

Ultrastable vacuum-gap Fabry–Perot cavities operated in air

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We demonstrate a vacuum-gap ultrastable optical reference cavity that does not require a vacuum enclosure. Our simple method of optical contact bonding in a vacuum environment allows for cavity operation in air while maintaining vacuum between the cavity mirrors. Vacuum is maintained long term, with no observed degradation in cavity stability for over 1 year after bonding. For a 1550 nm laser stabilized to a 9.7 mL in-vacuum bonded cavity, the measured Allan deviation is 2.4×10^{-14} at 1 s, and its phase noise is thermal-noise-limited from 0.1 Hz to 10 kHz, reaching about -105 dBc/Hz at 10 kHz offset frequency. This represents the highest stability of any oscillator operated without a vacuum enclosure, to our knowledge. Furthermore, we demonstrate a 0.5 mL in-vacuum bonded cavity created using microfabricated mirrors and cavity dicing, with phase noise reaching -95 dBc/Hz at 10 kHz offset frequency. By relieving the need for high-vacuum enclosures, we greatly enhance the portability and utility of low-noise, compact, cavity-stabilized lasers, with applications ranging from environmental sensing to mobile optical clocks to ultralow-noise microwave generation. © 2024 Optica Publishing Group under the terms of the [Optica Open Access Publishing Agreement](#)

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1. INTRODUCTION

Ultrastable laser systems play a pivotal role across various technological and scientific domains, including precision timekeeping [1,2], precision spectroscopy [3], photonic microwave generation [4–6], and gravitational wave detection [7]. The conventional approach to constructing an ultrastable laser system involves locking a laser to a highly stable vacuum-gap Fabry–Perot (FP) cavity [8]. These rigid FP cavities, typically ranging in length from several centimeters to half a meter, can achieve remarkable stability through careful design and environmental control. Amazingly, proper cavity mounting and isolation results in vacuum-gap FP cavities that reach the stability limit determined by stochastic volumetric fluctuations in the cavity mirrors and high-reflection coatings, resulting in room-temperature length fluctuations below 10^{-16} m, equivalent to only a fraction of a proton charge radius [9]. By combining decimeter-long cavities with cryogenic operation, length instability below 10^{-17} m has been achieved, corresponding to a laser fractional frequency instability of only 4×10^{-17} [10].

Robust and field-deployable ultrastable laser systems are attractive for out-of-the-lab applications that can benefit from the low phase noise and high stability of ultrastable lasers, such

as satellite ranging and interferometry [11], photonic-based radar systems [12,13], mobile optical atomic clocks [14], and environmental sensing [15,16] (Fig. 1). Traditional vacuum-gap FP cavity systems, despite their superior performance, have significant drawbacks for such out-of-lab applications, mainly due to their large size and weight, as well as the need to maintain ultrahigh vacuum through constant active pumping. Therefore, there have been efforts to miniaturize these laser systems, broadly along two distinct paths: the development of solid-state dielectric resonators and the miniaturization of vacuum-gap FP cavities. Stable dielectric resonators include fiber delay lines [17–19], integrated spiral resonators [20–22], bulk fused silica FP [23–25], whispering-gallery-mode (WGM) resonators [26,27], and stimulated Brillouin scattering (SBS) in ring resonators [28]. Dielectric resonators, particularly on-chip resonators, can have the advantage of small size and manufacturability with lithographic techniques. But with performance limited by thermorefractive noise and the large thermal expansion coefficient typical of fiber, crystalline, and on-chip waveguide materials, the fractional instability of such resonators is typically above 1×10^{-13} . Indeed, it is useful to note that the highest-stability dielectric resonators are housed in vacuum enclosures with exquisite temperature control.

