Resonant magnon assisted optomechanical magnetometer

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We demonstrate a hybrid mechanical and magnetic resonator coupled to a whispering gallery mode cavity for magnetic field detection at room temperature. We obtain a peak magnetic field sensitivity of 103 pT Hz−1/2, in a frequency range from 50 MHz to 1.1 GHz, with a bandwidth of up to 100 kHz. While the sensitivity is in the intermediate range of state-of-the-art magnetometers, the broad bandwidth and working frequency range are far larger, by about a factor 100 and 1000, respectively, in comparison to the best micro-electro-mechanical systems Lorentz force magnetometers. Our results demonstrate that our hybrid system can be used to build large-bandwidth sensors useful for real-time applications such as high-speed detection of oscillating magnetic fields and for high-resolution imaging methods.

INTRODUCTION

Cavity optomechanics (OM) focuses on the low-energy interaction between photons and mechanical objects embedded in an optical cavity with main applications as high performance detectors and as interfaces for quantum information processing [1,5]. OM cavities enable ultra-sensitive optical transduction of mechanical motion at different scales, from km-scale systems like LIGO [2] to nanomechanical systems [3]. Stimuli read-out experiments based on such platforms has already reached the state of the art for force sensors [4] and accelerometers [5].

In a similar spirit, new lines of research recently emerged, namely cavity optomagnonics [3,7] and magnomechanics [8], that investigate the utility of magnons (quanta of collective oscillations in the alignment of spins in a magnetic material). The use of magnons in solid-state quantum and classical devices is highly convenient since their frequencies can be tuned in a wide range (from MHz to THz) and can have long lifetimes [9]. This has led to the advent of a new class of hybrid systems, studying the coupling between photons, both in the microwave and optical regimes, with phonons and magnons residing in magnetic materials. This new platform offers the possibility of studying the fundamental interaction between these three quasi-particles and to investigate macroscopic quantum phenomena at room temperature. In addition, the interaction of mechanical elements with magnetic fields make optomechanical devices also efficient magnetometers, i.e optomechanical magnetometer (OMM) [10] in terms of small size [11], high sensitivity [12], large dynamic range [13] at room temperature operation. The ability to measure low magnetic fields over a broad frequency range is important for numerous applications and plays an important role in areas such as geology, space exploration, biology [13] and medical imaging [15].

In this Letter, we report a hybrid mechanical and magnetic resonator based on a magnetic insulator yttrium iron garnet (YIG) thin film coupled to a silica resonator. We show that the combined coupling of optical whispering gallery modes (WGM) to a mechanical breathing mode in the silica resonator and the magnetostrictive properties of YIG film forms a sensitive detector of magnetic fields. While its excellent sensitivity, outperforms other magnetometers based on optomechanics, its working frequency, bandwidth is comparable with the state of the art magnetometers operating , at room temperature.

The Basic transduction principle involves the conversion of an RF magnetic field, that resonantly excites magnons, to mechanical vibrations employing magnetostrictive in the YIG film [16,17]. Although the frequency of the magnons and mechanical breathing mode in the silica microsphere may differ, the magnon frequency can be tuned by a static magnetic field and thus for specific conditions may overlap, giving rise to a modulation of the WGM of the silica microsphere due to the OM interaction. We show that by tuning the magnon res-
onant frequency on the YIG film with an external static magnetic field it is possible to maximize the peak sensitivity and extend the response bandwidth of the detector. We attain a maximum sensitivity of about 100 pT Hz$^{-1/2}$ in a frequency range from 50 MHz to 1.1 GHz, with a bandwidth ranging from 30 to 100 kHz operating at room temperature.

**EXPERIMENTAL SET UP AND CHARACTERIZATION**

A schematic picture of the OMM principle is shown in Fig. 1. The sensor can be modeled as a Fabry-Perot optical interferometer in which one of the mirrors responds mechanically to an applied magnetic field. Typically, in a realistic system this response is due to magnetostriction in the bulk of the material, the generation of an oscillating stress when a magnetic field is applied. This stress acts as a source force for mechanical motion of the mirror, greatly amplified when the initial drive is resonant with a mechanical eigenfrequency. The two main forces actuating the mechanical modes are thus the thermal Langevin force ($F_{th}$) and the one associated with the RF magnetic field ($F_{mag}$). These forces cause a variation of the cavity length, shifting the optical resonance by $\delta \omega_{optical} = Gx$, where $G$ is the optomechanical coupling rate, defined as the optical frequency shift by a unit mechanical displacement [18]. An illustration of the central part of the hybrid system is shown in Fig. 1b. It consists of a 0.5×0.5 mm$^2$ and 1 µm thick film of YIG grown over a Gadolinium Garnet substrate. On top of the YIG film, we dropped the silica (Barium-Titanium-Silicate) microspheres with a diameter between 40 µm and 70 µm [19, 20]. These microspheres are used as high-quality OM cavities supporting both optical whispering gallery modes and mechanical breathing modes with large OM coupling rates [21, 22].

