Optomechanical Magnetometry with a Macroscopic Resonator

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We demonstrate a centimeter-scale optomechanical magnetometer based on a crystalline whispering gallery mode resonator. The large size of the resonator, with magnetic field integration volume of 0.45 cm^3, allows high magnetic field sensitivity to be achieved in the hertz to kilohertz frequency range. A peak sensitivity of 131 pT Hz$^{-1/2}$ is reported, in a magnetically unshielded non-cryogenic environment using optical power levels beneath 100 μW. Femtotesla range sensitivity may be possible in future devices with further optimization of laser noise and the physical structure of the resonator, allowing applications in high-performance magnetometry.

I. INTRODUCTION

Whispering gallery mode (WGM) resonators play an important role in modern optics, with applications as laser cavities [1], resonant filters [2], optical switches [3], and precision sensors [4–7] among other areas. They have been recently used for magnetometry [8, 9] based on the ideas of cavity optomechanics [10]. WGM resonator based optomechanical magnetometry combines the ultra-high optical transduction sensitivity of WGM resonators with the giant magnetostriction of materials such as Terfenol-D, achieving high sensitivity while allowing room-temperature operation, low optical power levels, and simple all-optical readout. Theoretical modelling indicates that future fully optimised devices that attain the fundamental thermomechanical noise floor may achieve sensitivity in the low, or even sub-, femtotesla range [11]. These advantages provide a pathway towards potential future applications in areas such as geophysical surveying [12], tests of fundamental physics [13, 14], medical imaging [15, 16], and space exploration [17, 18].

Optomechanical magnetometers based on microscale on-chip WGM resonators have achieved 200 pT Hz$^{-1/2}$ magnetic field sensitivity at megahertz frequencies [8, 9]. However, due to a combination of noise sources at low frequency and poor low frequency mechanical response, magnetic field sensing in the hertz to kilohertz frequency range was only possible using inherent mechanical nonlinearities within the magnetostrictive material [9]. This indirect approach caused a sacrifice in sensitivity to 110 nT Hz$^{-1/2}$. The hertz-kilohertz frequency range is crucial to many applications including, for instance, magnetic anomaly detection [19], geological surveying [20] and magnetoencephalography [16]. To enable highly sensitive magnetic field sensing in this regime, we have developed a centimeter-scale crystalline WGM resonator based magnetometer, which features reduced thermomechanical noise, lower frequency mechanical resonances, and higher optical quality factor than previously demonstrated optomechanical magnetometers. By embedding the magnetostrictive material (Terfenol-D) within the WGM resonator, sub 10 nT Hz$^{-1/2}$ sensitivity was achieved over most of the frequency band from 127 Hz to 600 kHz, with a peak sensitivity of 131 pT Hz$^{-1/2}$ at 127 kHz.

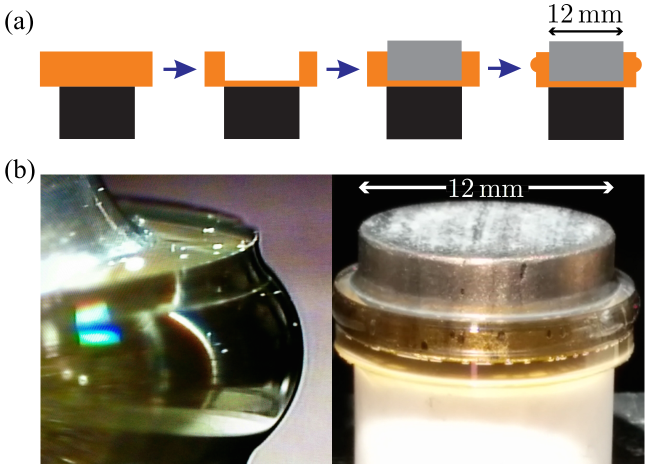

FIG. 1. (a): The fabrication process. Black area: ceramic, yellow area: CaF$_2$, gray area: Terfenol-D [Etrema products Inc.]. (b) Optical microscope images of the resonator.