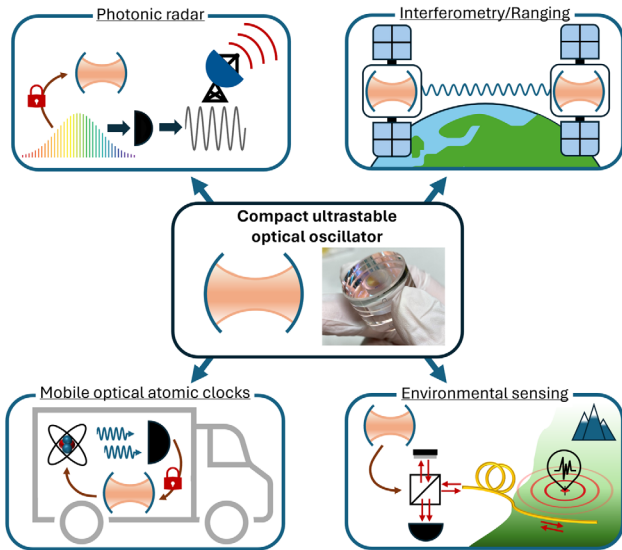


Fig. 1. Compact ultrastable laser applications. Compact and field-deployable ultrastable laser systems can be utilized in various applications, such as photonic-based radar systems [12,13], satellite ranging and interferometry [11], mobile optical atomic clocks [14], and environmental sensing [15,16].

Alternatively, the size of traditional vacuum-gap FP cavities can be reduced to make them compact and portable [29–31]. For example, a vacuum-gap FP with a volume of only 8 mL has been used to demonstrate fractional frequency instability of only 7×10^{-15} at 1 s [31]. While such high performance has been demonstrated with greatly reduced cavity size, the requirement for a vacuum enclosure and vacuum pump is not eliminated, and represents a barrier to the realization of compact and portable field-deployable systems.

In this work, we demonstrate laser stabilization with 10^{-14} level fractional frequency instability with a sub-10 mL volume cavity while operating without a vacuum enclosure. The cavity performance represents the highest stability ever achieved across optical, microwave, or radio frequency domains without vacuum operation. To accomplish this, we have devised a simple and straightforward method to bond the cavity in vacuum, essentially turning the cavity itself into a vacuum cell. With this bonding, and with the cavity surrounded by atmospheric pressure, the optical phase noise is at the mirror coating noise limit across 5 decades of offset frequencies, from 0.1 Hz to 10 kHz, reaching a phase noise level below -100 dBc/Hz at 10 kHz offset. The fractional frequency stability likewise reaches the thermal noise limit, and is only 2.4×10^{-14} at 1 s. For one of our in-vacuum bonded cavities that has been operated for over 1 year, we see no degradation in either phase noise or frequency stability. Furthermore, we combine the in-vacuum bonding method with micro-fabricated mirrors to demonstrate a 0.5 mL volume miniature cube cavity. This cavity is diced from an array of miniature cavities, and achieves phase noise of -95 dBc/Hz at 10 kHz offset and competitive Allan deviation performance. Thus these in-vacuum bonded cavities enable a significant simplification of the vacuum-gap FP-based ultrastable laser system, removing the bulky vacuum enclosure and active vacuum pumping requirements, without degrading the performance. With unprecedented frequency stability and phase-noise properties in a compact setup, this work points towards a truly portable and field-deployable ultrastable optical reference.

2. VACUUM REQUIREMENT ANALYSIS AND MEASUREMENT

The vacuum requirement for ultrastable FP cavity systems arises from the desire to eliminate cavity length fluctuations coming from variations of the refractive index in the optical beam path, such that the cavity can operate at the thermal noise limit determined by the cavity mirror substrates and coatings. Vacuum in ultrastable FP cavity systems is typically held with an ion pump, since this pump type has no moving parts that could couple vibrations to the cavity. However, ion pumps best operate in the high- and ultrahigh-vacuum regimes, that is, at pressure levels below 10^{-6} hPa. As we show in this section, this is far below what is required for the cavity to operate at the thermal noise limit.

First, we estimate the residual gas pressure that allows us to reach our cavity thermal noise limit using a model developed for LIGO [32]. In this model, noise caused by refractive index fluctuations is derived from a microscopic picture that considers the effects of individual molecules entering the optical beam path. As shown in more detail in Supplement 1, assuming a constant beam radius w_0 and ideal gas condition, the resulting single-sideband optical phase noise on an optical carrier at frequency ν at offset frequencies below 100 kHz is well approximated by

$$\mathcal{L}(f) \approx \sqrt{\frac{m}{2}} \frac{8\pi^2 \alpha^2}{L w_0} \frac{P}{(k_B T)^{3/2}} \frac{\nu^2}{f^2}, \quad (1)$$

where α is the polarizability of the gas molecules, m is the mass of the individual gas molecule, L is the cavity length, P is the residual gas pressure, k_B is the Boltzmann constant, T is the system temperature, and f is the offset frequency.

