Locking and laser-frequency tracking of a microsphere whispering-gallery mode

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ABSTRACT

We report advances in compression tuning of fused-silica microsphere whispering-gallery resonances and a practical use of the improved compression tuner. The advances include extending the tuning range and enhancing the tuner's response speed; these lead to the new application of using the tuner to lock to a laser, keeping a single whispering-gallery mode on resonance as the laser frequency is scanned. The resonance frequency of the mode to be locked is weakly modulated by axial compression of the microsphere, and phase-sensitive detection of the fiber-coupled optical throughput is used for locking. Using a laser wavelength of either 1570 nm or 830 nm, we demonstrate a locked tracking range exceeding 30 GHz for a microsphere of 120 GHz free spectral range. The improved tuner design that makes this application possible allows coarse tuning over 1 THz and piezoelectric tuning over 80 GHz. Compression modulation rates of up to 13 kHz have also been achieved with this tuner, producing a tuning speed of at least 16 GHz/ms.

Keywords: microspheres, whispering-gallery modes, optical resonators, fiber-optic components, frequency locking

1. INTRODUCTION

In an optical whispering-gallery mode (WGM), light propagates around the equator of a dielectric microsphere, spatially confined by total internal reflection to a narrow beam near the surface of the microsphere. A WGM can be tangentially polarized (TE) or radially polarized (TM), and has an evanescent component that extends into the space outside the sphere. The extremely low losses of WGMs in fused-silica microspheres allow them to be used as high-*Q* microresonators.[1,2] There are losses due to radiation, surface scattering, absorption, and coupling, but for fused-silica microspheres in the size range of 50-1000 μm in diameter, used with visible or near-infrared light, the dominant intrinsic loss is surface scattering.[2,3] The net intrinsic loss is low enough that the quality factor $Q = \nu/\Delta\nu = \omega\tau$ ($\nu = \omega/2\pi$ is the light frequency, $\Delta\nu$ is the WGM linewidth, and τ is the photon lifetime in the mode) can be as large as 10^{10}, though more typical measured values range from 10^6 to 10^8, depending on the coupling loss. Such microresonators have the potential to be used in many areas, including cavity QED,[4] atom trapping,[5,6] laser stabilization,[7] microlasers,[8-10] nonlinear optics,[11-13] nonlinear-optical thin-film diagnostics,[14] and evanescent-wave sensing.[15] However, their resonant frequencies are morphology-dependent, i.e., fixed by the geometry of the sphere, and thus not easily tunable. This limitation severely limits the utility of these microresonators; it is therefore very desirable to have a method to control the frequency of a WGM resonance.

One way to tune WGM resonances is by changing the temperature of the sphere.[4] This gives at most a 2.5/λ GHz/K shift (where λ is the optical wavelength in μm), primarily due to change in the refractive index,[16] but the effect is slow and its practical range is limited. A better tuning method makes use of axial compression[17] or stretching[18,19] of the microsphere. The corresponding change in path length for equatorial modes allows fast tuning over much of a free spectral range. Compression tuning is described in more detail in the following section, and subsequent sections describe our experimental apparatus, tuning results, and locking results, followed by a summary and conclusions.

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2. MODE FREQUENCIES AND TUNING

In addition to the polarization, three integers are needed to specify a WGM. The mode number ℓ is, approximately, the number of wavelengths in the sphere's circumference. The mode order q is the number of radial intensity maxima, and $\ell-|m|+1$ gives the number of maxima in "latitude" (where $|m|\le\ell$). The "fundamental" WGM has q = 1 and $|m|=\ell$ and thus a single transverse maximum. The WGM resonant frequencies are given approximately by[7]

$$\nu_{q\ell m}^{i}=\delta\left[\ell+1/2+A_q\left((\ell+1/2)/2\right)^{1/3}-\Delta^i\pm\varepsilon^2\left(\ell-|m|\right)/2\right]. \tag{1}$$