The experimental setup is shown in Fig. 1c. An infrared tunable laser source is used to couple light into the WGM of the microsphere using a micro-looped tapered fiber placed close enough to ensure overlap between the evanescent fields of the fiber fundamental mode and the WGM. The mechanical motion is detected by measuring the RF modulation of the transmitted light, which is collected and sent to a fast photo-detector with an operational bandwidth of 12 GHz. The output signal could be analyzed by a spectrum analyzer (SA) and a vector network analyzer (VNA). The latter is also used to inject RF signals into a shorted end microstrip waveguide (MSW) which we use in order to generate RF magnetic fields (see Fig. 1c). The MSW is also used to characterize the magnon modes of the YIG film. A static magnetic field $B_{DC}$ is generated with two coils connected to a current source that allows us to tune the intensity of the magnetic field up to $\sim 10$ mT. All experiments were carried out at room temperature.

In Fig. 1d we show the typical optical transmission spectrum from a microsphere of about 40 µm in diameter with multiple WGMs. The mode used here near 1509 nm has a quality factor of $10^8$ and is coupled to several mechanical radial breathing modes of the microsphere (Fig. 1f). The mechanical resonances are found at 109, 206, 292, 338, and 465 MHz. The displacement profiles of the first three modes obtained using COMSOL Multiphysics software are shown in Fig. 1e (inset). Due to the refractive index contrast between the YIG film ($n = 2.19$) and the BTS microsphere sphere ($n = 1.4$), we use an intermediate layer of 100 nm of PMMA that preserves the high Q-factors of the optical modes.

The method used to excite and measure uniform magnon modes, from MHz to GHz range, in the YIG film, is the broadband ferromagnetic resonance method (FMR). The MSW creates a RF field perpendicular to $B_{DC}$ that excites the precessional motion of the magnetization around $B_{DC}$. When the excitation frequency matches the ferromagnetic resonance condition, a uniform magnon is resonantly excited, i.e. energy is absorbed. Consequently, part of the incident energy is absorbed and a dip is observed in the reflection spectrum on the VNA. As the resonance frequency depends on $B_{DC}$, it is possible to tune the frequency of the magnon resonance from 0.2 to 1 GHz by the $B_{DC}$ (see Fig. 1f). In the case of a thin film with a static magnetic field applied in-plane and the RF field perpendicular to the direction of magnetization $M$, the resonance frequency is $\omega_0 \equiv \gamma \sqrt{B_{int}(B_{int} + \mu M)}$, with the internal field $B_{int} = B_{an} + B_{DC}$, $B_{an}$ being the anisotropy field and $\gamma = g\mu_B/\hbar$ the gyromagnetic ratio (See Supplementary Information). We note that the linewidth of the magnon mode reported on Fig. 1f decrease as a function of $B_{DC}$ from about 46 MHz to 24 MHz (at 2.5 mT). At low $B_{DC}$ values, the magnetization is not uniform, leading to inhomogeneous spectral broadening of the observed resonance.

**RESULTS AND DISCUSSION**

A spectral response of the system with and without applied magnetic excitation at a calibration frequency $\omega_{cal}$ is shown in Fig. 2a. For a RF power level (-10 dBm) at $\omega_{cal}$=206 MHz, we observe a peak response on the thermally excited mechanical motion signal at that frequency, when the signal is analyzed with the SA. The force induced by vibrations on the YIG modifies the mechanical spectrum of the microsphere with a corresponding Signal-to-Noise-Ratio (SNR) of 8 dB. As shown in Fig. 2a, we observe a linear dependence of square root of SNR at frequency $\omega_{cal}$ on the applied RF magnetic field ($B$). The amplitude of the field $B$ acting on the YIG is obtained by estimating the RF current that passes through
FIG. 1: (a) Conceptual schematic of the optomechanical magnetometer. The optomechanical system is modeled as a Fabry-Pérot cavity with a moving mirror. $F_{th}$ and $F_{mag}$ denote the thermal force and the magnetostrictive force due to the magnon. (b) Schematic representation of the central part of the experimental setup, including a strip waveguide, a ferromagnetic YIG film and a barium-titanium-silicate microsphere. (c) A simplified schematic of the full experimental setup. A fiber taper is used to probe the optomechanical modes of the microsphere. Two electromagnetic coils are used to generate static magnetic fields, used to tune ferromagnetic (magnon) resonance modes on the YIG film. (d) Optical whispering gallery modes spectrum measured on the microsphere. The inset shows a simulation of the optical WGMs. (e) Mechanical breathing spectrum of the microsphere. Only thermally driven activated mechanical motion is observed corresponding to radial breathing modes of the sphere. The inset shows the displacement profile of the first three modes. (f) Magnon resonances measured on the YIG film applying different static magnetic fields by detecting the reflected signal $Re(S_{11})$ in the VNA.

