Optomechanical control of quantum cascade laser frequency combs

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ABSTRACT

Quantum cascade laser-based frequency combs have attracted much attention as of late for applications in sensing and metrology, especially as sources for chip-scale spectroscopy at mid-infrared fingerprint wavelengths. A frequency comb is a light source whose lines are evenly-spaced, and only two frequencies are needed to describe the system—the offset and the repetition rate. Because chip-scale combs have large repetition rates, for many spectroscopic applications is important to be able to change both parameters independently, without substantially changing the comb spectrum or spectral structure. Although it is possible to modulate both the offset and the repetition rate of a comb by tuning the laser current and temperature, both properties affect the laser by changing its index of refraction, and both frequencies will be affected. Here, we show that by integrating a mirror onto a MEMS comb drive, the dispersion and group delay associated with a quantum cascade comb's cavity can be modulated at kilohertz speeds. Because the MEMS mirror primarily affects the group delay of the cavity, it is able to adjust the comb's repetition rate while leaving the offset frequency mostly unaffected. Since this adjustment is linearly independent from current adjustments and can be adjusted quickly, this provides an avenue for mutual stabilization of both parameters. In addition, we show that dynamic modulation of the comb drive is able to allow the laser to recover from comb-destroying feedback, making the resulting comb considerably more robust under realistic conditions.

Keywords: Quantum cascade lasers, mid-infrared, frequency combs, optical MEMS

1. INTRODUCTION

Chip-scale frequency combs such as those based on quantum cascade lasers[1–3] (QCLs) have substantial potential as sources for broadband sensors in the mid-infrared fingerprint region.[4,5] By using an optical nonlinearity to phase lock the normally uncorrelated modes of a multi-mode laser, comb operation can be achieved for a given configuration of the laser. However, one of the challenges associated with these devices is that even with suitable dispersion engineering,[6,7] they frequently possess many different types of states, including various comb states and multi-mode regimes. These regimes are not only a function of the dispersion of a laser, but also its history. For example, a comb subjected to feedback could enter into a different comb state or even a single-mode or multi-mode state.[8] The multiplicity of states arises because QCL combs rely on spatial hole burning to achieve broadband operation, and effectively try to minimize the round-trip gain of the laser. However, there can be multiple local minima of this pattern, giving rise to different configurations of amplitudes and phases.[9]

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Several methods have been proposed for dynamically modifying this state, including multi-section geometries[10] and external Gires-Tournois Interferometer (GTI) mirrors.[11] Though the former method is chip-scale and high-speed, it can create artifacts in the resulting spectrum. The latter method can greatly affect the cavity's dispersion and can compensate for bias-induced dispersion changes,[12] but it does so relatively slowly and at the expense of making the laser no longer chip-scale. In this work, we show that the state of quantum cascade laser frequency combs can be effectively controlled (as well as continuously tuned) by using quasi-integration with a microelectromechanical mirror. This approach is both high-speed and chip-scale, allowing us to dynamically access different states of the laser without affecting its electrical or thermal properties. It also allows us to reproducibly measure this hysteresis.

2. EXPERIMENTAL RESULTS

A schematic of the devices constructed is shown in Figure 1a. A MEMS comb drive was fabricated in a commercial foundry and bonded alongside a mid-infrared QCL, effectively acting as an external GTI. The whole system is approximately 1 cm long. An optical image of the bonded device is also shown. However, prior to the bond the MEMS was affixed to a wide-travel translation stage, and its effect on the beatnote of the QCL was studied (shown in Fig. 1b). As expected, the beatnote of the QCL varies roughly periodically in the displacement of the MEMS mirror,[11] with the effect of the mirror decreasing rapidly as its optical cross section is reduced. Note that at large displacements the mirror is effectively absent and the beatnote is broad, indicating a multimode regime. We fix the MEMS to a location where the beatnote is narrow and verify that this is indeed a comb regime by performing SWIFTS[2,8,13,14]—shown in Fig. 1c—where the agreement between the spectrum product $\left(\left\langle|E(\omega)|^2\right\rangle\left\langle|E(\omega+\omega_0)|^2\right\rangle\right)^{1/2}$ and the SWIFT spectrum $|\langle E(\omega+\omega_0)E^*(\omega)\rangle|$ verifies comb formation.