In Eq. (1), i denotes TE or TM, $\delta=c/2\pi a_e n$ is the microsphere's nominal free spectral range, n is the index of refraction of the sphere, a is the sphere radius (a_e, equatorial; a_a, axial), and A_q is the q^{th} zero of the Airy function (A_1 = 2.338, A_2 = 4.088, A_3 = 5.521, etc.). The different forms of Δ^i give the polarization shift of the WGM frequencies: $\Delta^{TE}=n\big/\sqrt{n^2-1}$ and $\Delta^{TM}=\left(n\sqrt{n^2-1}\right)^{-1}$. In forming a microsphere, a small amount of eccentricity results; for the last term in Eq. (1), the upper sign is used for an oblate spheroid and the lower sign for the prolate case, where the eccentricity is given in terms of the ellipsoid major and minor radii a_+ and a_- as $\varepsilon^2=\left(a_+^2-a_-^2\right)\big/a_+^2$. Representative values for ε^2 are 0.01 - 0.03, so a_e and a_a typically differ by about 1%.[7,17]

Axial compression of the microsphere results in tuning of the WGM frequencies:

$$\frac{\Delta\nu}{\nu}=-\frac{\Delta a_e}{a}-\frac{\Delta n^i}{n}+\frac{\ell-|m|}{\ell a}\left(\Delta a_e-\Delta a_a\right), \tag{2}$$

where the first two terms on the right-hand side come from the fractional change in δ, and the last term results from the change in eccentricity; tuning due to the change in Δ^i is negligible. In terms of the fractional change in axial radius, the above expression for tuning can be written as

$$\frac{\Delta\nu}{\nu}=\frac{\Delta a_a}{a}\mu\left[1+b^i-\left(\frac{1+\mu}{\mu}\right)\frac{\ell-|m|}{\ell}\right]. \tag{3}$$

Because our tuner's contact-surface configuration is similar to that of Ref. 17, we use their strain results, specifically, that $\mu=\left|\Delta a_e/\Delta a_a\right|$ = 0.11 (rather than the fused-silica Poisson ratio of 0.17), and that the photoelastic contribution is b^{TE} = -0.14 or b^{TM} = 0.07. Since $\ell\approx1500$ for our sphere at 1570 nm, the eccentricity-change term contributes approximately -0.16 for $\ell-|m|=24$ (roughly the maximum observed here), and so path length change is the dominant tuning effect.

3. EXPERIMENTAL SETUP AND COMPRESSION TUNER

For our experiments, a microsphere was fabricated by melting the end of an optical fiber using a hydrogen-oxygen torch; the microsphere used in this work had a diameter of 550 μm. A sketch of our experimental layout is shown in Fig. 1. Light from a tunable laser, either an extended-cavity diode used at 1570 nm or a cw Ti:sapphire used at 830 nm, was injected into an angle-polished fiber that had been tapered for coupling into the WGMs.[20,21] The taper was made by heating and stretching a short section of a single-mode fiber (SMF-28) to a diameter of 20 μm or less, then hydrofluoric-acid etching to a 5-10 μm diameter. By positioning this bi-tapered fiber in contact with the sphere, better than 90% coupling, at a Q of about 2×10^6, could be achieved. (We typically get Qs of several times 10^6 with contact-fiber coupling; this is the overcoupled limit, where coupling loss is dominant.) A fiber polarization controller (not shown) allowed excitation of WGMs of either polarization. The fiber throughput was detected as either the laser or microsphere was tuned, with sharp dips in transmitted power indicating the excitation of WGMs. Alternatively, we could detect light coupled out of the microsphere by a single-tapered fiber (not shown in Fig. 1) positioned on the other side of the microsphere from the input taper. In this case, WGM excitation produces a sharp peak in the output.

A schematic of our compression tuner is shown in Fig. 2. To improve the tuner's response speed, its moving mass was minimized by using aluminum except for the compression pads. The flexibility of the upper compression arm allows the design to accommodate a large range of microsphere sizes. During microsphere fabrication, a short axial stem is left attached.

The microsphere is then mounted in the tuner by inserting the stem into a short length of hypodermic tubing having an outer diameter of 300 μm. The tubing's 50-μm inner diameter makes 100 μm the practical lower limit on microsphere diameter for this tuner. Although fiber coupling was used for convenience, prism coupling[22] would be facilitated for spheres of diameter greater than 300 μm by using tubing above as well as below the sphere. Flexing of the lower arm preloads the piezoelectric actuator (PZT).

