Optomagnonic whispering gallery microresonators

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Magnons in ferrimagnetic insulators such as yttrium iron garnet (YIG) have recently emerged as promising candidates for coherent information processing in microwave circuits. Here we demonstrate optical whispering gallery modes of a YIG sphere interrogated by a silicon nitride photonic waveguide, with quality factors approaching $10^6$ in the telecom c-band after surface treatments. Moreover, in contrast to conventional Faraday setup, this implementation allows input photon polarized colinearly to the magnetization to be scattered to a sideband mode of orthogonal polarization. This Brillouin scattering process is enhanced through triply resonant magnon, pump and signal photon modes - all of whispering gallery nature - within an “optomagnonic cavity”. Our results show the potential use of magnons for mediating microwave-to-optical carrier conversion.

Hybrid magnonic systems have been emerging recently as an important approach towards coherent information processing.¹⁴ The building block of such systems, magnon, is the quantized magnetization excitation in magnetic materials.¹⁰,¹¹ Its great tunability and long lifetime make magnon an ideal information carrier. Particularly, in magnetic insulator yttrium iron garnet (YIG), magnons interact with microwave photons through magnetic dipole interaction, which can reach the strong and even ultrastrong coupling regime thanks to the large spin density in YIG.¹⁶ Besides, the magnon can also couple with the elastic wave¹³ and optical light¹¹ because of potential as an information transducer that mediates inter-conversion among microwave photon, optical photon and acoustic phonon. Long desired functions, such as microwave-to-optical conversion, can be realized on such a versatile platform.

Magneto-optical (MO) effects such as Faraday effect have been long discovered and utilized in discrete optical device applications.¹⁴,¹⁵ Based on such effects, magnons can coherently interact with optical photons. On the one hand, magnon can be generated by optical pump.¹⁵,²² On the other hand, optical photons can be used to probe magnon through Brillouin light scattering (BLS).¹⁴,²³ However, in previous studies the typical geometries are all thin film or bulk samples inside which the optical photon interacts with magnon very weakly, usually only through a single pass. For high efficient magnon-photon interaction, it is desirable to obtain triple resonance condition of high quality ($Q$) factor modes, i.e., the magnon, the input and the output optical photons are simultaneously on resonance.

In this Letter, we demonstrate the magnon-photon interaction in a high $Q$ optomagnonic cavity which simultaneously supports whispering gallery modes (WGMs) of optical and magnon resonances. With high-precision fabrication and careful surface treatment, the widely used YIG sphere structure, which is inherently an excellent magnonic resonator, exhibits high optical $Q$ factors in our measurements. YIG has a high refractive index (2.2 in the telecom c-band), which poses a challenge for efficient light coupling with silica fiber tapers. By employing an integrated silicon nitride optical waveguide with an effective index (around 2.0) matching that of YIG, we can efficiently couple to both the TM and TE optical resonances in the YIG sphere. By driving the system with an optical pump, the magnons excited by an input microwave signal can be converted into optical signal of a different color. Our demonstration shows the great potential of YIG sphere as a platform to bridge the gap between magnon and optical photons, paving the way towards using magnon as a transducer for coherent information processing between distinct carriers.

In magnetized YIG material, magnons are the collective excitations of spin states of Fe³⁺ ions.²³ The creation or annihilation of a single magnon corresponds to the ground spin flip. At the microwave frequencies, the magnon state can be manipulated straightforwardly by magnetic dipolar transition using the oscillating magnetic fields of microwave photons. While at the optical frequencies, the magnon manipulation becomes difficult because the magnetic transition is negligible whilst direct spin-flip by electric dipole transition is forbidden.²⁵ Alternatively, the optical photons can modify the ground state spin through a two-photon transition by means of an orbital transition and spin-orbit interaction (the MO effect).¹⁴ Such a process has been previously studied using conventional Faraday setup,²⁶ in which light propagates parallel to the magnetic field and interacts with magnon in a single pass. It is natural to consider shaping the YIG into an optical cavity to boost up the magnon-photon interaction as light passes the magnetic material multiple times. Therefore, we propose to use a whispering gallery resonator made by YIG to provide enhanced magnon-photon coupling in a triply resonant configuration, and the mechanism is explained in the following discussions.

