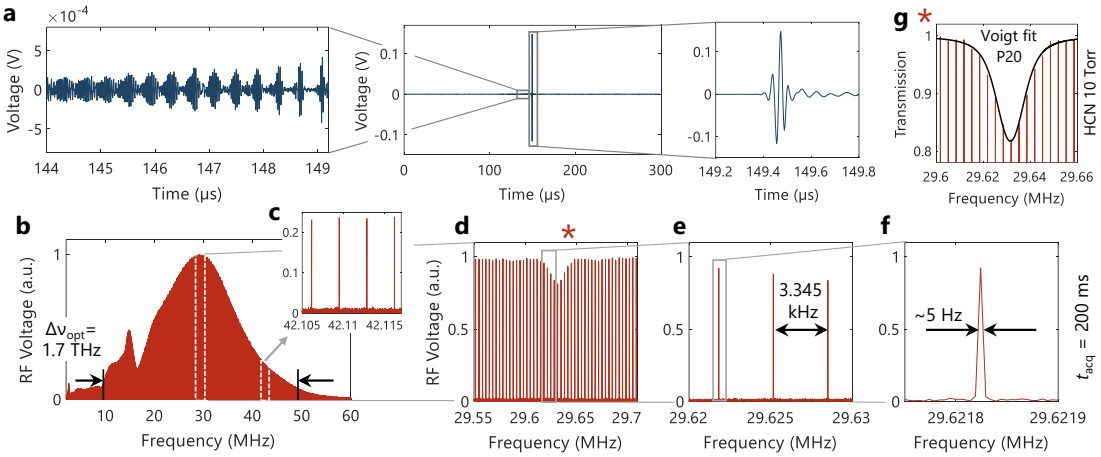

Fig. 2. (a) Computationally coherently averaged 668 interferograms measured in 200 ms yielding a single trace with more than 80 dB of dynamic range. The side panels show zoomed parts of the inferferogram: the free-induction decay caused by interaction with $H^{13}C^{14}N$ at low pressure (10 Torr) on the left, and a centerburst on the right. (b) Mode-resolved RF spectrum consisting of ~12 000 discrete lines calculated from a stream of all interferograms mapping ~1.7 THz of optical bandwidth centered around ~192.4 THz (1558 nm). (c) Part of the spectrum lying far away from the carrier showing the efficacy of the computational correction. (d) Mode resolved measurement of $H^{13}C^{14}N$ *P*20 line plotted with a zoom on the RF comb teeth in (e) and (f) demonstrating the transform-limited RF linewidth. (g) Normalized transmittance retrieved from (d) overlaid with a theoretical Voigt profile at 10 Torr using parameters from Ref. [5].

Here, we propose a drastically simplified all-fiber dual-comb laser (Fig. 1) that requires only a few basic fiber components to perform high-resolution measurements of low-pressure (10 Torr) hydrogen cyanide ($H^{13}C^{14}N$) without additional CW lasers, control electronics or nonlinear spectral broadening. The dual-comb generation mechanism relies the existence of two orthogonally polarized pulses in the cavity with different repetition rates provided by the birefringence of a short section of polarization maintaining fiber [4]. We use a graphene-based saturable absorber on a PMMA substrate [6] transferred onto the facet of an angle-polished fiber connector. The electrical power of 0.35 W delivered to the pump diode enabled sustained dual-comb operation at an unprecedentedly high repetition rate for this architecture (142.4 MHz) over dozens of hours, as plotted in panels (b)-(f) of Fig. 1. The system was built on a tabletop rather than on an optical table, and was left completely unstabilized overnight to test its susceptibility to changing environmental conditions. A sudden change in the optical and RF spectra around 7 a.m. is related to the start of the building heating system and morning laboratory activities.

Using a fast oscilloscope with 12 bits of vertical resolution in oversampling mode, we performed a 200 ms long dual comb measurement of a 10 Torr hydrogen cyanide reference gas cell, as shown in Fig. 2. We utilized a novel computational coherent averaging technique that did not require to compute an expensive cross-correlation function to correct the stream of interferograms for averaging to a single trace as in Fig. 2a. Panels (b)-(g) in Fig. 2 show the efficacy of the procedure in tooth-resolved mode showing a transform-limited RF linewidth of ~5 Hz. The theoretical Voigt profile for *P*20 line based on Ref. [5] overlaid on the dual-comb spectrum corresponds well with the data and proves the capability of the system to perform high resolution molecular spectroscopy at low pressures.

Acknowledgments

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