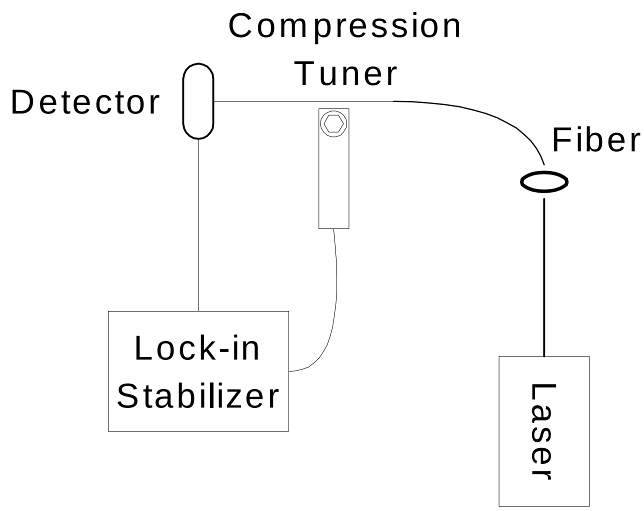

Fig. 1. Experimental setup. The lock-in stabilizer can use the detector signal to lock a WGM to the laser, or it may simply be used to apply a dc bias voltage to the compression tuner's PZT.

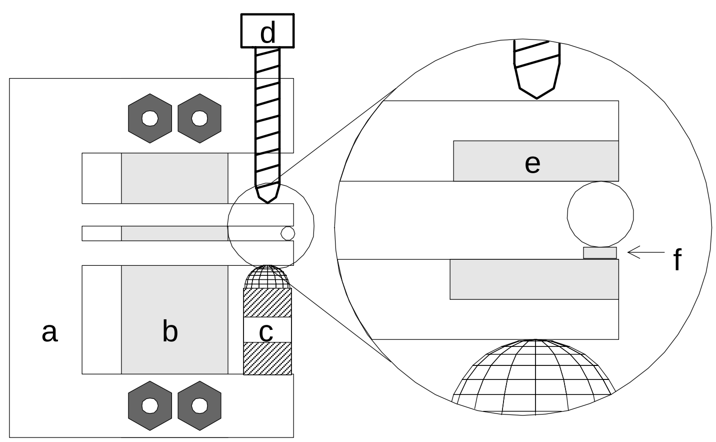

Fig. 2. Compression tuner. (a) Main body is 44×38×6-mm aluminum. (b) Stainless steel brace minimizes flexing of main body. (c) Piezoelectric actuator. (d) Manual tuning screw. (e) Hardened steel compression pad. (f) Stainless steel hypodermic tubing, inserted into hole in lower steel pad.

4. TUNING RESULTS

A figure of merit for tuning is the ratio of the tuning range to the free spectral range (FSR); this ratio will be approximately independent of microsphere size for a given tuner. Our microsphere had a nominal FSR of 120 GHz. This value is only weakly wavelength-dependent, so the same FSR applies both at our primary wavelength of 1570 nm and also at

830 nm, which we used for comparison with earlier results. Adjustment of our tuner's manual tuning screw allows coarse tuning over several free spectral ranges, permitting a choice of which set of modes to make accessible to PZT tuning. The manual tuning range was approximately 500 GHz (4.2 nm) at 1570 nm and 1 THz (2.2 nm) at 830 nm. Applying PZT voltages of up to the specified maximum of 150 V gave a fine-tuning range of 36 GHz (0.30 nm) at 1570 nm and 80 GHz (0.18 nm) at 830 nm. The latter value, two-thirds of a FSR, is nearly a factor of two greater than previously reported for compression tuning,[17] and also better than reported for stretch tuning.[18,19] The observed PZT-tuning ranges correspond to an axial diameter compression of approximately 1 μm. This is a fraction of the 7 μm expected for a 150-V bias, but a larger fraction than in previous work,[17] probably due to our use of harder contacting materials. The tuning ranges were measured by scanning the laser and noting the displacement of modes with PZT bias, as will be illustrated below. The frequency scale was calibrated using a commercial confocal optical spectrum analyzer with a FSR of 2 GHz. With other microspheres, we have more recently obtained PZT tuning of two-thirds of a FSR at 1570 nm, which would correspond to about 1.2 FSRs at 830 nm.

The tuning speed was measured by applying a 5-V peak-to-peak sine wave to the PZT; the resulting scan range is shown in Fig. 3 as a function of the frequency of this voltage signal. Using this method, the maximum tuning speed found was at least 16 GHz/ms, as seen in Fig. 4. These figures show that we could get significant tuning at a modulation rate of up to 13 kHz, thirty times faster than before,[17] due to the lighter tuner design. The strangely linear dependence of scan range on modulation rate is probably due to the added influence of driving the PZT through an effective low-pass filter, by simply connecting it directly to a function generator. We are currently correcting for this and expect to find that doing so will increase our measured tuning speed significantly.

