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Major Goals: Magnetometers are important for diverse applications such as geological surveys, material science, medical imaging, and defence [1]. For many of these applications sensitivity is a key metric. The current state-of-the-art in ultra-sensitive magnetometry is provided by Superconducting Quantum Interference Devices (SQUIDs) and Spin Exchange Relaxation Free magnetometers (SERFs), which enable detection of pico- to femtotesla magnetic fields. However, technical limitations constrain the breadth of applications. SQUIDs require a cryogenic environment, increasing complexity, cost, size, and power consumption. SERFs typically have sub-kHz bandwidth, are difficult to integrate, and require magnetic shielding due to their low dynamic range [2, 3]. By contrast, magnetostrictive magnetometers suffer none of these drawbacks, but typically have two to five orders of magnitude worse sensitivity.

Magnetostrictive alloys, such as Terfenol-D, physically deform in the presence of a magnetic field. This physical deformation is read-out capacitively in typical magnetostrictive magnetometers. Crucially, sensitivity is constrained by the capacitive read-out, not fundamental noise sources such as thermomechanical fluctuations. We have previously developed a new type of magnetostrictive magnetometer based on an on-chip micro-scale cavity optomechanical system, where mechanical motion is strongly coupled to the optical cavity resonance frequency. Laser light is fiber-optically coupled into the cavity, with detection of the emitted field allowing ultrasensitive read-out of mechanical deformations. These magnetometers have the potential to offer comparable sensitivity to the state-of-the-art in the field, offer significant advantages in size, resolution, bandwidth, dynamic range and power consumption, and do not require cryogenic cooling. They consequently have significant potential for applications in magnetometry such as ultralow field magnetic resonance imaging, magnetoencephalography, uranium enrichment and detection of liquid explosives. The primary aim of this project was to achieve ultrahigh sensitivity.

Accomplishments: As outlined in our proposal, the primary aim of this project was to develop cavity optomechanical magnetometers that provide state-of-the-art performance over size scales ranging from several tens of micron to centimeters. We progressed this aim via three different architectures: on-chip microtoroidal resonators, centimetre-scale polished crystalline resonators, and on-chip double-disk structures. We outline progress on each of these devices below.

* Microtoroidal on-chip magnetometers

The sensitivity of the initial design of our cavity optomechanical magnetometer was limited by poor coupling of the magnetostrictive material (Terfenol-D) to the optical cavity (toroid). The reason for this poor coupling was that the Terfenol-D was affixed on top of the toroid so that deformation in the presence of a magnetic field did not act directly on the torus, and poorly interacted with the most sensitive flexural mode of the toroid. Therefore, in order to improve sensitivity, a new sensor architecture was designed and fabricated. This new architecture placed the Terfenol-D inside a cavity within the toroid so that magnetostrictive deformation could act directly on the torus. The new architecture was fabricated at UQ using successive photolithographic, wet (HF) and dry (XeF_2 gas) etches and laser reflow steps before the Terfenol-D material (Etrema) was micropositioned into the cavity and held in place with epoxy.

We have developed the fabrication technique to the point that it is quite reproducible, around 40% of all devices showing magnetic field sensitivity in the picotelsa range. We are further advancing the fabrication of devices in collaboration with scientists at the Australian Defense Science and Technology Group (Department of Defense), who have now developed a terfenol-D sputter coating system that this compatible with our device fabrication flow, and we expect to allow the epoxy deposition step in our current process to be eliminated.

- Microscale Toroidal on-chip Magnetometer (High Frequencies):

The final devices exhibit typical optical quality factors as high as 10^8 with multiple relatively broad mechanical modes (Q ~ 40) providing broadband mechanical response over the frequency range from 0.5 to 130 MHz. This allows the fundamental thermal noise limit to micromechanical magnetometry to be reached, a limit typically precluded by several orders of magnitude in magnetostrictive magnetometers that rely on electrical readout.

For linear measurements of the high frequency sensitivity, the Terfenol-D is magnetized using a permanent bias magnet to maximize the linear magnetostrictive response. A pair of solenoids is then used to create a spatially uniform signal magnetic field across the device at radio frequencies. Light from a 1550 nm shot noise limited tunable fiber laser is guided through a polarization controller and evanescently coupled into the microtoroidal optical cavity via a tapered optical fiber. The laser frequency is thermally locked to the half maximum of an optical resonance. Strain in the resonator induced by the Terfenol-D shifts the optical resonance frequency, thus modulating the amplitude of the transmitted light. This transmitted field is detected on an InGaAs photodiode, with only 50 μW of resonant light required at the detector to achieve good signal-to-noise. Network/spectral analysis allow the magnetic field sensitivity to be determined as a function of signal frequency.