A key assumption in the derivation of Eq. (1) is that the residual gas molecules pass through the beam without collisions with other molecules. This means that the mean free path of the molecules should be much larger than the cross-sectional diameter of the beam, which puts an upper bound on the pressure for this assumption to be valid. For our compact optical reference cavities, the average beam radius is around 0.2 mm, such that the applicable pressure range is below about 0.1 hPa (assuming the gas is predominately nitrogen molecules maintained at 300 K). If the cavity length is 6.35 mm and the optical carrier frequency is 1550 nm, Eq. (1) suggests $\mathcal{L}(1 \text{ Hz}) \approx -44$ dBc/Hz and $\mathcal{L}(1 \text{ kHz}) \approx -104$ dBc/Hz at a pressure level of 0.1 hPa, which are well below the thermal noise limit such a cavity can achieve [33]. Thus, it should not be necessary to have a high-vacuum environment for the cavity to perform at its thermal noise limit. In fact, the required vacuum level is expected to be quite moderate.

To verify this conclusion, we experimentally measured the phase noise of a 1550 nm laser locked to a 6.35-mm-long cavity operating at different pressure levels. The experimental setup is shown in Fig. 2(a). A 1550 nm commercial fiber laser is locked to the cavity via the Pound–Drever–Hall (PDH) method, with fast feedback control achieved through an acousto-optic modulator (AOM) and slow feedback control through the laser’s piezoelectric tuning port. The cavity has a vent hole and is mounted in a vacuum chamber placed inside an acoustic isolation box on a vibration isolation stage. Connected to the vacuum chamber are a vacuum gauge and an ultrahigh-vacuum (UHV) valve. First, we pump the vacuum chamber pressure down to 10^{-7} hPa using a turbo pump, then close the UHV valve and disconnect the pump. Without active pumping, the vacuum chamber does not hold at 10^{-7} hPa and the pressure will slowly rise. A heterodyne beat is

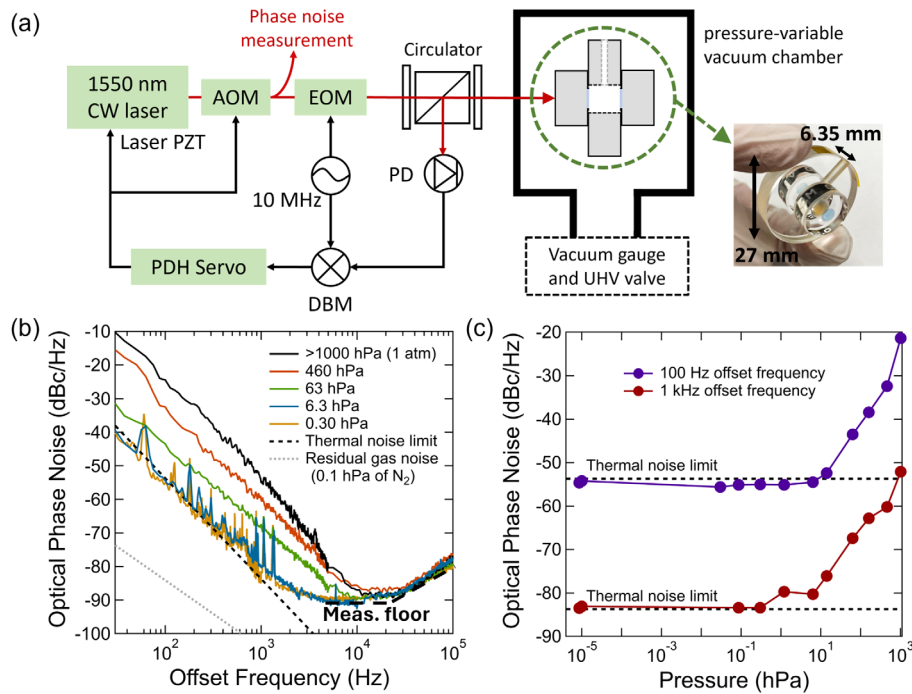


Fig. 2. Vacuum requirement measurement. (a) Experimental setup. A 1550 nm continuous wave (CW) laser was stabilized via the Pound–Drever–Hall (PDH) method to the 6.35-mm-long reference cavity, which was mounted in a pressure-variable vacuum chamber. A portion of the light after the acoustic-optic modulator (AOM) was taken to beat with a stable reference for phase noise measurements at different pressure levels. PZT: piezoelectric transducer. EOM: electro-optic modulator. DBM: double-balanced mixer. PD: photodetector. UHV: ultrahigh vacuum. (b) Selected phase noise traces at different pressure levels plotted with the estimated thermal noise limit of the cavity and the residual gas noise for 0.1 hPa of nitrogen molecules. After 1 kHz offset, the measurement is limited by the signal-to-noise ratio (SNR) of the heterodyne beat. (c) The change of phase noise levels at 100 Hz offset frequency and 1 kHz offset frequency as pressure increases. The uncertainty in the pressure reading is estimated to be about 30% for the pressures below 100 hPa and 50% for the pressures above 100 hPa.

