

Elastic-Tape Picture of a Bi-Directional Kerr-Lens Mode-Locked Dual-Comb Ring Laser

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Abstract: A fixed point of a bi-directional dual-comb ring laser is investigated. Using dual-comb spectroscopy we show how changes in the combs' relative repetition and offset frequencies are correlated, giving insight into the combs' mutual coherence. © 2020 The Author(s)

OCIS codes: 140.3560, 300.6300, 300.6360

1. Introduction

Since the development of frequency comb technology, a method known as linear dual-comb spectroscopy (DCS) has attracted attention as a powerful optical method for rapid and high-resolution measurements of materials' absorption spectra. DCS is also being developed for practical applications outside the laboratory such as chemical sensing and atmospheric monitoring [1]. In linear DCS one frequency comb is used to interrogate the sample and the second comb (Local Oscillator LO) with a slightly different repetition rate is used to sample the response. The resulting interferogram is acquired by a single photodetector. In the frequency domain, linear DCS produces a Radio Frequency (RF) comb spectrum (resulting from these two optical combs after beating against each other on a photodetector) that directly maps onto the optical absorption spectrum of the sample. Recently, DCS has been applied to nonlinear spectroscopy for chemical sensing applications [2,3] and there has been significant progress in developing DCS sources from single and compact resonators to make DCS a field deployable device. For example Ideguchi et al. [4] have recently developed a compact Kerr-lens mode-locked Ti:Sapphire bi-directional ring laser and demonstrated dual-comb spectroscopy using a single laser cavity. They have explained that the two outputs of the ring laser have different repetition rates due to the self-steepening effect and have shown that the relative repetition frequency can be tuned (from 0 Hz to ~850 Hz) e.g. by moving one of the curved mirrors in the cavity. However their paper does not report about behavior of the relative offset frequency between the combs (which is also affected by the self-steepening effect) while tuning the relative repetition frequency. In addition, since the two outputs are generated from the same cavity it is interesting to investigate if these changes are correlated with each other and how they affect DCS signals in different spectral regions (within the laser spectrum). This information is important to understand the mutual coherence between the combs that will help extend the bi-directional laser system into different spectral regions (via nonlinear processes such as second harmonic generation SHG, spectral broadening etc.). We also hope that this information will aid efforts to stabilize two bi-directional laser systems to enable rapid and high resolution multidimensional coherent spectroscopy using a compact apparatus [2,3].

2. Experimental Setup

To investigate the behavior we built a Kerr-lens mode-locked bi-directional dual-comb ring laser (Fig.1 a). Our laser consists of 2 curved mirrors (CM1 and CM2 with focal length $f=15$ cm), one flat laser mirror and an output coupler with 99 % reflectivity. A 2.3 mm path length highly-doped Ti:Sapphire crystal with an absorption coefficient of 4.75 cm^{-1} at the pump wavelength 532 nm is mounted at Brewster's angle and pumped with 6 W pump laser (532 nm) that is focused with a $f=4.2$ cm lens. The laser cavity is astigmatically compensated and both curved mirrors and the flat mirror are negatively chirped to compensate for positive group velocity dispersion (GDD) of 140 fs^2 introduced by the crystal. The optical spectra of two outputs (comb1 and comb2) are shown in Fig.1 (b). The combs are operated at repetition rates of ~724.77 MHz (comb1) and 724.77 MHz+337 Hz (comb2). A PZT mounted behind the CM1 mirror is used to scan the relative repetition frequency. To obtain a dual-comb signal the two laser outputs were interfered on a fast photodetector (1GHz) and the signal was digitized using a fast oscilloscope.

3. Results

To investigate DCS signals in different spectral regions we measured the signals at 836, 821 and 800 nm separately. For these measurements we used an optical bandpass filter (FWHM = 3 nm) centered at 850 nm and tilted its angle to center it at 836, 821 and 800 nm, respectively. We adjusted the CM1 mirror (using PZT) to change the relative repetition frequency by 59 Hz (first measurement (836 nm filter)), 86Hz (second measurement (821 nm filter)) and 121 Hz (third measurement (800 nm filter)) and recorded the spectral shifts of the dual-comb signals. The results are shown in Fig. 1 (c,d,e) where we plot the Fourier transforms of single bursts (temporal overlap of

comb 1 and comb 2 pulses). Despite the fact that the changes in the relative repetition frequency for these three measurements are not exactly the same, it is still clear that the dual comb signal generated by the frequency modes near 821 nm experience almost no spectral shift and the ones far away from it (800 and 836 nm) experience much bigger spectral shifts (hundreds of kHz to a MHz). The results seem to be quite opposite from the results that one obtains in traditional dual-comb spectroscopy (two-separate lasers) where a change in comb's cavity length causes DCS beat signals to stretch/shrink and shift by $n \cdot \delta(\Delta f_{\text{rep}})$ (where n is a comb mode number and $\delta(\Delta f_{\text{rep}})$ is a change in the relative repetition frequency). For our laser n is $\sim 5 \cdot 10^5$ (for a mode near 821 nm) which corresponds to spectral shifts of tens of MHz for the given experimental $\delta(\Delta f_{\text{rep}})$ values.