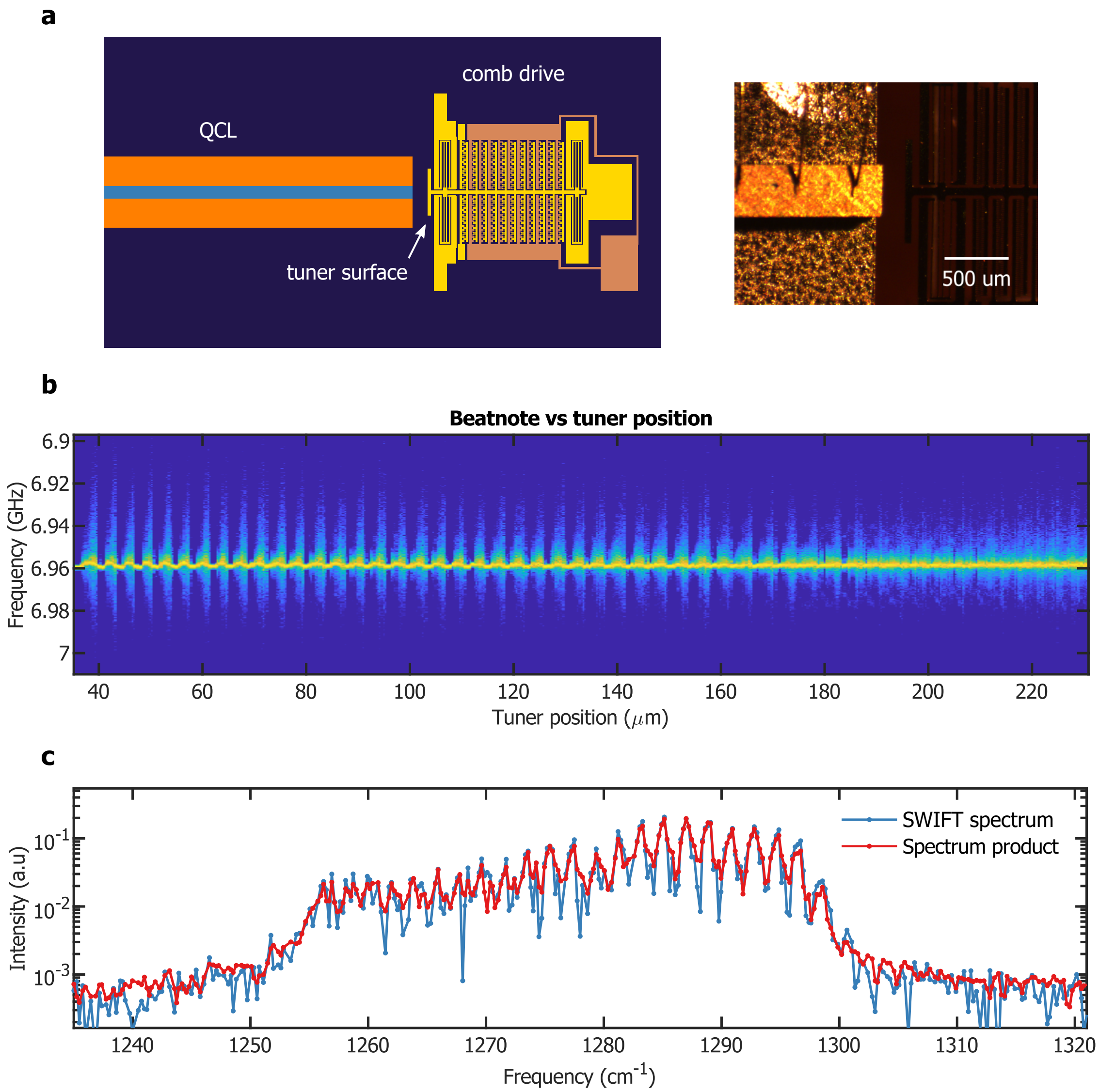

Figure 1. a. Basic schematic of the MEMS tuner, along with an optical image. b. Beatnote map of an unbonded MEMS device, as measured on a QWIP. c. SWIFTS spectrum of QCL in a narrow beatnote regime.

