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Phase locking of a THz QC-VECSEL to a microwave reference

Christopher A. Curwen, Jonathan H. Kawamura, Darren J. Hayton, Sadhvikas J. Addamane, John L. Reno, Benjamin S. Williams, and Boris S. Karasik

***Abstract*—High resolution frequency study and phase-locking have been performed on a terahertz quantum-cascade vertical-external-cavity surface-emitting-laser operating around 2.5 THz. A subharmonic diode mixer is used to down convert the THz signal to a 100 MHz intermediate frequency that is phase locked to a stable 100 MHz microwave reference. Between 90-95% of the QC-VECSEL signal is locked within 2 Hz of the multiplied RF reference, and amplitude fluctuations on the order of 1-10% are observed, depending on the bias point of the QC-VECSEL. The bandwidth of the locking loop is ~1 MHz. Many noise peaks in the IF signal are observed, likely corresponding to mechanical resonances in the 10 Hz-10 kHz. These peaks are generally -30 to -60 dB below the main tone, and are below the phase noise level of the multiplied RF reference which ultimately limits the phase noise of the locked QC-VECSEL.**

***Index Terms*— Terahertz metamaterials, quantum cascade lasers, surface emitting lasers, laser stability, laser noise, phase locked loops.**

I. INTRODUCTION

TERAHERTZ (THz) quantum-cascade lasers (QCLs) are a leading candidate for providing high power (milliwatt level) coherent THz radiation from a compact, electrically driven semiconductor source [1]. As the THz frequency range is rich in atomic and molecular rotational and vibrational resonances, THz QCLs can be essential tools for building THz spectroscopy systems [2, 3]. They are also of particular interest as local oscillators for astrophysical heterodyne receivers. However, a number of performance challenges must be addressed for THz QCLs to be effective sources for spectroscopy, such as frequency stability, frequency tunability, and beam quality. While frequency stability is a common issue for semiconductor lasers, issues of beam quality and frequency tunability are particularly acute for THz QCLs due to the subwavelength thickness of metal-metal waveguide resonators typically used [4]. Such subwavelength facets result in poor, diffracted output beams, and also makes it difficult to couple external signals into the device, reducing the effectiveness of external cavity configurations that are typically used to tune the lasing frequency over broad bandwidths [5, 6]. Such facet coupling efficiency can be improved with use of a surface-plasmon (SP) waveguides [7], however the coupling is still far from ideal, and SP waveguides require lower operating temperatures due to higher losses and reduced confinement of the THz mode to the QC gain material.

One approach that can address many of the challenges facing THz QCL performance is the THz QC vertical-external-cavity surface-emitting-laser (VECSEL) [8, 9]. The QC-VECSEL is based on an amplifying metasurface reflector that, when combined with an external feedback mirror, forms an external cavity laser. Because the metasurface has a large surface-radiating area (millimeter scale), it couples efficiently to fundamental Gaussian modes of the external cavity, resulting in a high-quality output beam. Additionally, the lasing frequency is determined by the length of the external cavity, which can be mechanically tuned over broad bandwidths [10, 11]. One remaining aspect that we investigate in this study is the frequency stability and phase-locking of the QC-VECSEL.

Frequency- and phase- locking of ridge waveguide THz QCLs has been demonstrated using a variety of techniques including: referencing the QCL to a more stable gas laser or frequency multiplier chain (FMC) source using a superconducting hot electron bolometer [12, 13] or diode mixer [14, 15], locking to an optical or THz frequency comb [16-18], locking to a subharmonic diode mixer with an RF synthesized pump [19, 20], direct injection locking with signal from a THz photomixer [21], and locking to a molecular absorption line [22-24].

In this paper, we report the stabilization of a THz QC-VECSEL by phase locking it to a microwave reference using a subharmonic Schottky diode mixer. While this technique was previously reported [19, 20], the external cavity nature of the QC-VECSEL likely makes it more susceptible to external mechanical noise sources that are not present in ridge waveguide devices. Additionally, the electronic frequency tuning behavior is different from that of a ridge waveguide, which prompts a call for a dedicated study (see Appendix).

