Mechanical stabilization of a microrod-resonator optical frequency comb

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***Abstract*— We present line-spacing frequency control of a microresonator-based optical frequency comb by way of mechanical actuation. Using this novel technique, we have achieved a record level of residual stability in the line spacing of 5×10^{-15} for 1 s averaging. This demonstrates the potential of microresonator combs to support clocks with stability derived from optical frequencies. This work has been performed with newly developed microrod optical resonators fabricated by use of CO_2-laser machining.**

I. Introduction

Femtosecond-laser frequency combs have revolutionized optical frequency metrology by providing a dense set of absolute reference lines that can span in excess of an octave [1]. Such devices enable distribution throughout the visible and near infrared ranges of stable, but isolated, laser frequencies referenced to atomic clocks. Moreover, the spacing of comb lines is typically in the GHz range allowing contact with traditional microwave frequency standards. Beyond their natural application as an optical clockwork, frequency combs are used in diverse applications including precision measurements of fundamental physics, direct spectroscopy and molecular fingerprinting [2], the calibration of astronomical spectrographs [3], [4], [5], and generation of low-noise signals [6], [7], [8].

An even broader range of applications may be possible if a frequency-comb spectrum could be produced with a miniature device, or ultimately if a full comb system could be integrated on a silicon chip. Recently, a new class of frequency combs has emerged based on nonlinear effects in optical microresonators [9], [10], [11], [12], [13], [14], [15], [16], [17], [18], [19]; these devices are henceforth denoted microcombs. In this case parametric oscillation and cascaded four-wave mixing in a CW-laser-pumped microresonator leads to the generation of numerous optical frequencies. The high optical Q and small mode volume of microresonators makes possible a sub milliWatt turn-on power. Microcombs require only a single continuous-wave laser source, but the usable frequency span of the comb depends on low dispersion, making material properties critical. Microcombs also present a unique platform for creating large line spacings (10's of GHz to THz). However, their suitability for precision optical frequency metrology is not yet known.

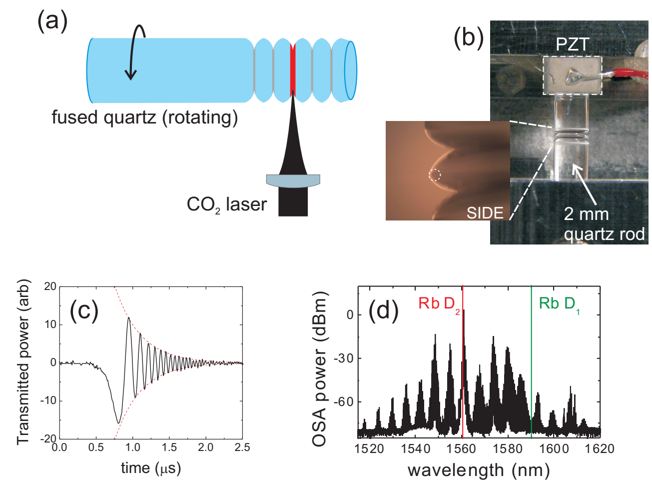

Fig. 1. (a) Schematic of our CO_2-laser machining system for creating ultrahigh Q microrod resonators for fused quartz. (b) Microrod resonator created with the setup in (a). The inset shows the profile of the 2 mm diameter resonator. The microrod is clamped with a PZT, which enables mechanical control the of the device's optical mode spectrum. (c) Ringdown measurement of the microrod optical Q. (d) Frequency-comb spectrum generated by way of nonlinear parametric oscillation and four-wave mixing in the microrod. The comb spectrum covers $\sim$ 100 nm about 1560 nm, and provides access to the D1 and D2 transitions of rubidium by way of second harmonic generation.

Here we report on a new microcomb platform and the generation, characterization, and frequency control of its optical and microwave outputs [20]. First, we introduce a simple and robust procedure for creating microresonators with $Q \sim 10^9$ by use of CO_2 laser machining. Using such devices we create a microcomb spectrum centered at 1560 nm and with mode spacing in the important 10's of GHz range. To tune the microcomb's frequency spectrum we have developed a novel technique based on the application of mechanical forces. We will discuss stabilization of both the microcomb's center frequency and its line spacing using the mechanical technique.