Next, we turn to the efficacy of the bonded MEMS device, shown in Fig. 2. The beatnote map is once again shown in Fig. 2a, but this time as a function of MEMS voltage instead of position. Because the bonded MEMS device is only capable of traveling a few microns, this beatnote maps is effectively a stretched version of Fig. 1b. Nevertheless, the distance that the MEMS can travel is sufficient to cover an entire period of the GTI periodicity, meaning that the device remains capable of manipulating the dispersion just as effectively as a discrete mirror. This periodic modulation is also evident in the center frequency—see Fig. 2—reflecting the fact that the group delay of the cavity is changed in addition to the dispersion. As a result, the QCL can be tuned into both a comb state and a multi-mode state, shown in Fig. 2b. Finally, by applying a step input to the MEMS device and measuring the step response of the optical output of the laser, we are able to measure the step response of the laser (Fig. 2d). The MEMS device is effectively a voltage-controlled mass on a spring, and as a result its response can be well-modeled by a Lorentz model; its resonant frequency is near 2 kHz and it has unity response up to around 3 kHz.

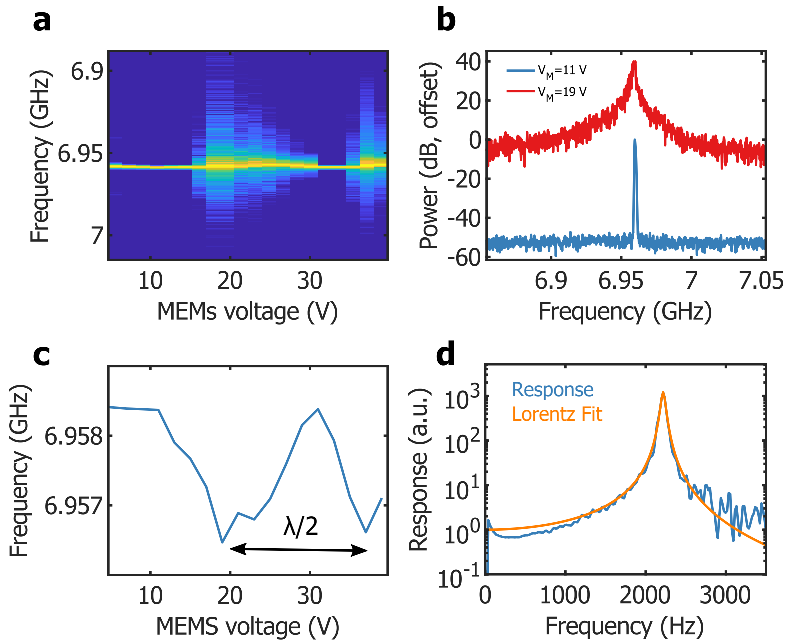

Figure 2. a. Beatnote map of the QCL as the MEMS voltage is scanned. b. Beatnote in a multi-mode and comb regime. c. Beatnote frequency of the QCL as the MEMS voltage is scanned. d. Frequency response of the MEMS mirror.

Figure 3 shows the tuning properties of the MEMS tuner. First, we beat the comb output with another comb on a quantum well infrared photodetector and perform a dual comb measurement. When the MEMS is tuned, we find that the dual comb signal tunes with a tuning coefficient of 31 MHz/V; when the device's current is tuned, we find a tuning coefficient of 122 MHz/mA (Figure 3a). The corresponding tunings of the beatnotes are coincidentally 79 kHz/V and 79 kHz/mA, respectively. In other words, tuning the current tunes the offset frequency more than tuning the MEMS. Nevertheless, the two tuning coefficients are linearly independent of each other (Fig. 3c), meaning that one parameter can be stabilized as the other is tuned or vice versa. For example, we show that the beatnote can be stabilized as the offset is tuned (Fig. 3d). We also note that current can be used to tune the offset of the laser over its full free spectral range, in principle allowing for gapless dual comb spectroscopy.