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II. Methods

QC-VECSEL design and characterization

The design and operating principles of the QC-VECSEL are illustrated in Figs. 1(a) and (b). At the heart of the design is an amplifying reflectarray metasurface that consists of subwavelength metal-metal ridge-waveguide antennas resonantly coupled to surface radiation. The ridges are loaded with THz QC gain material such that incident radiation couples to the gain material via the waveguide antennas and is amplified before radiating back out in the reflected direction. Finite-element simulations of the reflection amplitude and phase of the metasurface tested in this work are plotted in Fig. 1(a). An insulating silicon dioxide layer is used between the top metal and semiconductor to selectively bias the center of the metasurface. When an external mirror is added (inset of Fig. 1(b)), the QC-VECSEL lases on the cavity mode with lowest diffraction loss, i.e. a fundamental Gaussian mode (assuming a perfect cavity).

The metasurface design has an 85 μm period and 16.35 μm wide ridges and used a hybrid bound-to-continuum/resonant-phonon active region design [25] (exact layer sequence can be found in [26]). The active region is only 5 μm thick (compared to the typical 10 μm) in order to improved heat sinking during continuous wave operation [26]. The metasurface has a total area of 2×2 mm^2, but only a central circular area 0.8 mm in diameter is biased. Additionally, the widths of the ridges are spatially varying to create a focusing phase profile with a focal length of 7 mm [27]. The metasurface was mounted with a fixed-length VECSEL cavity. The output coupler consists of a mesh of 3 μm wide metal lines deposited at a 15 μm pitch on a 200 μm thick z-cut crystal quartz substrate. The output coupler transmission was ~12% at 2.5 THz. The QC-VECSEL cavity was ~450 μm long and lasing occurred at 2.51 THz. The current, voltage, and output power data for the QC-VECSEL are plotted in Fig. 1(b). The device is operated in continuous wave and outputs ~1.2 mW of THz power at a heat sink temperature of 77 K (measured outside the cryostat with a 90% transmissive cryostat window).

Experimental Setup

The experimental setup is illustrated in Fig. 2(a). A subharmonic diode mixer is used to down convert the QC-VECSEL signal to an intermediate RF frequency that can then be phase locked to an RF reference source. This strategy has been demonstrated in [19, 20, 28]. Here, we start with a ~11 GHz signal generator (Agilent E8257D), followed by a Spacek Labs tripling amplifier (A345-3XW-31), followed by a JPL-made passive tripler. This local oscillator (LO) chain can generate >100 mW at ~100 GHz, but only ~8 mW are needed to pump the subharmonic mixer. The 2.5 THz QCL signal mixes with the 25th harmonic of the LO. The mixer is a modified version of the device described in [20]. The QC-VECSEL beam is focused via an HDPE lens into the mixer's diagonal feed horn antenna. The IF signal is set to ~3 GHz, amplified by 60 dB, filtered through a 500 MHz wide

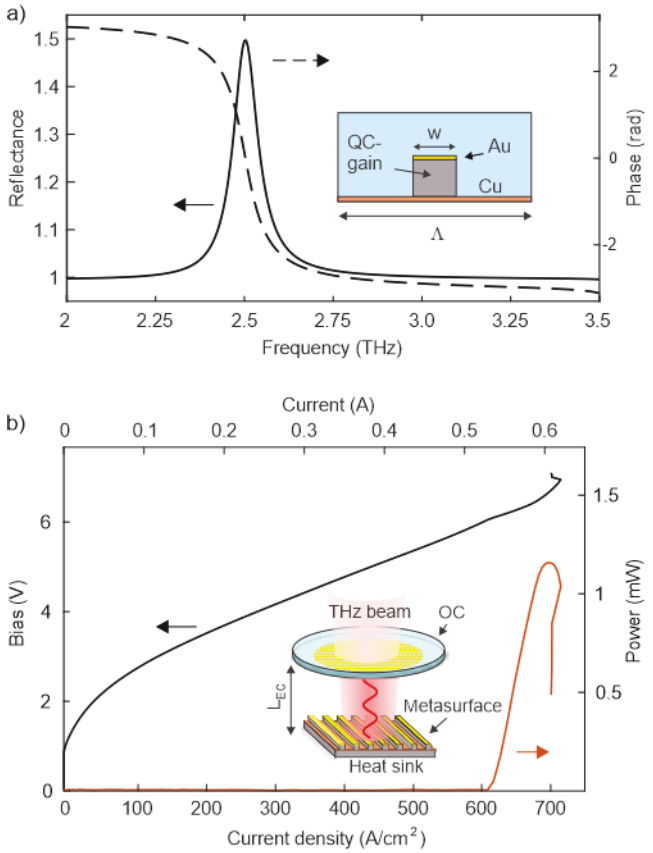

Fig. 1. (a) FEM simulated magnitude and phase of the metasurface reflectance with 20 cm^{-1} gain applied to the QC material. Metasurface structure is illustrated in the inset. (b) Measured lasing characteristics of the resulting QC-VECSEL, illustrated in inset.