II. Microrod Fabrication

Figure 1a shows a schematic of our fabrication procedure. A focussed CO_2 laser selectively evaporates material from a rotating fused-quartz rod. Applying the CO_2 laser at two locations separated by 0.3 mm results in a thin "microrod" resonator; see Fig. 1b. Our fabrication approach has significant advantages including a 1 minute processing time, control of

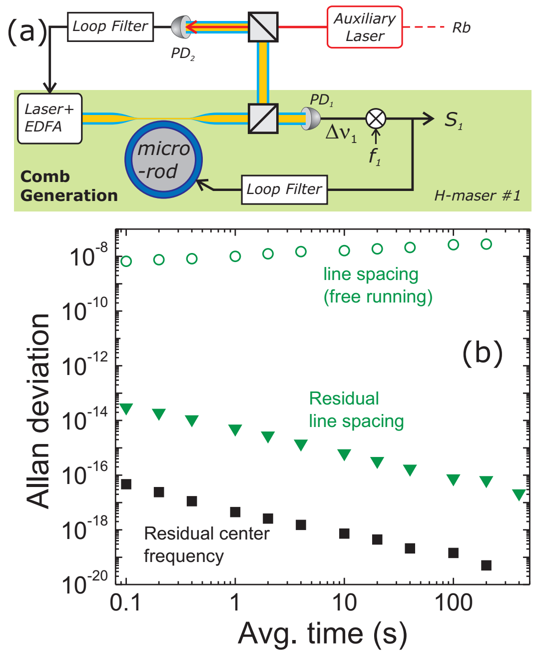

Fig. 2. (a) Experimental setup for comb generation and stabilization of the center frequency and line spacing. The resonator optical modes are accessed by way of a tapered fiber. We stabilize the center frequency to an auxiliary laser, which is in turn locked to a Rb transition at 780 nm. The line spacing is stabilized to a H-maser referenced frequency synthesizer. (b) Allan deviation of the free running line spacing (open circles, green), residual line spacing (triangles, green), residual center frequency (squares, black). The stabilized data here demonstrates the potential of microcomb technology to support modern optical frequency references with stability surpassing for example H masers [20].

the resonator size and shape over a wide range, and ultrahigh optical Q. Since the CO_2 laser heats the material much beyond the melting point, after it cools down the surface roughness is extremely low to support whispering-gallery modes. The ringdown measurement shown in Fig. 1c demonstrates the Q of a microrod device. These data were obtained by probing a microrod optical mode with a rapidly-scanned laser frequency. The decay of interference between the field exiting the microrod and the laser characterizes the optical losses. By pumping a microrod device with ~ 30 mW of optical power, we generate the frequency comb spectrum shown in Fig. 1d. This spectrum spans a range of $\sim$100 nm about the 1560 nm pump wavelength.

III. Microcomb stabilization by way of mechanical forces

We investigate the potential for microcombs to be used in optical frequency metrology applications by stabilizing its center frequency and line spacing to fixed frequency references [21], [20]. Specifically, the center frequency of the comb is controlled directly with the pump-laser frequency. A thermal-locking mechanism keeps the pump laser on the microrod resonance [22]. Figure 2a shows a schematic of our system. We stabilize the center frequency to an auxiliary laser, which in turn is frequency doubled to 780 nm and stabilized to a Rb transition. The center frequency lock utilizes a standard optical phase-locked loop and the auxiliary laser is locked with the Pound-Drever-Hall method. The residual Allan deviation of frequency fluctuations between the comb center and the auxiliary laser is shown in Fig. 2b. At 1 s averaging time the Allan deviation reaches a fractional value of 5×10^{-18}, which is sufficient to support modern optical clocks. Future experiments will explore the absolute stability of the comb center frequency and that of the various teeth by making measurements against fixed frequency references. Our micro-comb system can access the wavelengths that correspond to the atomic Rb D1 and D2 transitions at 795 nm and 780 nm, respectively. These transitions provide a convenient testbed for all-optical stabilization of a microcomb.

We also present an investigation of microcomb line-spacing control and stabilization by way of mechanical actuation. A major advantage of our microcomb platform is the capability to produce optical spectra with a line spacing in the 10's of GHz range. This enables straightforward photodetection and precise analysis of the line spacing using only conventional electronic techniques without the need for any auxiliary frequency comb; see Fig. 2a. For example, Fig. 2b shows the Allan deviation of the free running microcomb line spacing. The level of fluctuations we measure is significant and for many applications in the optical domain they must be controlled with respect to a stable frequency reference.

The resonant frequency and mode spacing of a microrod resonator can be controlled by axial compression using a piezoelectric actuator (PZT). An image of our system in shown in Fig. 1b. Axial compression induces a radial expansion of the fused-quartz rod according to Poisson's ratio and Young's modulus for the material, and the PZT displacement. This mechanism offers a line spacing tuning range of $\sim$1 MHz and a bandwidth of 25 kHz. Importantly, we can use the PZT as the feedback element in a phase-locked loop that controls the microcomb line spacing with respect to an H maser. The results of this (residual) stabilization, which achieves fluctuations at the 5×10^{-15} level at 1 s of averaging, are show in Fig. 2b

IV. Conclusion

We have presented a novel microrod platform for micro-comb generation based on CO_2-laser machining of fused quartz rods. Further, we have stabilized the center frequency and line spacing of the frequency comb they create. Here the feedback mechanism for the line spacing is mechanical force, which enables wideband frequency control beyond the thermal timescale associated with the optical mode volume of a resonator. Future work will focus on expanding the range of the comb to take advantage of self-referencing techniques, which offer stability beyond traditional electronic oscillators.

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