II. RESONATOR FABRICATION AND CHARACTERISATION

The WGM resonator was fabricated using the Ultra-precision Machining Facility at the Australian National University, housing a Moore Nanotech 250 UPL diamond turning lathe. WGM resonators are particularly well-suited for fabrication by diamond turning due to their cylindrical symmetry. We fabricated the resonator from

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CaF$_2$ due, primarily, to the previously demonstrated capability to achieve exceptionally high optical quality factors using this material [21]. We expect that similar results to those reported here could alternatively be achieved using other materials such as quartz [22], lithium niobate [23], or magnesium fluoride [24]. The fabrication process of the magnetometer is shown in Fig. 1(a). A bulk of CaF$_2$ crystal, which was attached to a ceramic pedestal using a vacuum compatible epoxy glue (EPO-TEX 353ND), was first rough-cut to form a WGM resonator with a diameter of 16 mm. Lathing was also used to bore a void in the top of the crystal WGM structure. The void was machined to a diameter 30 μm larger than the actual size of the disk of Terfenol-D (of diameter and thickness approximately 12 mm and 4 mm, respectively, resulting in a magnetic field integration volume of 0.45 cm^3). The 15 μm gap was the minimum that allowed the epoxy glue, due to its viscosity, to uniformly fill the interface of the two materials. Next, we machined the final WGM structure with the radius of curvature of the resonator's rim of 1.616 mm [25].

The final step is to polish the resonator to achieve an extremely smooth surface, i.e., a high intrinsic optical quality factor. Using the lathe to rotate the WGM resonator and ensuring that the resonator was precisely centred on the rotational axis, polishing was accomplished using a polishing pad and diamond slurry. Starting with 0.5 μm particle size, large chips on the surface of the resonator left after cutting were removed and using progressively smaller particle sizes down to 0.05 μm, the final polishing was achieved. The physical structure of the resonator is shown in Fig. 1(b).

The optical quality factor of the WGM resonator was characterized via cavity ringdown measurement [26], using the setup shown in Fig. 2(a). Alternatively, the quality factor could be determined by sweeping the laser frequency over the optical resonance and determining the linewidth of the resonance. Cavity ringdown was chosen here to avoid inaccuracies introduced both by thermo-optic effects, where optical heating of the resonator shifts its resonance frequencies and thereby modifies the observed lineshapes [27], and by possible laser frequency calibration errors. A fiber laser of wavelength $\lambda = 1550$ nm was critically coupled into the resonator using a prism mounted on a 3-axis nanopositioning stage. Critical coupling was achieved by locating the prism at a distance from the resonator which minimized the power totally-internally reflected from the prism surface, and therefore maximized the intra-resonator power. An optical intensity modulator with a 35 ps rise/fall time and a 20 dB extinction ratio was used to rapidly switch off the laser intensity. The exponential decay of light out of the resonator was then detected using a fast photodiode. The resulting cavity ringdown measurement is shown in Fig. 2(b). The cavity lifetime τ_e was determined to be 233 ns from an exponential fit to the data (grey line in Fig. 2(b)), which corresponds to an intrinsic optical quality factor of $Q \equiv \Omega\,\tau_e = 2\pi c\,\tau_e/\lambda = 2.8 \times 10^8$, where Ω is the angular frequency of the laser, and c is the speed of light in vacuum [28]. We note that this quality factor is significantly lower than the best reported quality factors for polished crystalline CaF$_2$ resonators [21]. Substantially higher quality factors were observed on initial alignment of the system, with degradation occurring due to surface imperfections introduced from repeated contact of the prism to the resonator surface. As discussed later, the quality factor was sufficiently high that our current experiments are limited by laser phase noise and mechanical characteristics, rather than cavity quality.