bandpass filter, down-converted to 100 MHz with a second mixer (Mini-circuits ZEM-4300+), and sent to the phase-lock loop (PLL) electronics (XL Microwave 800A). The PLL uses the bias on the QC-VECSEL as a frequency/phase tuning mechanism to correct for any difference in phase between the reference and IF signals. The bandwidth of the PLL is ~1 MHz. The IF signal is monitored with a -10 dB coupler and a Keysight PXA signal analyzer The down-conversion is performed in two steps because the PLL requires an IF frequency around 100 MHz, but the THz subharmonic mixer has significant IF noise in the vicinity of 100 MHz. The output of the PLL provides both the DC bias and the superimposed error correction. The output of the PLL is also monitored on and oscilloscope. We observe a conversion loss of ~100 dB.

IV. Results

We first measure the free-running absolute frequency and frequency stability of the QC-VECSELs with the phase-lock loop off. The results are plotted in Fig. 2(b) as a function of device bias. Total frequency tuning across the dynamic range of the device is ~1 GHz. The high-resolution spectrum of the THz signal is measured via the IF on the signal analyzer. The non-linear frequency tuning characteristic with bias is related to external feedback from the mixer (17 cm distance), and is well modeled by a Lang-Kobayashi feedback model [29]. If single millisecond scans are collected, a narrow spectral line