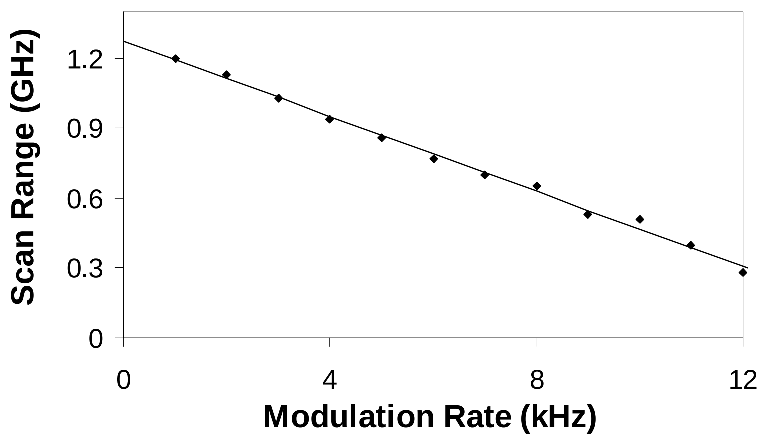

Fig. 3. Scan range, for a 2.5-V amplitude sinusoidal voltage applied to the PZT, versus frequency.

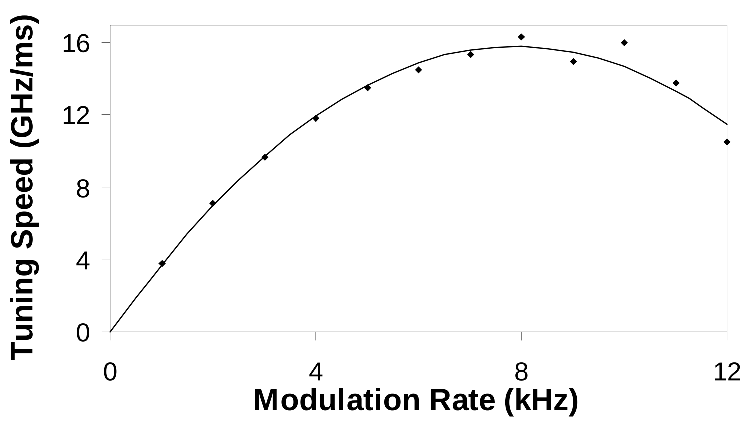

Fig. 4. Maximum tuning speed, calculated from the scan range data shown in Fig. 3.

5. LOCKING RESULTS

For locking a WGM to the laser, we used a commercial lock-in stabilizer designed for the stabilization of CO_2 lasers. Its 518 Hz modulation signal and dc bias were combined in a capacitive voltage divider for application to the PZT; an applied modulation amplitude of 15-30 mV gave the best lock, and the applied bias could be as large as 150 V. We chose to lock under conditions that would provide a stringent test of the stability of the technique, and so did not isolate the microsphere/fiber system from building vibration or air currents. Furthermore, the taper was chosen so that many modes were excited (perhaps up to q = 8 and $\ell - |m| = 25$), as seen in Fig. 5, where the 1570-nm laser was scanned over 19 GHz. The four laser frequency scans in traces (a)-(d) of Fig. 5 are over the same range, with different bias voltages applied to the PZT. All the modes have the same polarization, but there is some variability in their relative positions from (a) through (d) because of the slightly different tuning rates for modes of different m. The deepest dip, indicating about 20% coupling to a mode with $Q \approx 2\times10^6$, is the one to which we locked. (More recently, we have observed WGMs with Qs of better than 10^7 at this wavelength with the same coupling technique, and have locked to them.) A scan of the same range, with that mode locked to the laser, is shown in Fig. 5(e). Note that the slow power variation (from fiber transmission) is the same in (a)-(e). From (e), it is evident that the locking never switches to a different mode, because doing so would result in an obvious displacement of the trace; the larger fluctuations may indicate the temporary overlap of a differentially-tuning mode with the locked one. The noise level on this trace is consistent with the approximately 150 mV peak-to-peak noise on the PZT bias. As a result of this noise, the effective lock point fluctuates with an amplitude of about one-fifth of the 90-MHz WGM linewidth. Fig. 5(f) shows a reduced scan of 8 GHz under conditions of more uniform fiber transmission, illustrating the constancy of locked-mode power throughput that is achievable with our locking method.