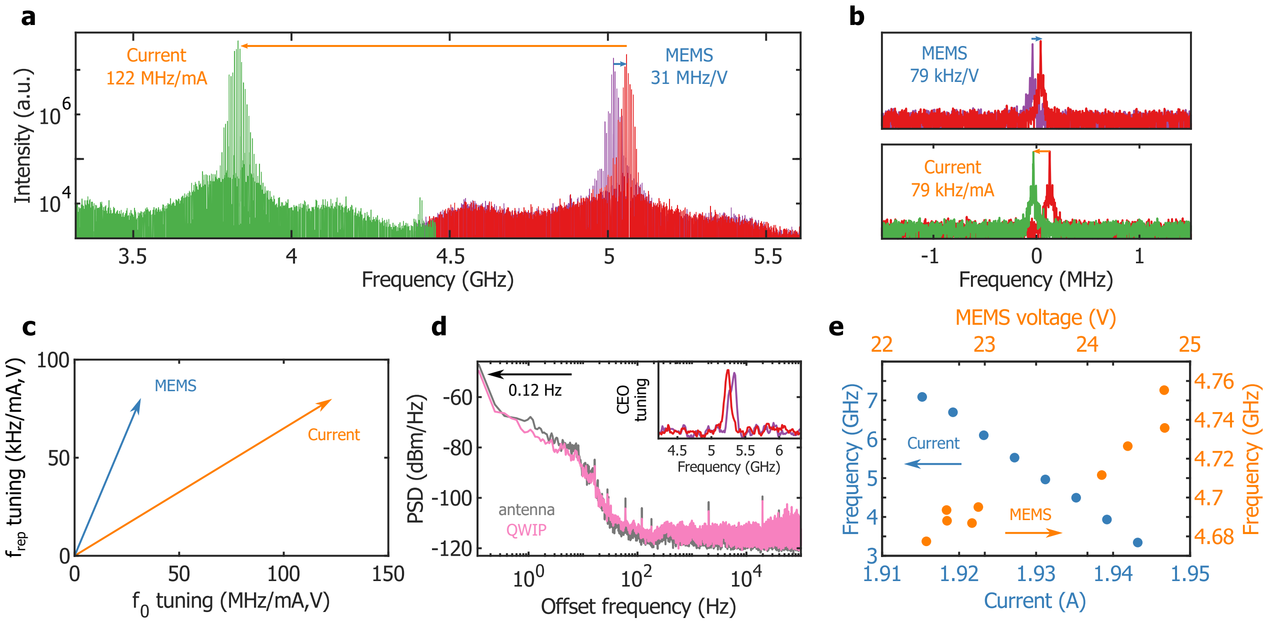

Figure 3. a. Tuning of a dual comb signal as the current and MEMS voltage are tuned. b. Tuning of the beatnote as the current and MEMS voltage are tuned. c. Comparison of the two tuning coefficients, demonstrating linear independence of the tuning directions. d. Out-of-loop stabilization of the beatnote as the offset is tuned. e. Dual comb offset tuning versus current and MEMS voltage.

Lastly, we show in Fig. 4 the existence of multiple comb states and how they can be accessed using the MEMS tuner. Fig. 4a shows the result of modulating the position of the MEMS position over millisecond timescales. At particular locations the beatnote is broad, but even when the beatnote is narrow it is apparent that there are two regimes: a lower frequency beatnote labeled as state A, and a higher frequency beatnote labeled as state B. The default (lower energy) state of the laser is state A, but when the MEMS tuner reaches its zenith, it is capable of abruptly switching into state B. This can be seen directly in parameter space using a hysteresis plot (Fig. 4b). Note that once the laser enters one state or the other it will not switch until it is reset by being forced to enter a multi-mode state. These different states are individually stable and can be understood as a consequence of the non-convexity of the spatial hole burning merit function. For example, we show in Figs. 4c and 4d two such solutions: both come close to minimizing the laser's gain, but they have drastically different spectra.