The measured magnetic field sensitivity of a typical device exceeds 2 nT Hz1/2 over the majority of the frequency range, with a peak sensitivity of approximately 30 pT/Hz^1/2 achieved at frequencies near 30 MHz, where the dominant mechanical modes are predominantly radial in nature and thus strongly coupled to the optical resonance frequency. This represents a four orders of magnitude improvement in sensitivity on the previous design of the sensor, and an small improvement on the best SQUID magnetometer of comparable size with the major benefits of not requiring any cryogenics and operating with microwatts of optical power.

Bandwidth is important for a range of magnetometer application, from searching for unknown signals to magnetic spectroscopy of condensed matter and liquid samples. Our current devices are capable of measuring magnetic fields over a range of frequencies from 0.5 to 130 MHz. The the 3dB bandwidth (the range of frequencies that achieve a sensitivity within a factor of two of the peak sensitivity) of our magnetometers is in the range of several tens of megahertz. To our knowledge this is several orders of magnitude superior to all previous ultrasensitive optomechanical magnetometers.

* Microscale Toroidal on-chip Magnetometer (Low Frequencies):

Many significant applications require sensitivity to magnetic fields in the Hz to kHz frequency regime, including magnetic anomaly detection (MAD), geophysical surveys and magnetoencephalography (MEG). This project demonstrated that nonlinearity of magnetostrictive materials provides a mechanism to mix low frequency magnetic signals up to higher frequencies. Using this approacj we achieved magnetic field sensing at frequencies between 2 Hz and 20 kHz, with a peak sensitivity of 150 nT/Hz^1/2 over the range 2 Hz to 1 kHz.

* Crystal Resonator (cm-scale) Magnetometer:

The principle of the CaF crystal resonator magnetometer is the same as the microtoroid based analogue. Deformation of a piece of Terfenol-D in a magnetic field is read out optically by the crystal resonator. The larger size and optical finesse of the crystal enables greater optical quality factors up to 10^10 to be reached, significantly greater than seen in microtoroids. It was anticipated that this will result in enhanced sensitivity, at the expense of greater sensor size, meaning that the two types of sensor would each be suited to different applications.

The cm-scale magnetometers have been successfully fabricated in a collaboration with colleagues at the Australian National University. The resonator fabrication was performed by diamond turning and polishing a CaF crystal to produce a smoothed exterior surface. To enable incorporation of Terfenol-D inside the crystal structure a diamond lathe was used to create a cylindrical hollow within the crystal. A Terfenol-D rod of diameter 12.4 mm (Etrema) was diced into 4 mm high disks using a high-speed diamond saw at UQ. The disk was fixed inside the CaF resonator with epoxy, thus completing the sensor.

The magnetic field sensitivity as a function of frequency was determined in a similar manner to the microscale devices discussed earlier for two centimeter scale devices, with similar results – in each case achieving sensitivity in the range of 100 picotelsa per root hertz. This device allowed precision sensing in a frequency band previously unavailable – particularly, the range from 1 to 500 kHz. The sensitivity was limited by a combination of laser frequency noise and limitations in the overlap between the expansion of the optical mode and the mechanical terfenol deformation.

* Double-disk designs

A new development from our project was the concept of double-disk optomechanical magnetometers. In such magnetometers, the optical field is hybridized between two vertically stacked silica disks, with the terfenol expansion modifying the distance between the disks. Our calculations of the thermomechanical noise floor of these devices indicate that they have the potential to achieve far superior sensitivity to our existing magnetometer designs, as well as all other precision magnetometers. They have the further advantages of requiring only a relatively low quality optical cavity, and therefore insensitivity to laser frequency noise, and of being fully integrable including terfenol deposition and waveguide coupling. We have yet to experimentally test this approach.

Training Opportunities: This project trained two postgraduate students, Stefan Forstner and Sarah Yu, who respectively graduated with a Masters and PhD.

Results Dissemination: Results were disseminated in invited and contributed talks in a range of international conferences and workshops; as well as in QuASAR program review meetings, and scientific publications.

Honors and Awards: During the period of the project, CI Bowen was awarded an Australian Future Fellowship, a highly competitive research fellowship from the Australian Research Council. He also gave 25 invited talks at conferences and workshops and 1 plenary talk.

Research from this project was featured on both the cover of Advanced Materials, and as the topic of a Nature News and Views article.

Protocol Activity Status:

Technology Transfer: Some of the magnetometer designs from this project were patented in the patents:
Australian provisional patent application. Magnetometer and method of fabrication. AU2013903621
International patent application. Magnetometer. PCT/AU2012/000395

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Abstract: We demonstrate a centimeter-scale optomechanical magnetometer based on a crystalline whispering-gallery-mode resonator. The large size of the resonator, with a magnetic-field integration volume of 0.45 cm3, 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 noncryogenic environment using optical power levels beneath 100 ?W. Femtotesla-range sensitivity may be possible in future devices with the further optimization of laser noise and the physical structure of the resonator, allowing applications in high-performance magnetometry.
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Nothing to report in the uploaded pdf (see accomplishments)"