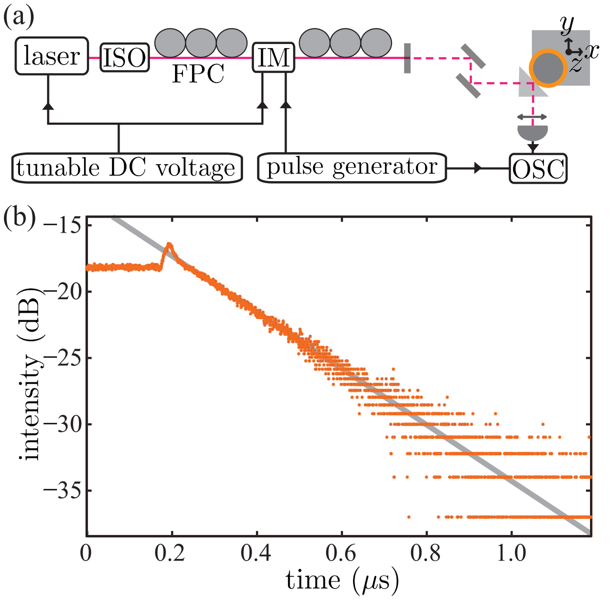

FIG. 2. Ringdown measurements. (a): Schematic of the apparatus used to perform ringdown measurement of the optical quality factor. FPC: fiber polarization controller, IM: intensity modulator [OC-192 Modulator JDS Uniphase], OSC: oscilloscope [Tektronix TDS 2024B], pulse generator [Stanford DG535], nanomax stage [Thorlabs MDT693A], prism [uncoated N-BK7 right angle prism], detector [New Focus Model-1811]. (b): Plot of the relative detected optical intensity, with the EOM used to shutter the optical field at $\sim$ 175 ns. The solid grey curve is an exponential fit to the data over the range 221–454 ns.

III. EXPERIMENT

Fig. 3 shows a schematic of the measurement setup. Light from the fiber laser was passed through an isolator and an electro-optic modulator (EOM), and then evanescently coupled to the resonator in the same manner as described in the previous section. The EOM was used to phase modulate the light at 13.6 MHz, well outside the resonator's linewidth ($\kappa/2\pi = \tau_e^{-1}/2\pi < 1$ MHz). The output field from the resonator was detected on an InGaAs photoreceiver. Electronic mixing of this output with a 13.6 MHz local oscillator generated a Pound-

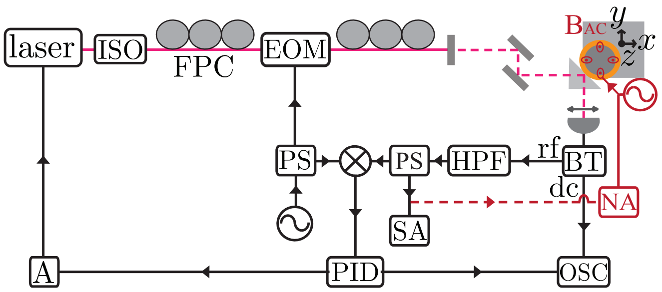

FIG. 3. A schematic of the experimental set-up used to perform magnetic field sensing. Laser [Koheras Adjustik C15], ISO: isolator [Thorlabs-OFR], EOM: electro-optic modulator [Covega Phase Modulator], NA: network analyzer [Agilent E5061B], SA: spectrum analyzer [Agilent N9010A], PID: proportional integral derivative controller [New Focus LB1005], BT: bias tee [Mini circuits 0.1-4200 MHz], HPF: high-pass filter [Mini circuits 0.07-1000 MHz], LPF: low pass filter [Mini circuits DC-1.9 MHz], PS: power splitter [Mini circuits 1-650 MHz], A: amplifier [ZFL-500].

Drever-Hall (PDH) error signal [29]. This error signal provided a measure of the deviation of the laser frequency from the cavity resonance frequency. In a similar approach to Ref. [30], this signal was used both to lock the laser to the cavity resonance, and to detect the effect of applied magnetic fields on the length of the cavity – i.e., it provided the magnetic field signal. To maximise the signal-to-noise ratio (SNR) of the sensor, a large modulation was applied to the EOM, transferring approximately half of the optical power into 13.6 MHz sidebands. It was found that only 40 μW of off-resonant light was required at the photoreceiver to resolve the noise of the optical field over the photoreceiver electronic noise floor. A coil with diameter of 6.5 cm and a total of 60 turns was positioned above the resonator, and used to generate the signal magnetic field to be detected. The strength of this field was calibrated using a commercial Hall probe [Hirst GM04]. A neodymium magnet was placed in close proximity to the resonator to pre-polarize the Terfenol-D, thereby enhancing its linear response to applied magnetic fields [9, 31].