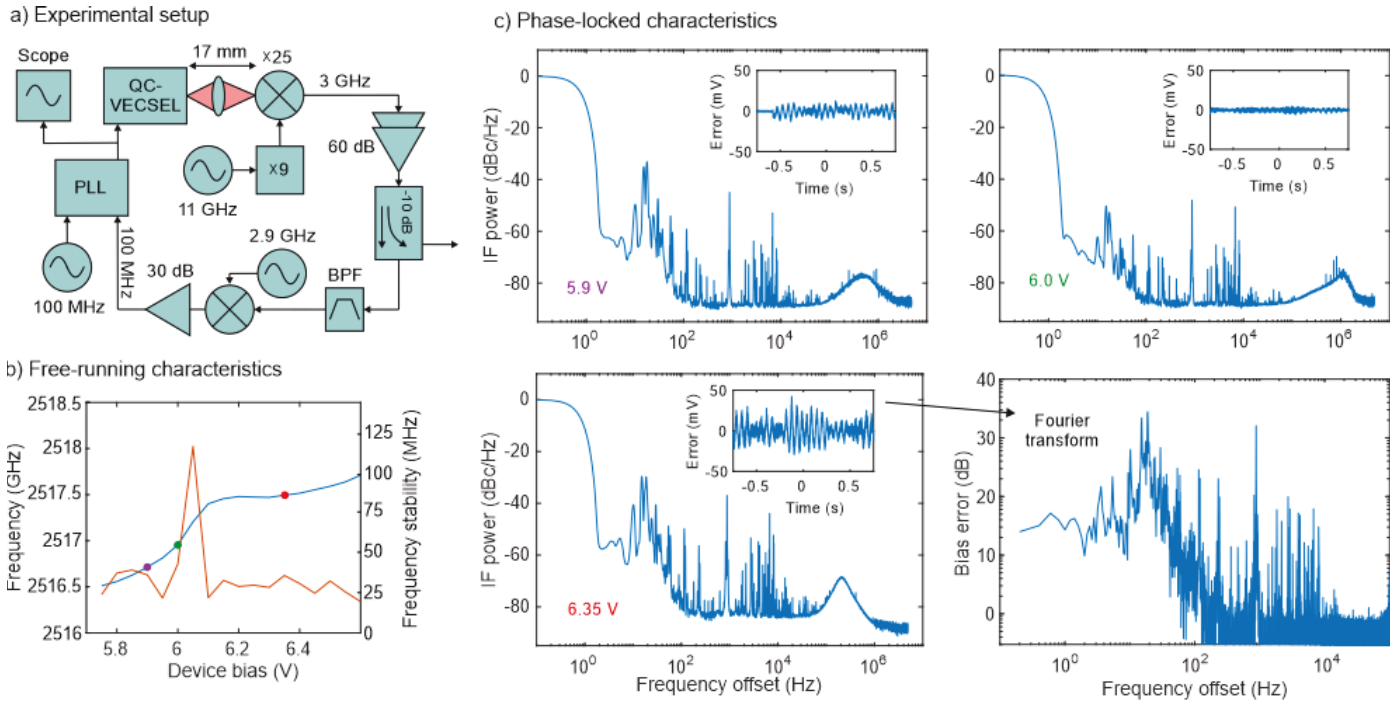

Fig. 2. (a) Block diagram of down conversion and phase-locking of the THz QC-VECSEL. b) Measured lasing frequency and frequency stability as a function of bias. c) Measured IF power with the phase-lock loop on. Insets time-domain measurement of bias fluctuations on the device, which are proportional to the error signal from the locking electronics. Fourier transform of the bias signal is plotted in the bottom right.

(limited by the resolution bandwidth of the observation) is observed that jumps-around on each sweep. The frequency stability is characterized by using the signal analyzer to perform max-hold measurements of the IF signal over the course of 5 seconds, capturing the maximum extent of the QC-VECSEL frequency jitter during the measurement time. The span of this jitter is plotted as frequency stability in Fig. 2(b), and is observed to be 25-50 MHz on average. We note that slow drifts in the VECSEL frequency are not captured in these measurements; the measured frequency jitter is the same whether hold time is tens of milliseconds or tens of seconds. Slow drifts are observed on the scale of minutes or hours, but not on the scale of the max-hold data recording time. For comparison, typical frequency jitter for ridge waveguide THz QCLs tend to be narrower, in the 1-10 MHz range [12, 15, 30, 31]. Utilizing a more rigid external cavity or a more stable bias supply was not observed to improve the frequency stability of the VECSEL, suggesting that the source of noise may be unstable feedback from optics in the setup.

In Figure 2(c), the single-sideband IF power spectrum while phase locking the QC-VECSEL is plotted for several different bias points. More than 95% of the power is contained within 2 Hz of the RF reference at all bias points (ratio of integrated IF power in a 2 Hz bandwidth and integrated power within the bandwidth of the PLL), and most of the unlocked power is in broad peaks around 1 MHz associated with the bandwidth of the PLL. It is observed that there are many noise peaks in the locked IF spectrum in the range of ~10 Hz – 10 kHz, which we assume to be associated with mechanical noise in the system, perhaps affecting the feedback. As the device is phase-locked, these peaks should correspond to amplitude noise, which is confirmed by measurement of error signal fed into the device bias while phase-locked (insets in plots in Fig. 2(c)). Fourier transform of the bias fluctuations matches well with the measured IF spectrum.

It is observed that the phase noise is significantly larger at certain bias points where the frequency tuning coefficient with bias is small (ex. 6.25 V versus 6.0 V), and smaller where the tuning coefficient is large (6.0 V). This is because the larger tuning coefficient allows a given frequency error to be corrected with a smaller change in device bias and output power. This is confirmed by observation that the error signal has peak-to-peak fluctuations on the order of 10 mV when biased at 6.0 V, and peak fluctuations of 100 mV when biased at 6.35 V, which corresponds to ~1 and 10% power variations, respectively. However, the noise peaks at higher kHz frequencies are not noticeably impacted by the device bias point. This is likely because the tuning curve in Fig. 2(b) is measured over a long timescale and is the combined result of thermal and electrical tuning. At lower frequencies, this curve applies, but at higher frequencies, only the electrical tuning response is present, which is apparently a more constant as function of bias. We note that the device could not be phase-locked in a small range of bias around 6.3 V, where the direction of the tuning coefficient briefly switches polarity, making the tuning coefficient non-monotonic. Such an issue was also observed in [32].