The optomagnonic cavity we used in our experiments is a single crystal YIG sphere. Due to the spherical symmetry, lights are confined in the sphere by total internal reflection and form WGMs. Each optical WGM is characterized by three mode numbers $(q, l, n)$, which correspond to the radial, angular and azimuthal order $(n = -l, \ldots, l)$, respectively.²⁷,²⁸ Moreover, the WGMs...
are also characterized by their polarization, i.e., the direction of their electric field distribution. Conventional Faraday setups require the bias magnetic field to be parallel to the direction of light propagation. However, for WGMs light propagates along the circumference of the sphere [Fig. 1(a)], therefore the bias magnetic field should be in the x-y plane. Due to the geometry symmetry, the MO effect vanishes for such a Faraday configuration. At first glance, the MO effect also vanishes for bias magnetic field along the z direction, since it requires circular polarization in respect to \( \mathbf{H} \) while WGMs are linearly polarized, either parallel (TE) or perpendicular (TM) to the z direction. However, thanks to the field gradient at the dielectric interface, there are non-zero optical electric fields along the propagation direction for the TE polarized WGMs. As a result, the electric field rotates within the x-y plane and forms a cycloid trajectory, similar to the elliptically polarized light propagating in free space. Therefore, the TE WGMs possess partial circular polarization and can have magnetic response via Faraday effect, as schematically illustrated in Fig. 1(a). Note that the pump light can propagate either clockwise (CW) or counterclockwise (CCW), with different conservation conditions accordingly, as will be shown below.

Similar to the optical WGMs, the magnon modes in YIG sphere can also be characterized by three mode numbers \( (q_m, t_m, n_m) \). For the uniform magnon mode with all the spins precessing in phase, the corresponding mode numbers are \((1, 1, 1)\). The microscopic mechanism of the magnon-photon interaction is intrinsically a three-wave process, as schematically illustrated by Fig. 1(b). Due to the spin angular momentum conservation, every time when the magnon number increases by 1 it indicates that the electron spin increases by 1, which corresponds to a two-photon transition in the form of \( \sigma^+ \rightarrow \pi \) (CCW) or \( \pi \rightarrow \sigma^- \) (CW). As a result, there would be only one optical sideband generated for a given pumping light direction. The mesoscopic model of the MO effect is represented by the permittivity tensor \( \epsilon_{ij} = \epsilon_0 (\sigma_{ij} - i f \epsilon_{ijk} M_k) \) where \( \epsilon_0 \) is the vacuum permittivity, \( \sigma_\pi \) is the relative permittivity of YIG, \( \delta_{ij} \) and \( \epsilon_{ijk} \) are Kronecker and Levi-Civita symbols, \( f \) is the Faraday coefficient, \( M_k \) is the magnetization, and \( i, j, k \) correspond to \( x, y, z \) direction, respectively. When the energy is conserved for the two-photon and magnon transitions that \( \omega_1 - \omega_2 = \omega_m \), the coupling strength between two optical modes is \( g = (\Delta \epsilon_{ij}(\mathbf{x}) E_{1,i}(\mathbf{x}) E_{2,j}(\mathbf{x})) d^3 \mathbf{x} \), where \( \Delta \epsilon_{ij} = \epsilon_{ij}(\mathbf{x}) - \epsilon_{ij}(\mathbf{x})_{0} \) is the normalized field of optical WGM, \( \epsilon_{ij}(\mathbf{x})_{0} \) and \( \epsilon_{ij}(\mathbf{x}) \) are the permittivity change is \( \Delta \epsilon_{ij}(\mathbf{x}) = -i f \epsilon_{0} \epsilon_{ijk} M_k(\mathbf{x}) \). As the field distributions are in the form of \( e^{i \sigma^p(x,y,z)} \) in the spherical coordinate along the azimuthal direction, \( g \) is non-zero only for the conservation of orbit angular momentum \( n_1 - n_2 = n_m \). Therefore, when the energy, spin and orbit angular momentum conservation relations, i.e., the triple resonance condition [Fig. 1(c)] and selection rule for our optomagnonic resonator, are simultaneously satisfied, the coupling strength \( g \) can be greatly enhanced. The schematic and optical images of the experiment assembly of our optomagnonic cavity integrated with...
Before studying the magnon-photon interaction, we first characterize the optical and magnon modes. The reflection microwave spectrum at $H = 1840$ Oe is plotted in Fig. 3(a), showing multiple dips that correspond to magnon modes (to observe high order modes, the YIG sphere is placed at the non-uniform fields of the antenna). In the zoomed-in spectrum of Fig. 3(b), the loaded $Q$ factor of the fundamental magnon mode $(1, 1, 1)$ is 1230. In the following magnon-photon interaction measurement, the YIG sphere is placed at the uniform microwave fields of the antenna output such that only the $(1, 1, 1)$ mode is excited. The optical transmission spectra are plotted in Fig. 3(c), where TE/TM polarized light in the waveguide are used to probe $\sigma^+/\pi$ polarized WGMs in the YIG sphere, receptively. Groups of optical resonances show up in the spectra, exhibiting large extinction ratio (beyond 10 dB) for both polarizations, which confirms the efficient coupling between the silicon nitride waveguide and the WGMs. The measured free spectral ranges for both $\sigma^+$ (1.0765 nm) and $\pi$ (1.1068 nm) polarizations agree with the prediction (1.1580 nm) for WGMs. Thanks to our surface treatments, very high optical $Q$ factors are achieved: $Q_{\sigma^+} = 5.93 \times 10^6$ and $Q_\pi = 7.63 \times 10^6$ [Figs. 3(d) and (e)].