taken between the cavity stabilized light and an optical frequency comb (OFC) fully stabilized to the local oscillator of a Yb atomic clock [34]. While the pressure inside the chamber rises, phase noise measurements are performed on the heterodyne beat at different pressure levels indicated by the vacuum gauge. The experimental results are shown in Figs. 2(b) and 2(c). The phase noise was limited by the cavity thermal noise limit at low pressures and only starts to deviate from this limit after reaching 0.30 hPa. (After 1 kHz offset, the measurement is limited by the signal-to-noise ratio of the heterodyne beat and noise from the optical frequency comb.) This measurement confirms that only a very moderate level of vacuum (< 0.3 hPa) is needed for the cavity to be thermal-noise-limited out to an offset frequency of at least 1 kHz, and that continuous vacuum pumping may not be necessary for best phase noise performance.

3. IN-VACUUM BONDING AND CAVITY PERFORMANCE

Demonstrations of vacuum-tight glass-to-glass optical contact bonds date back at least 60 years [35]. Furthermore, we note that the strength of optical contact bonding between smooth and well-prepared glass surfaces can be on the same order as the strength of the bulk glass [36,37]. However, we are unaware of any prior investigation that shows that the achievable vacuum seal from an optical contact bond can support thermal-noise-limited, ultrastable cavities, or that the required vacuum level can be held long-term. In this section, we describe experiments where we bond cavities in

vacuum, then lock lasers to the cavities without a vacuum enclosure to demonstrate thermal-noise-limited phase noise performance. Moreover, with repeated low-phase-noise measurements in the months since the initial bonding, we establish the longevity of the in-vacuum bond.

We have bonded several cavities to date using standard off-the-shelf components. Here we describe the essential elements of the bonding technique and results from one of our cavities. More details on the bonding and results from our other cavities may be found in Supplement 1. The mirror substrates and cavity spacer are all made with ultra-low-expansion (ULE) glass. They have a cylindrical shape with a diameter of 25.4 mm and a length of 6.35 mm. The spacer has a 10 mm diameter center bore hole but, importantly, does not contain a vent hole. One of the mirror substrates has a 1 m radius of curvature (ROC), whereas the other mirror is flat. Both mirrors have a highly reflective ($>99.999\%$) dielectric coating, and the coating diameter is less than that of the bore hole. The contacting surfaces on the mirrors and spacer are superpolished to the level typical of optical contact bonding, with an average surface roughness of a few angstroms. The in-vacuum bonding setup is illustrated in Fig. 3(a). After cleaning, the substrates were placed into a specially designed, vacuum-compatible holding structure that easily aligns the mirrors and spacer concentrically. One mirror substrate was placed at the bottom of the holding structure with the spacer resting directly on top of it. The top mirror substrate is held by friction about 2 mm above the top surface of the spacer. The holding structure containing all three pieces is then placed in a vacuum bellows valve, which is connected