IV. RESULTS AND DISCUSSION

The response of the magnetometer to applied signal fields was characterised via spectral and network analysis of the PDH error signal. Fig. 4a shows the power spectral density $S(\omega)$ of the error signal at frequencies above the 13.6 MHz optical sideband frequency, measured using a spectrum analyzer. This power spectral density constitutes the noise floor of our measurements. It was found to be relatively insensitive to the prism-resonator coupling rate via observations over a range of prism coupler positions away from critical-coupling. Similarly, magnetic field noise due to Barkhausen fluctuations within the neodymium magnet [32] was found to have no observable effect on the measurement noise floor via observations of the power spectral density as the magnet was displaced vertically.

It was verified that the resonator was capable of detecting magnetic fields by applying a reference magnetic field with root mean square (RMS) amplitude $B_{\mathrm{ref}} = 7.8\ \mu$T and frequency ω_{ref} =200 kHz. This caused a corresponding tone at 200 kHz in the power spectral density of the error signal (see Fig. 4(a)). The magnetic field sensitivity at 200 kHz was then determined following Ref. [8] as

$$B_{\mathrm{min}}(\omega_{\mathrm{ref}}) = \frac{B_{\mathrm{ref}}}{\sqrt{\mathrm{SNR} \times \mathrm{BW}}} = 1.4\ \mathrm{nT\ Hz}^{-1/2}, \qquad (1)$$

where SNR = 49.7 dB is the ratio of the signal height at ω_{ref} to the corresponding noise floor (see Fig. 4(a)), and BW = 330 Hz is the spectrum analyzer resolution bandwidth. The dynamic range of the magnetometer was tested by measuring the response as a function of signal field amplitude. A linear response was observed over the full accessible range of signal field strengths, up to field strengths as large as 72 microtesla which exceeds the earth's field (see inset in Fig. 4(a)).

The spectrum analyser noise floor in Fig. 4(a) combined with the system response, as quantified by network analysis, allowed the magnetic field sensitivity to be determined over the full hertz-to-kilohertz frequency range. Specifically, the magnetic field sensitivity is given by [8]

$$B_{\mathrm{min}}(\omega) = \sqrt{\frac{S(\omega) N(\omega_{\mathrm{ref}})}{S(\omega_{\mathrm{ref}}) N(\omega)}}\, B_{\mathrm{min}}(\omega_{\mathrm{ref}}), \qquad (2)$$

where $S(\omega)$ is the noise power spectrum observed without any applied magnetic field, and $N(\omega)$ is the system response obtained by sweeping the frequency of the magnetic field and recording the power contained within the spectral peak using a network analyzer, shown in Fig. 4(b). Below 140 kHz the structure in the system response is dominated by three mechanical eigenmodes of the device. Finite element simulations of these modes are shown in Fig. 4(d), with the simulated frequencies matching closely to the observed frequencies evident in Fig. 4(b). Note that the dispersive feature at the fundamental radial breathing mode resonance frequency (69.8 kHz) results from interference of the response of that mode and the background response of the device. Inspection of the measured error signal power spectrum (Fig. 4(a)) shows that the thermomechanical noise of all of these three mechanical eigenmodes is beneath the laser phase noise floor, indicating that the precision of magnetic field measurement with this device will be limited by laser noise rather than thermomechanical noise. Above 140 kHz, the system response is suppressed with increasing frequency, with complex structure existing due to the presence of multifold higher frequency mechanical resonances.

