Dual-Comb Spectroscopy with Two On-Chip III-V-on-Silicon 1-GHz Mode-Locked Lasers

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Abstract: A dual-comb interferometer with two semiconductor lasers on silicon photonic chips enables an optical resolution of 1 GHz, over a 0.7-THz span. The spectrometer directly and unambiguously samples near-infrared rovibrational transitions without spectral interleaving.

1. Introduction

Dual-comb spectroscopy opens up novel opportunities for laboratory- and field-spectroscopy, by improving the recording time, the resolution and the accuracy of broad-spectral-bandwidth spectrometers [1]. A dual-comb spectrometer measures the time-domain interference between two frequency combs of slightly different line spacing. Dual-comb spectrometers show an intriguing potential for a gas-phase sensor fully integrated on a photonic chip, which could benefit from the recent exciting developments towards integrated frequency comb sources [2]. Most existing on-chip comb generators however have a line spacing higher than 10 GHz, too large for sampling unambiguously an infrared absorption spectrum of rovibrational transitions in small gas-phase molecules.

While interleaving spectra overcomes this difficulty [3], in some conditions it may also decrease the precision of the determination of the line parameters and it prevents some applications such as time-resolved spectroscopy of non-reproducible events. In this work we present a dual-comb interferometer which consists of two III-V-on-silicon mode-locked lasers on photonic chips, with a 1-GHz linespacing and a span of 1 THz. We show that the interferometer can be operated, in the telecommunication region, with sufficiently low intensity and phase noise to enable the recording a dual-comb spectra with 1000 resolved comb lines over the entire laser span. Gas-phase spectroscopy with this interferometer, where the molecular profiles are over-sampled by the comb lines, is underway.

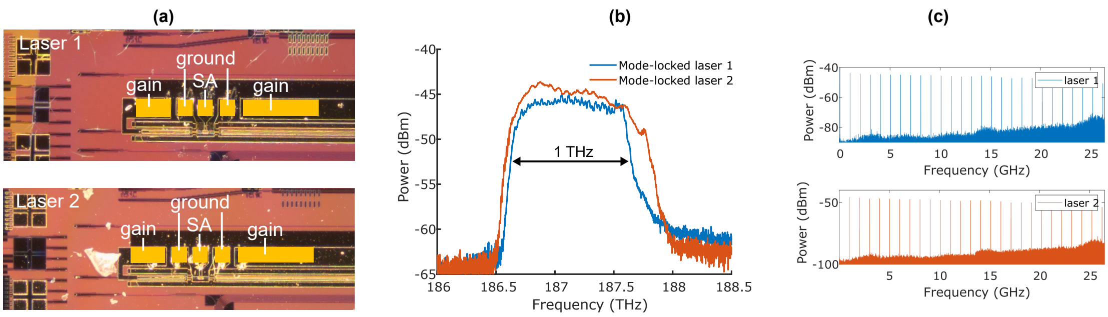

Fig. 1. Overview of the III-V-on-silicon mode-locked lasers. (a) Micrographs of both III-V-on-silicon mode-locked lasers. (b) Optical spectra of both lasers measured with 50 pm resolution. (c) RF spectra of the III-V-on-silicon mode-locked lasers, illustrating stable mode-locking.

2. Experimental results

Our mode-locked lasers (Fig.1a) have a very compact footprint ($< 1\text{mm}^2$) and can be fabricated at the scale of a full wafer [4]. The oscillator cavity is formed by low-loss ($<$ 0.4 dB/cm) silicon waveguides, which enable a comb-line spacing smaller than that of any other type of on-chip frequency comb sources. A gain medium and a saturable absorber, made of InGaAsP quantum wells, are bonded on top of the silicon-waveguide layer and permit the generation of train of pulses of a duration of about 7 ps.

Two separate chips, with about 15 lasers each – though only one of 1-GHz repetition frequency per chip – are employed for dual-comb spectroscopy. An electrical power of approximately 100 mW is needed per laser for mode-locked operation, which could be provided by a AAA battery. The optical output of each laser oscillator is coupled into a cleaved single mode fiber, providing an optical power of approximately 10 μW. Their optical spectra, centered at 187 THz, overlap over a span of almost 1 THz (Fig.1b). Their repetition frequencies, of about 1 009 MHz (Fig.1c), have a fitted Lorentzian full width at half maximum of less than 20Hz at 100-Hz resolution bandwidth. For a dual-comb interferometer to provide meaningful spectra, the coherence between the two comb generators must be maintained over the measurement time. In our set-up (Fig.2a), coherence times of about 100 μs are achieved by optically injection-locking one optical line of each comb with a continuous-wave laser, as already investigated in a preliminary report of dual-comb spectroscopy with one such semiconductor mode-locked laser and an electro-optic-modulator-based comb generator [5].

Dual-comb spectra with approximately 700 resolved comb lines are averaged within 15 ms. Figure 2b illustrates one such spectrum with optical injection locking at 187.6 THz. Although the spectrometer is still under optimization, its main features are already obvious: the comb line spacing of 1 GHz enables to directly interrogate pressure-broadened molecular profiles, which are typically of a width of several GHz in the near-infrared region; the span, of about 700 GHz, is broad enough to distinguish several different isotopologues or different species. In this contribution, we demonstrate a proof-of-concept towards the first dual-comb interferometer on a photonic chip able of fully-multiplexed gas-phase molecular spectroscopy. Molecular spectra of $^{12}C^{16}O$ and $^{13}C^{16}O$, together with a sensitivity analysis, will be presented at the conference.

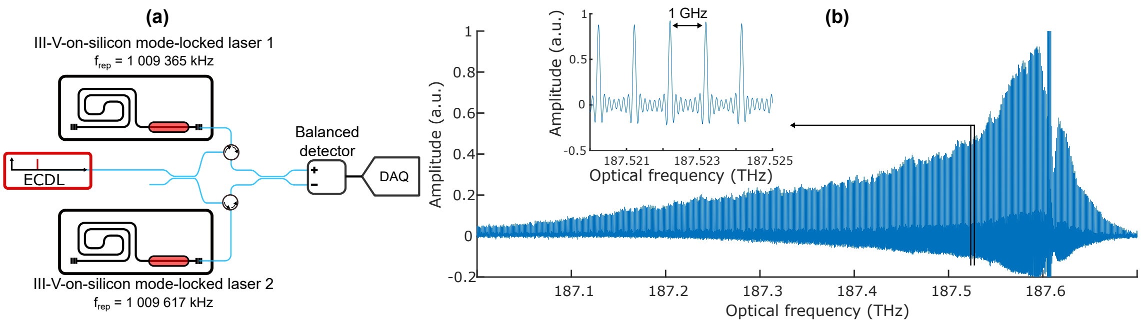

Fig. 2. (a) Schematic layout of the dual-comb interferometer. (b) Dual-comb spectrum of two on-chip mode-locked lasers with approximately 700 resolved comb lines, with a line spacing of 1 GHz (inset).

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