In Fig. 3, we use a second subharmonic diode mixer to observe the QC-VECSEL signal while still phase-locked by the first mixer. The second mixer operates on the 3rd harmonic of an 833 GHz LO [33]. The synthesizers used at the start of

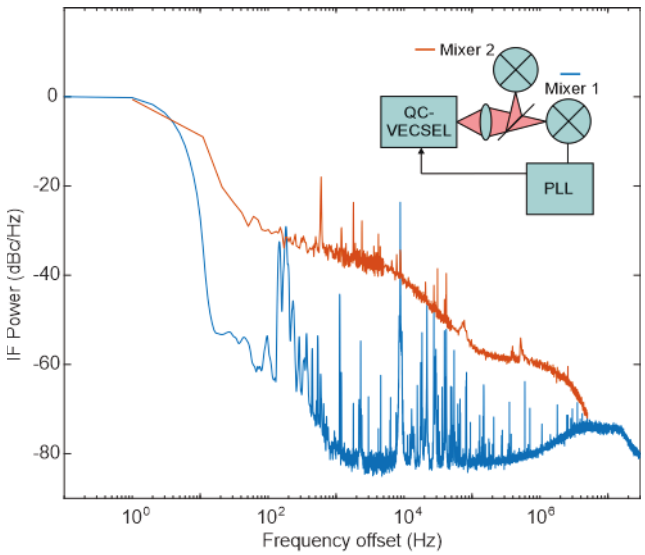

Fig. 3. Phase noise comparison between locking mixer (mixer 1, blue) and observing mixer (mixer 2, red).

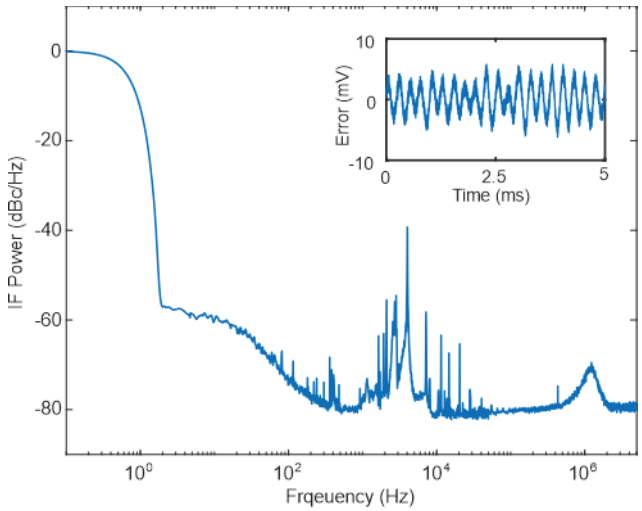

Fig. 4. Reduced phase noise of QC-VECSEL mounted in more mechanically rigid dewar.

LO chains for the two mixers are synchronized. The phase noise is much larger according to the second observing mixer, and is in good agreement with the expected stability of the multiplied-up reference which experiences a degradation in phase noise according to 20 $\log_{10}(N)$, where N is the multiplication factor. A similar effect is observed when locking with the second mixer [34] and observing with the first. Therefore, it is demonstrated that the true phase-noise of the locked VECSEL is limited by that of the reference.

Last, for comparison, we tested a second, 3.4 THz QC-VECSEL (same as device in [10]) in a second, more mechanically rigid dewar (Kadel KR373 versus IRLabs ND-3). The metasurface is mounted in a fixed-length VECSEL cavity, same as the 2.5 THz device. The phase-locked IF power spectrum of the second QC-VECSEL is plotted in Fig. 4. It is observed that all peaks in noise below 1 kHz are nearly extinguished, and the higher frequency noise is reduced, but some noteworthy peaks are still present. This improvement is indicative that vibration of the dewar may be the primary source of noise / frequency instability.