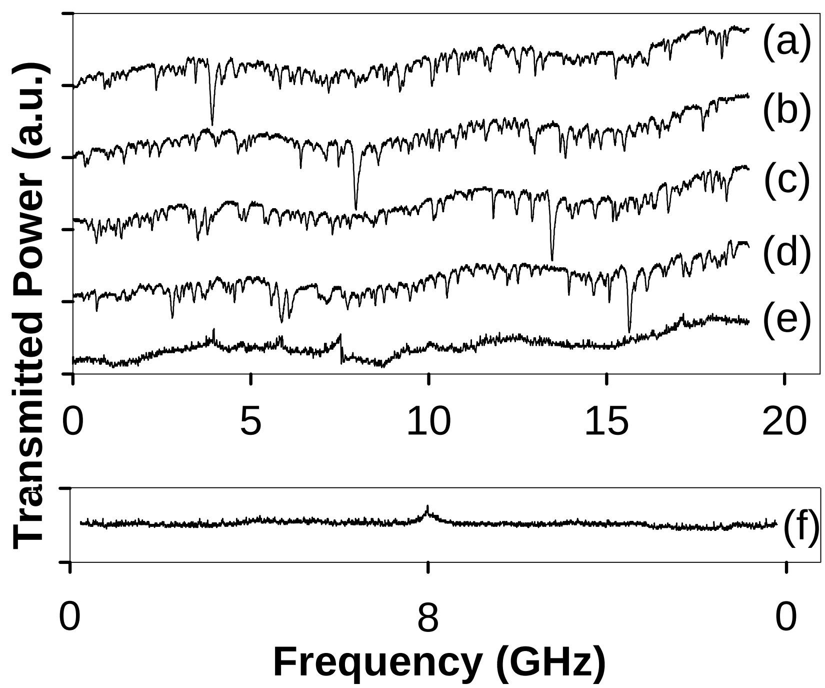

Fig. 5. Unlocked and locked frequency scans at 1570 nm. (a)-(d) WGM mode spectrum observed as the laser is scanned over a 19 GHz range; an increasing frequency shift is seen for PZT bias voltages of 68 V, 88 V, 118 V, and 130 V, respectively. The baseline for trace (a) is at the frequency axis, and successive traces have been displaced vertically. (e) Frequency scan where the WGM with the deepest dip in (a)-(d) is locked to the laser. The baseline is the same as for trace (d). (f) Another locked frequency scan (and return), with more uniform fiber transmission than in (a)-(e). No mode hops are observed in either locked trace.

Another verification of the robustness of WGM locking and tracking is shown in Fig. 6, where the PZT bias keeping a WGM locked to the 1570-nm laser (New Focus, model 6328) is plotted as the tuning signal applied to the laser's frequency-modulation input is ramped up and down. This is again the 19 GHz tracking range shown in Fig. 5(a)-(e). The lighter, smooth curve in Fig. 6 is the bias predicted from the laser frequency tuning as observed with an optical spectrum analyzer. Comparison of the two curves in Fig. 6 shows that most of the hysteresis seen in the bias is actually hysteresis in the laser tuning, with only a small contribution coming from the slight nonlinearity of the compression tuner's PZT. A mode jump would appear as a displacement of the bias curve by an amount on the order of ten times the noise level, and none are seen. The locking and tracking range shown in Figs. 5 and 6 is 19 GHz, but we were able to extend this to 30 GHz, the maximum scan range of the 1570-nm laser. Locking to the 830-nm laser worked just as well, and again the maximum tracking range was limited only by that laser's frequency scan range of 40 GHz. At 830 nm the WGMs had, typically, $Q \approx 5\times10^6$. Even under the environmentally noisy conditions that we used here, a WGM would remain locked to either laser for hours, with the laser scanning at rates of up to 2 GHz/s.