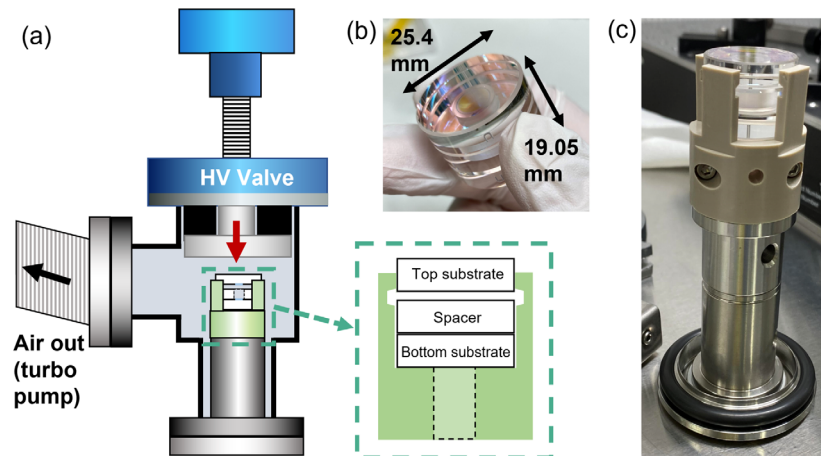


Fig. 3. In-vacuum bonding method. (a) The mirror substrates and the vent-hole-less spacer are aligned by a vacuum compatible holding structure, which holds the top mirror substrate about 2 mm above the spacer. The holding structure is then placed inside a high-vacuum (HV) bellows valve, which is connected to a turbo pump. Rotating the handwheel of the valve presses the top mirror down and bonds the cavity. (b) Photograph of an in-vacuum bonded cavity. (c) Photograph of the holding structure containing the mirror substrates and spacer.

to a turbo pump. A vacuum gauge is included between the bellows valve and the turbo pump to monitor the pressure. The pressure quickly falls below 10^{-5} hPa, after which we rotate the hand wheel of the valve to lower the inner top surface such that it presses the top mirror substrate into contact with the spacer. While maintaining a compressive force on the bonded cavity, we then shut down and remove the turbo pump. The bonded cavity, surrounded by atmosphere pressure, is then held under the continuous compression force inside the vacuum valve for a few days before being removed for measurements. A picture of an in-vacuum bonded cavity is shown in Fig. 3(b), and a picture of the holding structure with mirror substrates is shown in Fig. 3(c).

A 1550 nm laser was locked to the cavity using the PDH technique as shown in Fig. 4(a), with locking electro-optics similar to what is shown in Fig. 2(a). The cavity finesse is 591,000, corresponding to a full-width at half-maximum linewidth of 40 kHz. The optical power level illuminating the cavity was near 200 μ W. To test the phase noise and frequency stability of the cavity, we mount the cavity at room air pressure into a Macor V-groove holder [Fig. 4(b)] enclosed by an air-tight metal enclosure. Without vacuum surrounding the cavity, we find an air-tight enclosure critical to keeping the cavity's temperature and outer-air pressure constant, yielding the best results. We did not determine the coefficient of thermal expansion (CTE) zero-crossing temperature of the cavity, and the temperature of the enclosure is actively maintained at an experimentally convenient choice of 30°C. The temperature fluctuation of the enclosure is on the order of 10 mK per day. Air pressure sensitivity of the cavity is discussed further in Supplement 1. Since we are primarily concerned with assessing the low-noise abilities of in-vacuum bonded cavities, the cavity geometry is not optimized for minimum acceleration sensitivity and was placed within a passive acoustic isolation box with active vibration cancellation.

To measure its phase noise, we split the cavity-stabilized light into two channels and compared against two independent ultra-stable optical references: an optical frequency comb stabilized to the local oscillator of an Yb optical atomic clock, and a 1550 nm laser stabilized to a 10-cm-long vacuum-gap cavity. The two heterodyne beat notes with the two references are digitally sampled

and cross-correlated to reveal the noise of our cavity-stabilized laser [29]. We have performed periodic measurements of the laser phase noise, allowing us to assess the longevity of the vacuum-tight bonding. Representative data are shown in Fig. 4(c) along with the cavity's thermal noise limit given by Brownian noise in the coatings [33]. At both 6 months and our most recent measurement at 11 months after bonding, the laser phase noise corresponds to the thermal noise limit of the cavity across nearly 5 decades of offset frequencies, from 0.1 Hz to nearly 10 kHz. At 2 weeks after bonding the noise below 10 Hz offset was slightly elevated, likely due to laser intensity noise coupling to the cavity length [38]. Laser intensity noise was improved before the 6- and 11-month measurements were made. As shown in Supplement 1, our other bonded cavities have been tested with less acoustic isolation and temperature control, and over 1 year since bonding, yet all achieve phase noise limited by the cavity thermal noise, with phase noise ≤ -100 dBc/Hz at 10 kHz offset.

