# Ultra-high-resolution dual-comb spectrometer based on densified gain-switching optical frequency combs

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**Abstract:** We demonstrate a dual-comb interferometer based on two externally densified gain-switching optical frequency combs and show its potential for ultra-high-resolution spectroscopy. 2022 The Authors.

## 1. Introduction

Optical frequency combs (OFCs) are a very powerful technology for a variety of applications, gas sensing being one of them. Dual-comb spectroscopy (DCS) [1] is a technique that benefits from this technology and allows fast, high resolution and high sensitivity sensing. It is based on the multiheterodyne beating in a photodetector of two OFCs operating at slightly different repetition rates. One of the combs, known as signal comb, travels through an absorbent medium and is sampled by a second comb acting as local oscillator. The interference of the two combs results in a down-converted RF spectrum whose lines are evenly spaced by the difference in the repetition rate of both combs, thus mapping the information encoded in the optical domain into the RF domain, where detection and processing are advantageous. The absorption and phase profile of the interrogated medium is retrieved from the amplitude and phase of the RF dual-comb spectrum. This makes it possible to measure the absorption of a specific gas with a resolution set by the line spacing of the combs using low bandwidth electronics, with a setup without moving parts, and in acquisition times on the order of milliseconds. The high resolution of the technique is however limited by the frequency separation of the comb lines, which is usually larger than tens of MHz. To further reduce this frequency separation several densification techniques can be applied. One of the most successful schemes, employed in [2], allowed to multiply the number of tones from a mode-locked OFC up to a factor 127 (from 100 MHz to 787 kHz), using an external phase modulator driven by a pseudorandom binary sequence (PRBS). We have previously demonstrated DCS using semiconductor lasers in gain-switching operation with optical injection and a resolution of 100 MHz [3]. In this work, we report a dual-comb spectrometer based on two gain-switched semiconductor lasers which are externally modulated using two electrooptic phase modulators (EOPM) driven by PRBSs. Our system benefits from the semiconductor laser platform advantages (low cost, small size, integrability in photonic circuits) and the gain-switching technique assets (simplicity, robustness, tunability), featuring a resolution of 4 MHz and an acquisition speed of 25 ms. The dual frequency comb generated, which is optimized for the application, contains 10,000 spectral lines in a 10 dB bandwidth. To validate the system, we measure the absorption profile of a HCN absorption line at 1,549.73 nm with extremely high resolution (500 comb teeth in a 2 GHz absorption linewidth).

## 2. Experimental results

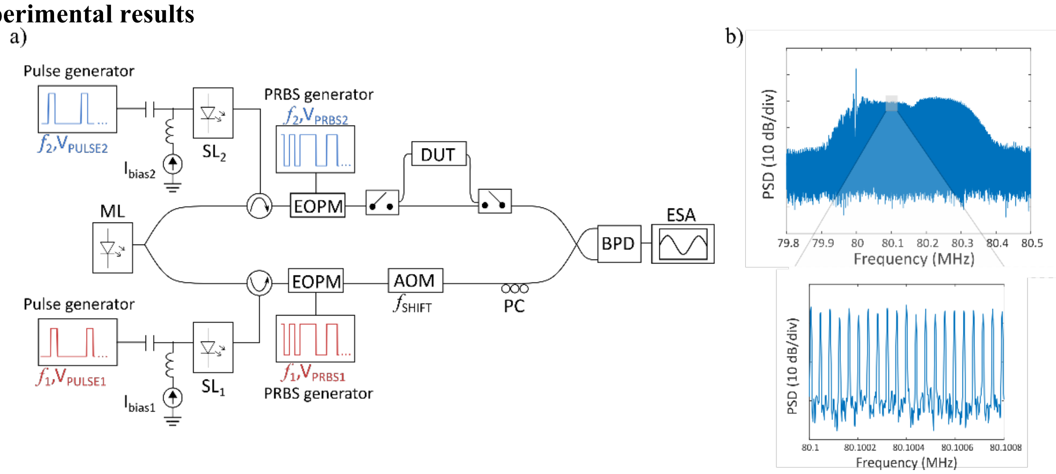


Fig. 1 a) Experimental setup for the proposed spectrometer. b) Dual-comb spectrum showing the spectral footprint of the gas measured with an ESA and zoom over 800 Hz (20 tones spaced 40 Hz).