VIII. Conclusions

In this paper, we have used a subharmonic diode mixer driven by a microwave synthesized LO to study the high-resolution frequency behavior and phase-locking of a THz QC-VECSEL. The free-running linewidths are found to be in the tens of MHz, and phase locked linewidths of <1 Hz are achieved. There are remaining noise peaks in the 10 Hz – 10 kHz frequency range resulting from amplitude fluctuations in the phase-locked device (a side effect of using the bias on the device as the mechanism of frequency and phase control). These noise peaks are 40-60 dB below the main tone, which is lower than the phase noise of the multiplied microwave reference, making them a non-issue with regards to spectral resolution, but the amplitude fluctuations increase the averaging time necessary to measure small signals and would limit the sensitivity of a measurement assuming a given Allan variance time for the system. Amplitude stabilization of QCLs has been demonstrated using a number of external components, such as a tunable beam block controlled with a voice coil [35], injecting power from an infrared laser into the QCL substrate to tune the refractive index via excitation of electron-hole pairs [36], and using a graphene based split-ring resonator metasurface [37]. These approaches may be adaptable to the VECSEL, depending on the actuation speeds (particularly for a beam block) and potential coupling to frequency tuning, resulting in a more complex coupled system. An intriguing alternate approach may be to phase-lock the QC-VECSEL using piezoelectric control of cavity length as the error correction mechanism, rather than the bias on the metasurface. The cavity only needs to be tuned by nanometers to correct for the frequency error, and piezoelectric stack actuators have demonstrated actuation frequencies as high as 500 kHz [38]. The output coupler transmission changes very little (<0.01%) on the MHz scale tuning needed to phase lock the device, so this should provide a mechanism for nearly pure frequency modulation, which will obviate the need for additional amplitude stabilization. Finally, we suggest that due to its large emitting aperture, the VECSEL is likely amenable to direct injection locking with a low-power, stable tone from a THz photomixer [21] or diode frequency multiplier. Such a scheme should lock the phases of the sources without inducing amplitude fluctuations. However, the power from these sources is extremely small at higher THz frequencies, and the signal must be coupled in through a low reflectance beam splitter because the QC-VECSEL only outputs power from one side (unlike a ridge waveguide that can be injected from the back facet and output from the front facet), which may make it difficult to inject sufficient power for locking. Such strategies and improvements will be investigated in continued studies.

Appendix: QC-VECSEL tuning coefficients

For the QC-VECSEL, the round-trip phase accumulation when lasing is given by $2kL_{ext} - \phi_{MS}(n) - \phi_{OC} = 2\pi m$ where k is the free-space wavenumber, L_{ext} is the length of the VECSEL external cavity, ϕ_{OC} is the output coupler (OC) reflection phase, and $\phi_{MS}(n)$ is the phase of the complex

metasurface reflection coefficient which depends on the refractive index of the QC gain material. If the refractive index of the QC material is tuned, the lasing frequency of the QC-VECSEL must tune in order to maintain a roundtrip phase accumulation that is a multiple of 2π. Using these round-trip expressions, and assuming $\phi_{OC} = \pi$, $\phi_{MS} \approx 0$ (operating near the center of the metasurface resonance), we can write the following expression for the frequency tuning (Δf) in response to a change in refractive index:

$$\frac{\Delta f}{f} = \frac{c}{4\pi f L_{ext}} \frac{d\phi}{dn} \Delta n = \frac{4Q_{MS}\Gamma}{\pi(2m+1)} \frac{\Delta n}{n}$$

Where n is the refractive index of the QC material, Δn is the change in refractive index, f is the operating frequency, Q_{MS} is the quality factor of the metasurface resonance (extracted from simulation), Γ is a near-field metasurface confinement factor (usually close to unity), and $d\phi/dn$ is the rate change of the metasurface phase with refractive index. The second equivalence is made by substituting $L_{ext} = (2m+1)c/4f$, and $d\phi/dn = (d\phi/df)(df/dn) = (4Q_{MS}/f)(\Gamma f/n)$, assuming a Lorentzian model for the metasurface resonance. This is the same as the tuning expression for a ridge waveguide, scaled by the factor $4Q_{MS}\Gamma/\pi(2m+1)$. Therefore, the tuning coefficient can be larger or smaller than that of a ridge waveguide, depending on the quality factor of the metasurface and the length of the external cavity.

For variations in the external cavity length of the VECSEL, we can start with the round-trip expression and use the same approach to write:

$$\frac{\Delta f}{f} = \frac{\pi(2m)}{\pi(2m+1) + 4Q_{MS}} \frac{\Delta L}{L}$$

We find the tuning is reduced by either increasing the length of the cavity or increasing the quality factor of the metasurface. The metasurface quality factor can reduce the tuning because the changing phase of the metasurface as the frequency is tuned works to counter the changing cavity length.

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