The laser's fractional frequency stability was also recorded, and is shown in Fig. 4(d). For measurements at 6 months and 11 months after bonding, the Allan deviation (ADEV) reaches the thermal noise limit at 1.6×10^{-14} for timescales less than 0.3 s. At 1 s, the ADEV is below 3×10^{-14} , and for longer timescales each measurement corresponds to a cavity drift rate in the range of 3–5 Hz/s. While the drift rate does vary, there has remained an overall one-way drift, corresponding to a continuous decrease in the optical frequency with a varying rate anywhere from 1 Hz/s to 5 Hz/s. The average drift rate over several months is about 3 Hz/s. The long-term drift is slightly larger than is typical of traditional all-ULE vacuum-gap cavities that are held in thermally shielded vacuum enclosures. The exact sources of the continuous one-way drift are still under investigation. However, we note that our spacer was not acid etched after machining, which is known to improve the dimensional stability of ULE glass [39,40]. Acid etch is common practice for ultrastable cavity spacers and will be incorporated in future cavity builds.

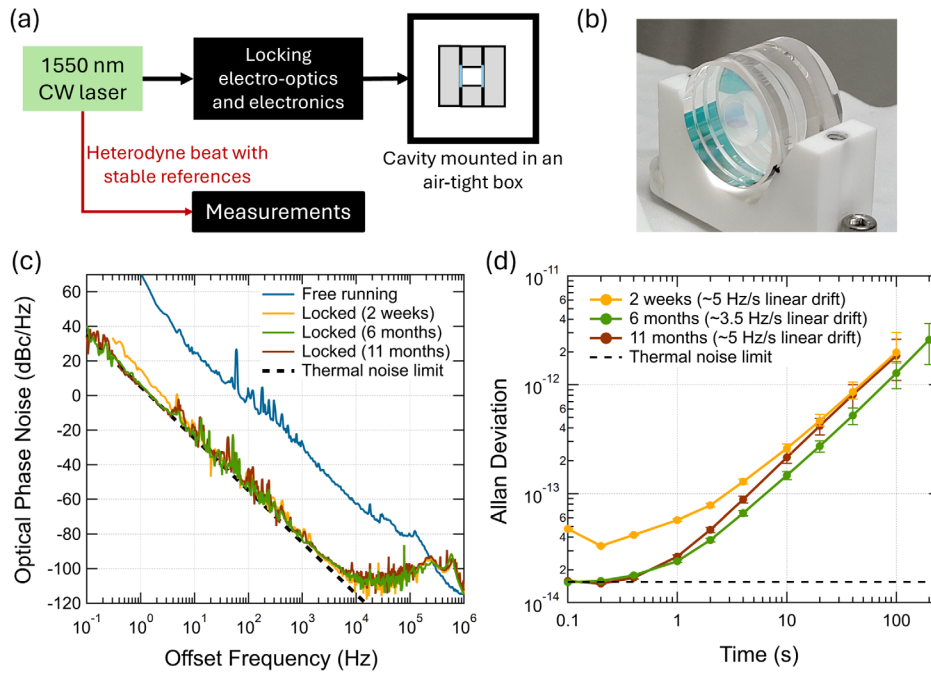


Fig. 4. Measurements on the in-vacuum bonded cavity. (a) Simplified diagram illustrating the measurement setup. A 1550 nm fiber laser was stabilized to the in-vacuum bonded cavity via the method of PDH. Part of the stabilized light was taken for phase noise and Allan deviation measurements. The in-vacuum bonded cavity was mounted in an air-tight metal box that is actively maintained at 30° C with acoustic and vibration isolation. (b) Photograph of the in-vacuum bonded cavity inside the V-groove holder made with Macor. The cavity rests on two Viton strips. (c) Phase noise of the laser stabilized to the in-vacuum bonded cavity, measured at different times after the cavity was bonded, together with the free-running laser noise and the cavity’s estimated thermal noise limit. (d) Allan deviation of the laser stabilized to the in-vacuum bonded cavity, measured at different times after the cavity was bonded, together with the cavity’s estimated thermal noise limit.

4. IN-VACUUM BONDED CAVITY WITH LITHOGRAPHICALLY FABRICATED MIRRORS

The successful creation of ultrastable cavities with in-vacuum bonding creates the opportunity to construct extremely compact cavity-stabilized laser systems. Towards this end, we combined the in-vacuum bonding technique with microfabricated mirrors to create an ultrastable resonator whose volume is only 0.5 mL.