Fig. 4(c) shows the sensitivity measured over the frequency range from 127 Hz to 600 kHz. A peak sensitivity of 131 pT $\mathrm{Hz}^{-1/2}$ is achieved at 126.75 kHz, close

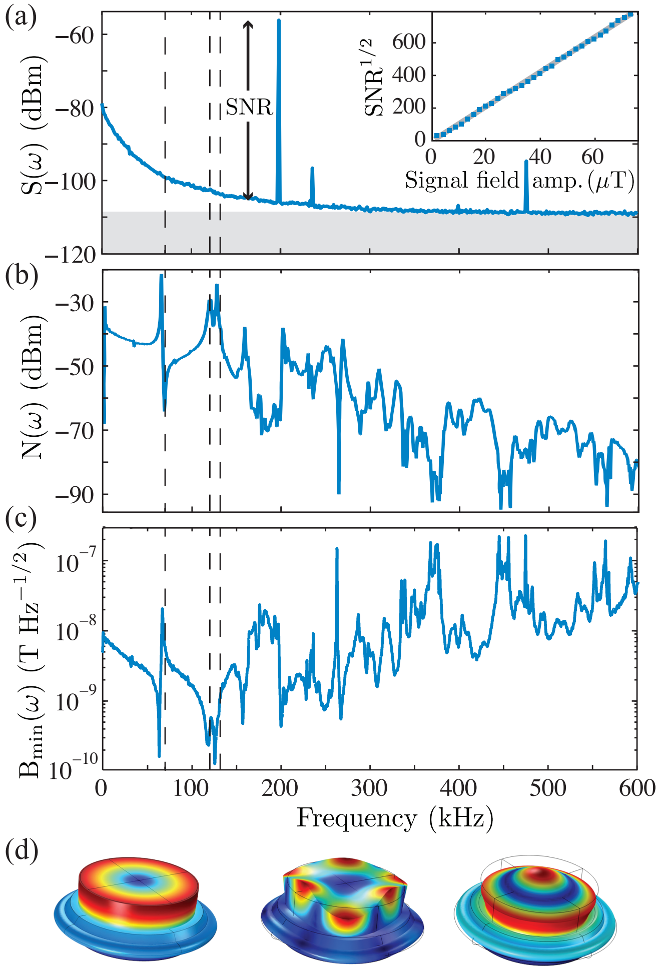

FIG. 4. Experimental results. (a) Power spectral density $S(\omega)$ of the error signal at offset frequencies above the 13.6 MHz optical sideband frequency, showing the response an applied magnetic field at 200 kHz. The grey shaded region indicates the shot noise floor. Inset: response to the magnetic field as a function of signal field strength, with 330 Hz spectrum analyzer resolution bandwidth. (b) System response $N(\omega)$ measured via network analysis as a function of applied magnetic field frequency. (c) Magnetic field sensitivity $B_{\min}(\omega)$ as a function of frequency. (d) Finite element modelling of mechanical eigenmodes of the device. From left to right, the modes are: the fundamental radial breathing mode at 69.8 kHz, a crown mode at 120.4 kHz, and the second order radial breathing mode at 131.9 kHz. The vertical dashed lines in (a)–(c) show the frequencies of these three modes.

to the eigenfrequencies of the mechanical crown and second order radial breathing modes, while similar sensitivity is also achievable at frequencies close to the fundamental radial breathing mode. Evidently, the sensitivity is enhanced by these mechanical resonances, and outperforms previous cavity optomechanical magnetometers in the same frequency range by around three orders-of-magnitude. The best previously reported result had sensitivity above 130 nT Hz$^{-1/2}$ over the full range of the measurements we report here [9]. The sensitivity is within a factor of two of the peak sensitivity over a 5 kHz frequency band, defining the overall bandwidth of the magnetometer.

The sensitivity of our current devices is constrained, predominantly, by the following two effects. Firstly, the overlap between the magnetostrictive expansion caused by the magnetic field and the dominant mechanical eigenmodes of the physical structure (those shown in Fig. 4(d)) is not optimized; and secondly, the optomechanical coupling between each of these eigenmodes and the phase of the intra-resonator optical field is not ideal – this is evident in the small mechanical displacement in the circumference of the device relative to the maximum displacement in the finite element simulations of Fig. 4(d). Each of these effects could be greatly mitigated by engineering the physical structure of the device to optimize the shape of the mechanical eigenmodes. Optimization of this kind has already been shown to allow substantially improved performance in many other cavity optomechanical systems (see for example [33–35]). Optical noise also constrains the sensitivity. Below 200 kHz laser phase noise is the dominant source of optical noise, while shot noise dominates above that frequency (see Fig. 4(a)). Consequently, improved sensitivity could be achieved using phase stabilization [36] and increased optical power, until eventually the thermomechanical noise of the mechanical eigenmodes dominates the optical noise and the thermomechanical noise floor is reached [8, 9]. At frequencies where the sensitivity is limited by shot noise rather than laser phase noise, the sensitivity could be further enhanced using a higher Q resonator. Quality factors as high as $Q = 3 \times 10^{11}$ have been realized for millimeter-scale CaF_2 WGM resonator at 1550 nm [21].