the MSW, by measuring the characteristic impedance of the of circuit and considering the applied RF power (see Supplementary Information). We use this magnetic field dependence in Fig. 2 to calculate the sensitivity, which is given by the field strength at which the spectral peak height is equal to the noise (SNR=1) for a 1 Hz measurement resolution bandwidth (RBW). The corresponding magnetic field at $\omega_{cal}$ is $B_{min}(\omega_{cal})=0.51 \mu T$ for RBW=30 kHz. Then, the sensitivity at $\omega_{cal}$ is given by $\delta B_{min}(\omega_{cal}) = \frac{B_{min}(\omega_{cal})}{\sqrt{RBW}}=2.94$ nT Hz$^{-1/2}$. The dynamic response of the sensor, $N(\omega)$, over a wide frequency range is measured by varying the input frequency from port 1 of the VNA and by looking at $S_{21}$, where port 2 is directly connected with the detector. As shown in Fig. 2, we observe a peak in the VNA signal $N(\omega)$ wherever $\omega$ is resonant with a mechanical mode with sufficiently high value of $G$ (see Fig. 1c). Due to the enhanced noise rejection of the VNA, we can detect modes at 374 MHz and 456 MHz that in the thermally activated spectrum obtained in Fig. 2 were below the noise level. By following a similar procedure as in Ref. [10], the frequency dependence sensitivity $\delta B_{min}(\omega)$ is obtained by combining the spectral calibration at a single frequency, the noise power spectrum in absence of a magnetic field $S(\omega)$, and the network response $N(\omega)$.

$$\delta B_{min}(\omega) = \sqrt{\frac{S(\omega) \cdot N(\omega_{cal})}{N(\omega) \cdot S(\omega_{cal})}} \delta B(\omega_{cal})$$

Fig. 2e shows the measured sensitivity over a frequency range from 50 to 500 MHz. The lowest sensitivity value obtained is 103 pT Hz$^{-1/2}$ close to the mechanical mode at 206 MHz. The sensitivity remains below 1 nT Hz$^{-1/2}$ within the linewidth of the mechanical resonances (about 10 MHz). The mechanical mode at this frequency presents a displacement field profile concentrated along the edge of the sphere (see Fig. 1e), and therefore a strong overlap with the optical whispering gallery mode, as shown in Fig. 1d.

The control of the magnon resonance frequency with
FIG. 2: (a) Mechanical spectrum of the silica microsphere excited by applying an RF magnetic field of 2.3 $\mu$T at 206 MHz, in red. The black curve corresponds to the mechanical mode without excitation. (b) Signal to noise ratio (SNR) of the system as a function of the applied RF magnetic field. (c) Power spectral density $S(\omega)$ measured with a spectrum analyzer and with RF field at 206 MHz. (d) System response $N(\omega)$ measured using a vector network analyzer as a function of the frequency of the RF field. (e) Magnetic field sensitivity $B_{\text{min}}(\omega)$ of the optomechanical magnetometer as a function of frequency. A peak sensitivity of $\delta B_{\text{min}}(\omega)=103$ pT is achieved close to the mechanical mode at 206.3 MHz.

$B_{\text{DC}}$ provides our system with precise tunability in the operational frequency range. In Fig. 3a, we show the system response $N(\omega)$ as a function of frequency for different $B_{\text{DC}}$ values. It is worth noting that for this measurement a second sphere with a similar radius, mechanical spectrum and optical quality factors was used. The grey curves of Fig. 3a, show VNA-FMR spectra as a function of frequency. As mentioned earlier the FMR frequency increases with increasing the $B_{\text{DC}}$, accompanied by a spectral narrowing of the dip. This behavior confirms that the signal appears only when the linewidth of the FMR resonance overlaps with the mechanical resonances of the microsphere. In addition, it evidences the presence of the mechanical modes whose thermal motion is not transduced above the noise level in the measurement without the RF drive, for example, the modes seen in the lowest panels of Fig. 3a. This confirms the necessity of the magnon to enhance the magnetostriction effect. In Fig. 3b we obtain the peak sensitivity for the different measured positions of the FMR mode. We note that the OMM detects magnetic fields even above 1 GHz (see Supplementary Information). The obtained sensitivities are comparable with the one reported in Fig. 3d ($\sim100$ pT Hz$^{-1/2}$). This allows determining an operational frequency range of at least 1.1 GHz. This value is just a lower bound of the operational frequency since we were not able to apply larger $B_{\text{DC}}$ due to experimental constraints. In a typical FMR setup, frequencies up to 20 GHz are easily achievable.