We fabricated an array of nine high-finesse, 35-cm-ROC mirrors on a 2-inch-diameter, 2-mm-thick ULE substrate, using the technique described in [41]. The mirror substrate was matched to a 2-inch-diameter, 3-mm-thick ULE spacer with nine bore holes,

and a high-finesse 2-inch-diameter, 2-mm-thick ULE flat. The mirror substrates and spacer were bonded in vacuum, similar to the procedure described above. After bonding, the multi-cavity structure was annealed and diced into separate individual cavities. More details on the creation of these cavities will appear in a future publication. One of these miniature cavities was then selected for phase noise and frequency stability testing. The measured cavity finesse is 400,000. The cavity was mounted in a purpose-built, air-tight enclosure made of aluminum as shown in Fig. 5(b), and the whole cavity system is placed within a passive acoustic isolation

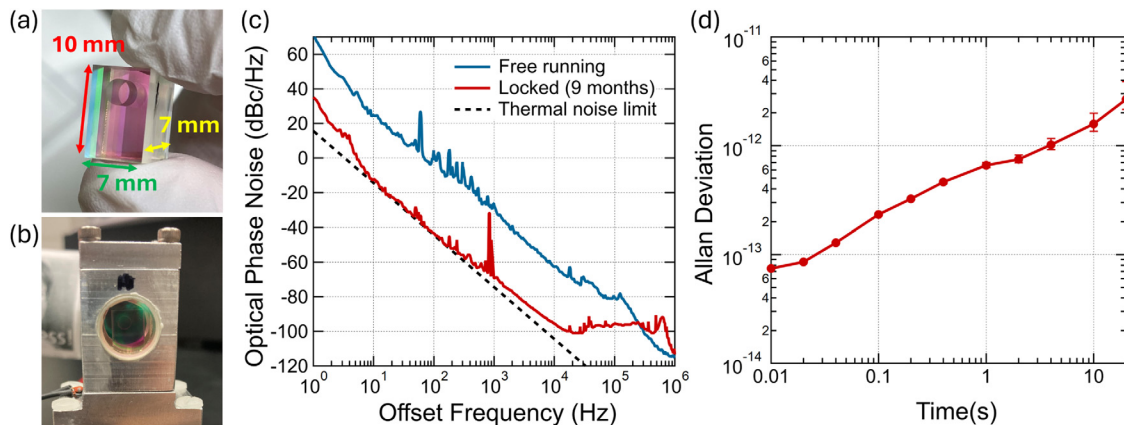


Fig. 5. Measurements on the in-vacuum bonded cavity with lithographically fabricated mirror. (a) Photograph of the cavity under test that was diced out of an array of cavities. (b) Photograph of the cavity inside the air-tight metal enclosure. (c) Phase noise measurement on a 1550 nm laser stabilized to the cavity. Blue: free running laser noise. Red: phase noise at 9 months after bonding. Black: estimated thermal noise limit of the cavity. (d) The corresponding measured Allan deviation.

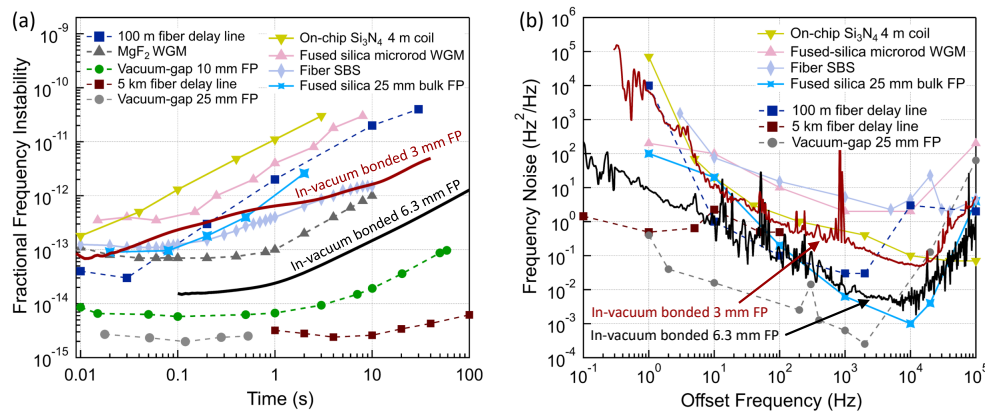


Fig. 6. Performance comparison of this work with various state-of-the-art compact optical resonators and ultrastable laser systems. (a) Comparison of fractional frequency instability expressed as Allan deviation. (b) Comparison of laser frequency noise (scaled to 1550 nm). On-chip Si_3N_4 4 m coil [22], fused silica microrod WGM [26], fiber SBS [28], fused silica 25 mm bulk FP [25], 100 m fiber delay line [18], MgF_2 WGM [27], vacuum-gap 10 mm FP [31], 5 km fiber delay line [19], vacuum-gap 25 mm FP [29]. Dashed lines represent the presence of vacuum environment.

box on a vibration isolation stage without active temperature stabilization. The optical power for this cavity was increased to about $500 \mu\text{W}$. This increase was to compensate for the broader cavity linewidth and resulting lower slope of the PDH discriminant.