While the results presented here extend the capabilities of cavity optomechanical magnetometers considerably, it is still possible to achieve superior sensitivity with other approaches. For instance, 1 cm diameter cryogenic superconducting interference (SQUID) magnetometers have been demonstrated with sensitivity of 1.5 fT Hz$^{-1/2}$ [37]. Alternatively, atomic-ensemble-based spin exchange relaxation-free (SERF) magnetometers allow all-optical precision magnetometry at room temperature; with sub-femtotesla sensitivity demonstrated using a 2.4 cm device [38]. This impressive performance comes with associated complexity of laser pumping as well as dynamic range limited well beneath earth-field [39]. Commercial room temperature electrical magnetometers have reduced sensitivity compared to these high performance counterparts, but offer the advantages of being robust, inexpensive and easily integrated with other electrical systems. Sensitivities as high as 100 fT Hz$^{-1/2}$ (Phoenix Geophysics, MTC-50) and 6 pT Hz$^{-1/2}$ (Bartington, MAG-03) are available using induction coil and flux gate magnetometers, respectively, with size-scales of a few centimeters.

From the discussion in the preceding paragraph, it should be clear that substantial further improvements are required for cavity optomechanical magnetometers to compete in terms of absolute precision with existing magnetometers, both high performance and commercial. Above and beyond the progress reported here, a three orders-of-magnitude improvement in peak sensitivity is necessary to achieve comparable performance to the best commercial induction coil magnetometers, putting aside the technical advantages of electrical read-out. A further two orders of magnitude are required to compete – on precision – with SQUID and SERF magnetometers. At frequencies away from the mechanical resonances, more substantial improvements are required. For instance, more than an order-of-magnitude reduction in sensitivity is observed at frequencies below a kilohertz, a frequency band relevant to many applications. This highlights a second limitation of our magnetometer, that due to the reliance on relatively high quality mechanical resonances, the response of the sensor is not flat with the sensitivity varying by several orders of magnitude across the measured frequency range. We would note, however, that this sensitivity variation is not fundamental to our magnetometer design. It arises when optical noise is the primary factor limiting the sensitivity. Future devices that achieve thermal noise limited performance at frequencies beneath the mechanical resonance frequency and have a single dominant mechanical mode would allow uniform sensitivity to be achieved at all frequencies up to the mechanical resonance [11]. This would allow bandwidths in the range of hundreds of kilohertz, competitive with commercial magnetometers and substantially larger than the kilohertz bandwidth typical of SERF magnetometers [38].

The substantial improvements in precision required to compete with commercial and state-of-the-art magnetometers are predicted to be achievable with the approach to magnetometry demonstrated here [11]. Optimized devices of similar design to those reported here, operating at the thermomechanical noise limit, could in principle achieve sensitivity at the level of 10 fT Hz$^{-1/2}$; while sub-femtotesla precision is predicted to be possible for alternative designs based on measurement of a vertical, rather than radial, magnetostrictive expansion. In the latter case, the vertical material expansion could be measured, for instance, using a macroscale double-disk whispering gallery mode resonator similar to that in Ref. [40], which provides the additional benefit of considerably larger optomechanical coupling compared to a single whispering gallery mode resonator. We would, further, emphasise that cavity optomechanical devices have the technical advantages of operating in both earth-field and room temperature environments, combined with microwatts optical power requirements and intrinsically low electromagnetic interference due to their all-optical design.

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