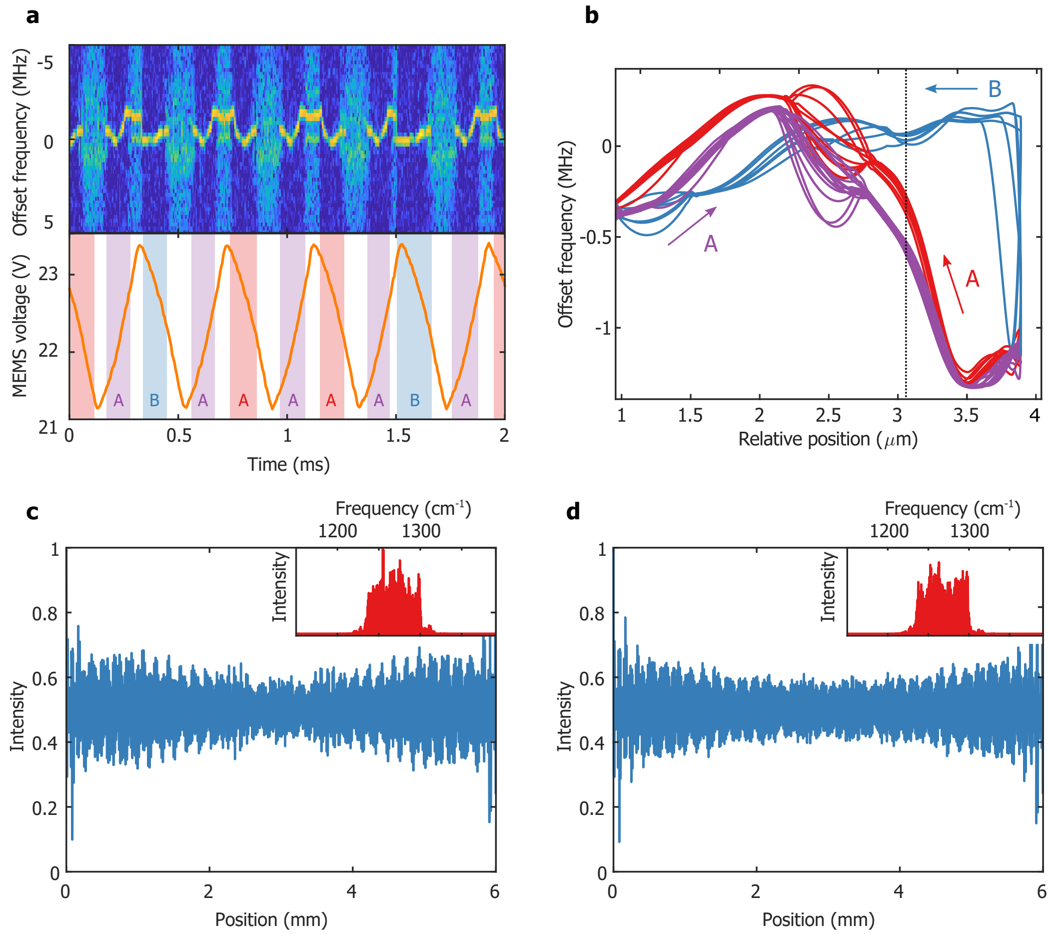

Figure 4. a. Effect of a fast periodic modulation on the MEMS voltage, demonstrating the existence of multiple comb states. b. Hysteresis plot of the comb state during this scan. c. and d. Two different possible comb states, with correspondingly different optical spectra.

3. CONCLUSION

We have shown that MEMS comb drives can be used to control chip-scale quantum cascade laser based frequency combs, without substantially increasing the size of the devices. We use them to select different comb states when more than one state is possible, and we also used them to simultaneously stabilize and tune both the offset frequency and the repetition rate.

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