The experimental results are shown in Figs. 5(c) and 5(d). The measured phase noise is thermal-noise-limited from about 10 Hz to about 300 Hz, reaching about -95 dBc/Hz at 10 kHz offset frequency. For offset frequencies below 10 Hz, the phase noise exceeds the thermal noise limit primarily due to temperature fluctuations, with additional noise contributions from coupling of the laser intensity noise. We anticipate much improvement in a well-controlled temperature environment combined with an optimized laser intensity servo. The deviation from the thermal noise limit after 300 Hz is still under investigation, but could indicate residual gas within the cavity. The Allan deviation is around 7.5×10^{-14} at 0.01 s and 6.5×10^{-13} at 1 s. As with the close-to-carrier phase noise, the frequency instability at these timescales is also limited by temperature and laser intensity fluctuations. Despite this, the low phase noise can immediately be utilized in applications where short-term phase stability is needed. For example, through the use of optical frequency division [4], this extremely compact cavity can support 10 GHz microwave generation with phase noise below -180 dBc/Hz at 10 kHz offset. With this bond-and-dice approach, we foresee a path towards mass production of such miniature ultrastable optical reference cavities.

5. DISCUSSION AND CONCLUSION

The context by which we may evaluate the performance of our in-vacuum-bonded compact optical reference cavities is shown in Fig. 6. Vacuum-gap FP cavities are now approaching the form factor associated with on-chip and whispering gallery mode resonators, but with superior phase noise and frequency stability performance. With the optical mode primarily propagating in vacuum, the thermorefractive noise that dominates solid-state dielectric resonators is largely eliminated. Furthermore, the use of ULE can provide orders of magnitude lower thermal expansion coefficients than crystalline, optical fiber, or on-chip SiN resonators, leading to a commensurately lower temperature sensitivity. We note that the lowest-noise dielectric resonators require operation

in high-vacuum and multilayer thermal shielding to achieve their high-stability results [19,27].

Compared to larger vacuum-gap FP resonators, the thermal-noise-limited phase noise of our cavities is higher due to the shorter optical cavity length. However, there are many applications for which this higher phase noise floor does not pose a limitation, while a smaller form-factor more easily enables out-of-the-lab use. As noted above, a compact optical reference cavity used in conjunction with an optical frequency comb can support microwave generation with phase noise much lower than conventional electronic sources [4], and common-mode rejection of laser noise in many fiber sensing applications relaxes the phase noise requirements at small offset frequencies [42]. Importantly, the higher thermal noise of compact cavities is less of an obstacle at higher offset frequencies—our demonstrated optical phase noise of -105 dBc/Hz at 10 kHz offset is one of the lowest at this offset frequency of which we are aware for a cavity of any size. However, it is also worth noting that, since the phase noise is limited by Brownian noise in the coatings, a longer cavity should result in improved noise performance.

In-vacuum bonded cavities can be further engineered for improved robustness and integration in compact laser systems. While our cavity demonstrations are of simple cylindrical and cubic geometries, in-vacuum bonding is amenable to other designs optimized for low acceleration sensitivity and rigid holding [29,30,43–46]. This will be critical for use beyond the laboratory. Furthermore, recent developments in integrating small FP cavities with waveguides on chip [47], when used in conjunction with low-noise on-chip lasers [48], should enable a low-noise, fully integrated chip-based reference-cavity system.

In summary, we have developed an in-vacuum bonding technique to provide vacuum-gap ultrastable optical reference cavities that operate surrounded by air. Despite the lack of a vacuum enclosure, the cavities perform at the thermal noise limit determined by Brownian noise of the coatings. By combining in-vacuum bonding with microfabricated mirrors, we created an ultrastable reference cavity whose volume is only 0.5 mL. We anticipate this advance in ultrastable laser technology will accelerate a variety of out-of-the-lab applications, including mobile optical atomic clocks, photonic radar, and sensing.

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Disclosures. The authors declare no conflicts of interest.

Data availability. Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

Supplemental document. See Supplement 1 for supporting content.

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