Optical interface for a hybrid magnon-photon resonator

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We study optical detection of magnetic resonance of a ferrimagnetic sphere resonator, which is strongly coupled to a microwave loop gap resonator. Optical fibers are employed for coupling the sphere resonator with light in the telecom band. We find that magnetic resonance can be optically detected in the region of anti-crossing between the loop gap and the ferrimagnetic resonances. By measuring the response time of the optical detection we rule out the possibility that microwave induced heating is responsible for the optical detectability.

Magnons are widely employed in a variety of devices [1–7], including narrow band oscillators [8], filters [9], and parametric amplifiers [10]. Magnons can couple with microwave (MW) photons [11,12], optical photons [13–23], phonons [24,25], and with superconducting qubits [26–29]. Hybrid magnon devices may help developing optical channels linking remote quantum computers [30–32].

Here we study a hybrid system composed of a MW loop gap resonator (LGR) strongly coupled to a ferrimagnetic sphere resonator (FSR) made of yttrium iron garnet (YIG) [33,34]. Optical fibers are employed for transmitting light in the telecom band through the sphere. The frequency of the hybrid FSR-LGR system is controlled using an externally applied magnetic field (generated by a magnetized Neodymium). We explore magneto-optic (MO) coupling and Faraday rotation of optical polarization, and demonstrate optical detection of magnetic resonance (ODMR) of the hybrid FSR-LGR system. ODMR of FSR has been demonstrated before in [35], by coupling a tapered optical fiber to whispering gallery modes of an FSR. However, the ODMR method that has developed in [35] is based on heating induced by MW driving, and consequently the response time of this method is relatively long (on the order of a second). As is shown below, the response time of our ODMR method, which is not based on heating, is significantly shorter (limited by the ring down time of the FSR, which is about 1μs).

The experimental setup, which is schematically shown in Fig. 1 is designed to allow exploring the MO coupling between MW and optical photons, which is mediated by FSR magnons. In Fig. 1, optical components and fibers are red colored, whereas blue color is used to label MW components and coaxial cables.

A MW cavity made of an LGR allows achieving a relatively large coupling between magnons and MW photons [36,38]. The LGR is fabricated from a hollow concentric aluminium tube. A sapphire strip of 260μm thickness is inserted into the gap in order to increase its capacitance, which in turn reduces the frequency $f_c$ of the LGR fundamental mode [39]. An FSR made of YIG having radius of $R_s = 125μm$ is held by two ceramic ferrules inside the LGR. The applied static magnetic field $\mathbf{H}$ is controlled by adjusting the relative position of the magnetized Neodymium using a motorized stage. The LGR-FSR coupled system is encapsulated inside a metallic rectangular shield made of aluminum (represented by the black colored rectangle in Fig. 1). The cavity is weakly coupled to a loop antenna (LA). More information about the FSR-LGR hybrid system, including its fabrication and magnetic energy density distribution, can be found in Ref. [38].

A vector network analyzer (VNA) is employed for measuring the MW reflection coefficient $|S_{11}|^2$. The plot shown in Fig. 2(b) exhibits $|S_{11}|^2$ in dB units as a function of the externally applied magnetic field $H$ and VNA frequency $f$. The measurement is performed in...
GIF is installed near the FSR (see Fig. 1). The length of the GIF is attached to the tip of one of the fibers that are index in the telecom band \([51, 54]\), a graded index fiber has an optical absorption coefficient \(\alpha\) as a function of frequency \(f\).

In our setup telecom light is transmitted through the FSR using single mode optical fibers. The FSR serves as a source \([\text{see Fig. } 1, \text{ and note that a circulator (C) and a MW spectrum analyzer (SA) are used to probe the back reflected MW signal.} \text{ The measured optical transmission shown in Fig. } 2(\text{a}) \text{ reveals Fabry–Pérot oscillation near the FSR resonance } f_s. \text{ The wavelength period of the Fabry–Pérot oscillation is observed to be } 1.77\text{nm. The oscillation is attributed to an optical cavity formed between both fibers coupled to the FSR due to Fresnel reflection at the fibers’ tips. The measured spacing of } 1.77\text{nm allows estimating the distance between the fibers to be } 700\text{µm.} \]

FIG. 2: Continuous wave measurements. In both (a) and (c) the ErS is employed as a source, and the optical transmission measurement is performed using the OSA. (a) Measured optical spectrum data as a function of SG frequency \(f\) with SG power of 20 dBm relative to measured optical spectrum corresponding to smallest SG frequency in the plot, with a fixed magnetic field of \(H = 140.13\mu T\), showing Fabry–Pérot oscillation near the FSR-LGR resonance. (b) VNA reflection \(|S_{11}|^2\) in dB units as a function of frequency \(f\) and magnetic field \(H\) with input power of \(-30\) dBm. (c) Optical intensity (in arbitrary units) measured at a specific wavelength of \(\lambda = 1524.292\)nm as a function of SG frequency \(f\) and magnetic field \(H\), with SG power of 20 dBm.