The experimental setup is shown in Fig. 1 a). Two stages can be distinguished: the generator of the densified dual OFCs and the interferometer itself. The OFC generator is based on a typical master-slave architecture. The master laser (ML) is a tunable semiconductor laser. The slave lasers ($SL_1$, $SL_2$) are two discrete mode lasers which are gain-switched using a combination of a DC bias current ($I_{bias1}$= 3mA, $I_{bias2}$ = 4.4 mA) and a train of electrical pulses ($V_{PULSE1}$ = $V_{PULSE2}$ = 4 Vpp) at repetition frequencies $f_1$= 500 MHz and $f_2$= 500.005 MHz, respectively. Both combs are modulated by two EOPMs driven by two PRBS of length 127. The bit rate of both PRBS matches with the repetition rate of the optical pulses and their amplitudes ($V_{PRBS1}$, $V_{PRBS2}$) correspond to the $V_\pi$ voltage of each modulator. The two combs, each traveling along a branch of the interferometer, finally beat in a balanced photodetector (BPD). The electrical signal at the output of the BPD is measured with an electrical spectrum analyzer (ESA). Two sequential acquisitions are performed to measure the fiber-coupled gas cell and the reference spectrum by switching the optical path.

The two densified OFCs have repetition rates of $f_1$/127= 3.937007 MHz and $f_2$/127= 3.937047 MHz, which results in a repetition rate difference ($\delta f$) of 40 Hz, yielding a compression factor of ~ $10^4$. To demonstrate the validity of the system, the profile of an absorption line ($\lambda_{abs}$ ~1,549.73 nm, FWHM ~2 GHz) of HCN enclosed in a sealed gas cell (25 Torr, 16.5 cm) is measured. Fig. 1 b) shows the dual-comb molecular spectrum measured with the ESA, whose RF bandwidth at 10 dB is ~400 kHz (optical bandwidth 40 GHz). This bandwidth, featuring 10,000 spectral tones, is optimized so that the dual-comb spectrum is contained in the first Nyquist zone, thus avoiding spectral overlapping with higher order zones. A comparison between the absorption line printed in the densified dual-comb (blue) and in the non-densified dual-comb (orange) is shown in Fig. 2 a). A total of 500 comb teeth lies within the FWHM of the line when using densified combs whereas in the case of the non-densified combs, just 4 tones lie within the transition. The densification improves the spectrometer resolution by a factor of 127 with no loss of power that is redistributed among all new spectral components. The absorption spectrum of the gas line is obtained by subtracting the sample-free spectrum and the spectrum of the gas cell path. Fig. 2 b) shows the low pass filtered transmission spectrum of the measured line (blue) retrieved at optical frequencies and a fitting of this curve to a Voigt profile (orange). The residuals of the fitting have a standard deviation of 0.04 and are shown in the bottom part of the figure. Although in the experiments a 2 GHz absorption line is measured to validate the system, much narrower spectral features can be accessed by the technique. Maintaining the operating conditions of the system, 40-MHz-wide transitions could be characterized with 10 tones within the feature. In addition, since the gain-switching technique allows modifying the repetition frequency of the combs by simply changing the frequency of the electrical modulation signals and the length of the PRBS signal used to drive the modulators can also be modified, the technique offers two degrees of freedom that permits adapting the resolution of the system to suit the requirements.

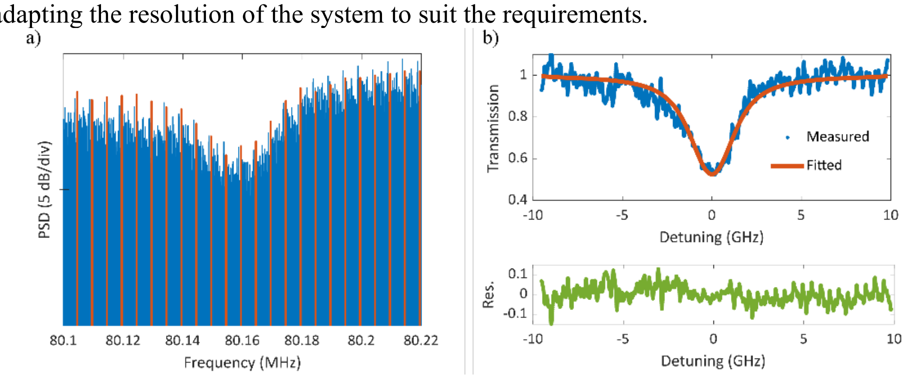


Fig. 2 a) Absorption region sampled by two dual frequency combs with different line spacings: densified comb (blue) and non-densified gain-switched dual frequency comb (orange). b) Measured absorption (blue), Voigt profile fitted to the experimental data (orange), and residuals from the fitting (green).

In conclusion, we present a semiconductor based dual-comb spectrometer in the near infrared region for ultra-high-resolution measurements. The operation conditions of the system in terms of bandwidth, resolution, and wavelength can be easily tailored to the requirements of the application while maintaining good spectral flatness, robustness, and repeatability.

## 3. References

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