As noted previously, in our experiment the FMR spectra are rather broad and this has several consequences. On the one hand, the operational frequency range is increased and we can cover several mechanical modes without changing the $B_{\text{DC}}$. On the other hand, much greater sensitivities could be attained with a narrower and deeper FMR. Indeed, given that in the setup that included the optical transmission experiment the electromagnets were placed several cm's away from the YIG sample, the magnon resonance linewidths are almost a factor of two larger compared to the ones obtained in Fig. 1f, which were obtained applying a homogeneous $B_{\text{DC}}$. Moreover, using microspheres with a smaller di-
We obtain a sensitivity below 1 nT Hz$^{-1/2}$ for detection of weak oscillating magnetic fields. To further support our interpretation that our signal is due to mechanical vibrations generated by magnetostriction on the YIG thin film, we used a high-frequency laser Doppler vibrometer technique to measure the vibrations at the surface in the absence of the microsphere (see Supplementary Information). In this latter case, we had to apply three orders of magnitude higher RF power to detect a signal. These results also confirm the high sensitivity of our hybrid system. The field sensitivity presented here shows a higher peak value compared to previous cavity OMM studies [10-13]. In those experiments, a magnetostrictive material (Terfenol-D) was used due to its high magnetostrictive coefficient [24]. Despite that single crystal YIG is found to be a factor of two less magnetostrictive than Terfenol-D [25], the high performance of the OMM reported here resides on the use of YIG for displaying a high quality FMR and the use of a high Q silica resonator.

Compared with room temperature operation devices like NV-based magnetometers, the device reported here shows a similar peak sensitivity as the device reported in Ref. [26] but with the advantage of having a fiber-based optical detection. Our sensitivities outperform electrically Lorentz-Force magnetometers [27] of comparable size by three orders of magnitude. On the other hand, our sensitivity is two orders of magnitude lower than magnetometers based on superconducting quantum interference devices [28, 29], reaching sensitivities of 1 fT Hz$^{-1/2}$ at $\sim$ 100 Hz. However, cryogenic environments are required for their operation, which boosts the cost of a technology based on these systems. The spin-exchange relaxation-free magnetometry, has the absolute state of the art peak sensitivity of 160 aT Hz$^{-1/2}$ at 40 Hz [30]. Frequency bandwidth is an important limitation in most of the mentioned magnetometers. Up to now the largest bandwidths, similar to our value of $\sim$ 100 kHz, are only obtained using anisotropic magnetoimpedance magnetometers, but they are restricted to work at low frequencies [31].

**CONCLUSIONS**

To conclude, we demonstrate a hybrid system composed by a magnetic resonator coupled by mechanical interaction to a whispering gallery mode optomechanical cavity for detection of weak oscillating magnetic fields. We obtain a sensitivity below 1 nT Hz$^{-1/2}$ in a frequency range from 50 MHz to 1.1 GHz limited by our experimental setup. A peak magnetic field sensitivity of 103 pT Hz$^{-1/2}$ is achieved, which can be further improved by optimizing the overlap between the magnon resonance and the mechanical resonance of the optomechanical cavity. In addition to the above excellent characteristics, the large frequency bandwidth up to 100 kHz, room temperature operation and simplicity in fabrication offer the opportunity of designing a high-performance magnetometer. Larger bandwidths are necessary for real-time applications such as high-speed detection, mechanical signal processing and for high-resolution imaging methods [15].

The conversion efficiency can be improved by using the microsphere detector made of ferromagnetic YIG. Efforts are made towards scaling down the YIG sphere size, and also for improving the surface quality of the YIG sphere to increase the WGM quality factors. Our hybrid system, in addition to the possibilities of designing a new magnetometer also open a path toward studying phenomena related to phonon-magnon coupling. Currently, magnons are gathering increasing attention in spintronics experiments (e.g. magnonics [32] and spin caloritronics areas [33, 34]) as a means of processing spin information and managing heat in nanoscale structures. Its superior properties make YIG a nearly ideal choice for spintronics applications. However, little is known about the underlying physical mechanisms involved, mainly related to phonon-magnon interactions. Our experiment can be exploited as a novel method to get information about these interactions, in particular investigating the phonon contributions via the magnetostrictive coupling.
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