To study the dependence on both the MW frequency \(f\) as well as magnetic field \(H\), the optical intensity is recorded at wavelength 1524.292nm [see Fig. 2(c)], at which the transmission is maximized [see Fig. 2(a)]. The SG frequency is varied from 3.8GHz to 4.05GHz, and the

the region of anti-crossing between the LGR fundamental mode at frequency \(f_s = 3.9235\)GHz and the Kittel mode at frequency \(f_s\) of the hybrid FSR-LGR eigen modes are given by \([42]\)

\[
f_{\pm} = \frac{f_c + f_s}{2} \pm \sqrt{\left(\frac{f_c - f_s}{2}\right)^2 + g^2}.
\]

where \(g\) is the FSR-LGR coupling coefficient \([43, 44]\). The frequencies \(f_{\pm}\) are calculated using Eq. \((1)\). A fitting procedure yields the value \(g/\langle 2\pi \rangle = 16\text{MHz}\). Note that in general, \(g\) is proportional to the FSR volume.

A polarization controller (PC) is employed to manipulate the light transmitted through the FSR. An optical spectrum analyzer (OSA) having resolution of 0.004nm is used to probe the transmitted light. All fibers are single mode having 125µm clad diameter and 9µm core diameter.

The OSA is employed for probing the transmitted light in the range 1520nm to 1540nm, as a function of MW driving frequency \(f\) applied to the LA, with a fixed magnetic field of 140.13mT [see Fig. 2(a)]. In this measurement, a signal generator (SG) operating at 20 dBm serves as a source [see Fig. 1] and note that a circulator (C) and a MW spectrum analyzer (SA) are used to probe the back reflected MW signal. The measured optical transmission shown in Fig. 2(a) reveals Fabry–Pérot oscillation near the FSR resonance \(f_s\). The wavelength period of the Fabry–Pérot oscillation is observed to be 1.77nm. The oscillation is attributed to an optical cavity formed between both fibers coupled to the FSR due to Fresnel reflection at the fibers’ tips. The measured spacing of 1.77nm allows estimating the distance between the fibers to be 700µm.

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FIG. 3: LIA measurements. (a) VNA reflection $|S_{11}|^2$ in dB units as a function of frequency $f$ and magnetic field $H$. The VNA input power is $-10$ dBm. (b) LIA measured voltage amplitude (in arbitrary units) as a function of SG frequency $f$ and magnetic field $H$, with SG power of $-10$ dBm. In both (a) and (b) the TL wavelength is 1530.87 nm and power is $-2.6$ dBm. (c) The dependence of LIA measured voltage amplitude $V_{LIA}$ (in arbitrary units) on LIA modulation frequency $f_{AM}$. For this measurement, the TL wavelength is set to 1538.556 nm and TL power is set to 6 dBm.

power is set to 20 dBm. The measured optical intensity peaks near the Larmor resonance, i.e. when $f \approx f_s$. Note that the splitting between $f_+$ and $f_-$ cannot be resolved in Fig. 2(c) due to anisotropy-induced Kerr nonlinearity.

Next we explore the response time of the above-discussed ODMR method. This is done in order to determine the role played by MW induced heating, which has a relatively long time scale. To that end, we perform experiments using a lockin amplifier (LIA). Components outlined by a thick black line in the setup sketch shown in Fig. 1 (TL, PD and LIA) are used only for the LIA measurements presented in Fig. 3. A tunable laser (TL) is used instead of the high bandwidth ErS. The OSA is replaced with a photodetector (PD) to measure the optical intensity. The LIA reference signal is used to amplitude modulate (AM) the SG signal at a modulation frequency $f_{AM}$, and the PD signal output is fed into the LIA input port. For LIA measurement shown in Fig. 3(c), the tunable laser wavelength is set to 1538.556 nm, which corresponds to the second highest optical intensity in the spectrum shown in Fig. 2(a).

Both the VNA measurement shown in Fig. 3(a) and the LIA measurement shown in Fig. 3(b) are performed with MW power of $-10$ dBm and TL optical power of $-2.6$ dBm. Figure 3(c) shows a plot of LIA voltage amplitude $V_{LIA}$ (in arbitrary units) as a function of modulation frequency $f_{AM}$. The measured dependency on $f_{AM}$ indicates that the ODMR response time is on the order of a microsecond. This observation suggests that the response time is limited by FSR damping, and it rules out the possibility that heating plays a dominant role in the underlying mechanism allowing the ODMR.

In summary, ODMR of FSR is demonstrated in the telecom band, and the possibility that MW induced heating is the underlying mechanism is ruled out. The ODMR method is compatible with ultra low temperatures (due to the very low optical absorption of YIG in the telecom band), and thus it may help developing an optical interface for superconducting qubits.

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The data that support the findings of this study are available from the corresponding author upon reasonable request.

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