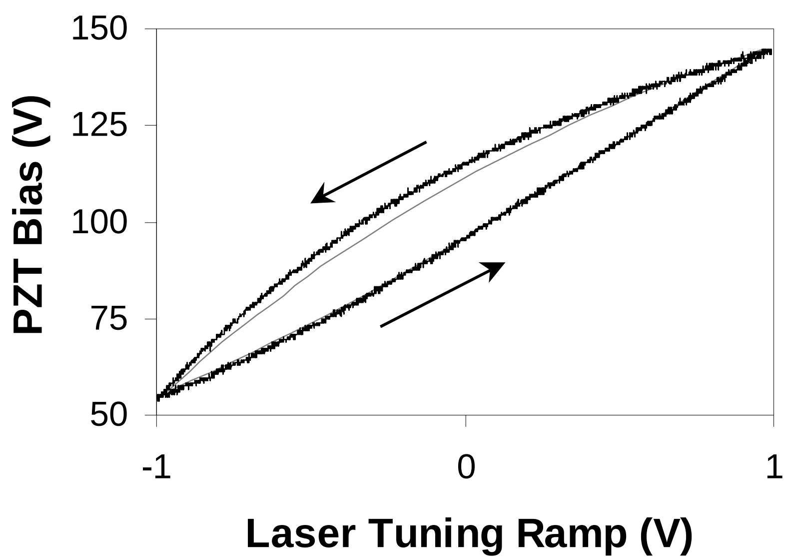

Fig. 6. Locked tuner PZT bias as it follows a frequency scan of the 1570-nm laser. Heavier curve: PZT bias; no mode hops are observed. Lighter curve: bias predicted from observed frequency hysteresis of laser tuning, assuming linear tuner PZT response.

We also tested the locking behavior by observing the transmission of fixed-frequency 830-nm light while a WGM was locked to the scanning 1570-nm laser. To do this, we simultaneously injected the beams of both lasers into the bi-tapered input coupling fiber. At that fiber's throughput end, we detected the 1570-nm signal and used it to lock. In addition, a single-tapered fiber was used for outcoupling as described above, and the 830-nm transmitted light was detected. As the locked microsphere followed the scanning laser, various modes were successively brought into resonance at 830 nm and their detection produced a WGM mode spectrum at that wavelength, in analogy with a typical scanning optical spectrum analyzer. Inspection of this mode spectrum also showed no obvious evidence of any locking mode hops. The best way to determine this, given the dense spectrum of excited modes, would be to compare the forward-scan and reverse-scan spectra. Unfortunately, the hysteresis in laser tuning made direct comparison difficult; while we could verify a one-to-one mapping of the spectra onto each other, this could not be done by simply superimposing the two traces. This difficulty could be overcome by programming our arbitrary waveform generator to provide an asymmetric ramp to the diode laser's frequency-modulation input, so that the laser frequency variation would be linear in time.

6. SUMMARY OF RESULTS

Some of our results for WGM frequency tuning, locking, and tracking are summarized in Table 1. These results, for a microsphere 550 μm in diameter, are representative of what we can achieve with the methods and apparatus described here. As noted above, using 1570 nm and other microspheres, we have observed PZT tuning ranges that are an even larger fraction of the FSR.

Table 1. Tuning Ranges for a 550-μm Diameter Microsphere at Two Wavelengths

Range	1570 nm	830 nm
FSR	120 GHz (1.0 nm)	120 GHz (0.27 nm)
Manual	500 GHz (4.2 nm)	1000 GHz (2.2 nm)
PZT	36 GHz (0.30 nm)	80 GHz (0.18 nm)
Locked*	30 GHz (0.24 nm)	40 GHz (0.09 nm)

*Limited by the lasers' continuous tuning ranges

7. CONCLUSIONS

Our new compression tuner allows for tuning over a greater range, and with faster response, than previously demonstrated.[17-19] The ability to lock a high-*Q* WGM to a laser, and to track the laser as it scans in frequency, will be useful for a number of potential applications of microsphere resonators, including cavity QED[4,18,19] and atom trapping.[5,6] Similarly, the tracking range demonstrated here is more than sufficient for the implementation of wavelength-modulation spectroscopy in WGM evanescent-wave atmospheric trace gas sensors.[15] Further reduction of the compression tuner's mass would enable even faster response, but the compression modulation frequency would still be restricted to less than the upper limit of the PZT response, which is 70 kHz. To achieve significantly faster scan rates, the locking modulation could be provided by the laser, with the tuner PZT used for application of the error correction signal to maintain lock; this technique would allow for the scan rate to be increased by three orders of magnitude or, equivalently, for WGMs of much greater *Q* to be used.

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