This discrepancy can be explained using the elastic tape formalism developed by Telle et al. [5] for Kerr-lens mode-locked Ti:Sapph lasers. According to this model, changing comb's cavity length causes comb modes to stretch/shrink with respect to a point which is located near DC. Also changing the refractive index of the Ti:Sapph crystal (e.g. by changing the pump intensity) causes comb modes to "breathe" with respect to a fixed point located near the carrier frequency. This model can be extended to a bi-directional ring laser as well. In our case, moving the curved mirror (CM1) affects the cavity length (for comb 1 and comb2) and the self-steepening effect strength for comb 1. A change in the cavity length affects both comb1 and comb 2 equally (the modes "breathe" with respect to a mode near DC as shown with black arrows in Fig. 1 (f)) and hence doesn't change the dual-comb signals. A change in the self-steepening effect strength for comb 1, on the other hand, affects both the repetition and offset frequencies (for comb 1) but these changes are canceled at a frequency mode near the carrier frequency. As a result, the other frequency modes of comb1 "breathe" with respect to this fixed point (strengths shown with green arrows in the figure). The sum of these two effects gives rise to the behavior of DCS signals shown in Fig.1 (c,d,e).

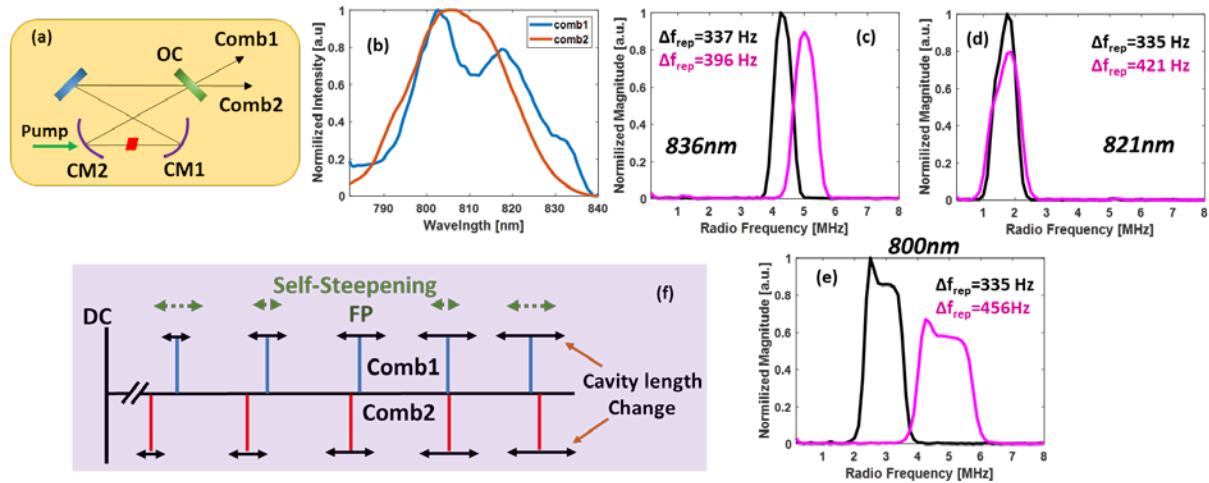


Fig.1 (a) Sketch of a bi-directional ring laser. (b) Optical spectra for comb 1 and comb 2. DCS signals (black) and their shifts (magenta) generated by frequencies at (c) 836 nm, (d) 821 nm, (e) 800 nm. (f) Elastic tape model, FP-Fixed point.

4. Conclusion

We have investigated the fixed points of a bi-directional dual-comb ring laser and behavior of DCS signals generated by the frequencies near and far away from the carrier frequency. We showed that the results are different from traditional DCS which we explained using the elastic tape formalism that we applied to a bi-directional ring laser. These results give insight into the mutual stability between the combs which will help extend the bi-directional laser system into different spectral regions (via nonlinear processes, SHG, spectral broadening etc.). We also hope the results will aid efforts to synchronize two bi-directional laser systems to enable rapid and high-resolution multidimensional coherent spectroscopy with a compact apparatus. **Funding:** This material is based upon work supported by the National Science Foundation under Grant No. [1904704]

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