To measure the interaction between optical photon and magnon, the YIG sphere is biased at $H = 2410$ Oe, corresponding to a magnon resonance frequency of $\omega_m/2\pi = 6.75$ GHz. The optomagnonic resonator is pumped by a TM polarized laser beam with 1 mW power, and the magnons are excited by an on-resonance microwave signal. The laser wavelength is scanned to search for the optical modes that satisfy the energy, spin and angular momenta conservation conditions. During the searching process, lock-in technique is adopted to improve the converted light signal to noise ratio. When the conservation conditions are satisfied, the output light is sent to a high resolution spectrometer for further analysis. It is worth noting that the density of optical WGMs is very large, as there are mode degeneracy in the polar direction and high order modes in the radial direction. As a result, the conservation conditions can be satisfied accidentally, similar to the Brillouin scattering in microsphere optomechanical cavities. A typical spectrum of converted photons as a function of the sweeping pump laser wavelength is shown in Fig. 4(a), where the passive transmission spectrum of the pump light is also shown accordingly. The correspondence between the resonances for pump light and the peaks of magnon-photon conversion implies the triple resonance enhancement in our optomagnonic cavity. The dependence of the converted photons on the microwave resonance [Fig. 4(b)] also confirms the participation of magnon in the inelastic light.
FIG. 4. (a) Optical pump transmission and the generated optical signal as a function of pump laser wavelength. The correspondence of the generated optical signal peak and the optical pump resonance dip indicates the satisfaction of the conservation conditions. (b) Microwave reflection and the generated optical signal as a function of the microwave frequency. (c) Optical spectrum of the device output when the triple resonance conditions are satisfied. The TM and TE components of the output light are separated by a polarization beam splitter. The TM component corresponds to the direct transmission of the pump light, while the TE component contains the scattered sideband. (d) Power dependence of the sideband on the pump light, while the TE component shows a single peak as it only contains the transmitted pump light. On the contrary, the TE component shows two peaks: a strong peak which corresponds to the transmitted pump light that is not completely filtered out, and a weak sideband which corresponds to the generated photons. Therefore we do have orthogonal polarizations for the generated signal and the pump light, which agrees well with our theory model. The linewidths of the measured pump and sideband signal are not the physical linewidth of the light but instead only represent the finite resolution (67 MHz) of the filter in the spectrometer. The centers of the pump peak and sideband differ from each other by 6.75 GHz, matching the input magnon frequency. The sideband appears only on one side of the pump as a result of the conservation conditions, as explained in above analysis. We measured the converted light at various microwave input powers, which clearly shows a linear power dependence [Fig. 4(d)], indicating a linear magnon to photon conversion. The fitted raw power (system) conversion efficiency is $5 \times 10^{-8}$. Considering the imperfect resonance coupling and in-line insertion losses for both the optical and microwave circuits, the internal power conversion efficiency is about $5 \times 10^{-3}$. The conversion efficiency can be improved by using YIG spheres of smaller size and smoother surface. Further geometry optimization, such as using YIG microdisk whose modal volume is orders of magnitude smaller, in combination with Faraday effect enhancement via doping, could lead to much improved conversion efficiencies.

In conclusion, we have demonstrated an excellent optomagnonic resonator that is made by a highly polished YIG sphere. Utilizing an integrated optical chip for high efficiency optical coupling, high-Q optical WGMs are observed in addition to magnon resonances in the YIG sphere after our careful surface treatment. When the triple resonance condition and angular momentum conservation condition are satisfied, the magnon is converted to optical photon with internal power efficiency of about 0.5%. This efficiency can be further improved by doping or geometry optimization. Our findings show that YIG sphere is a promising platform for designing complex hybrid systems, which holds great potential to realize information inter-conversion among magnon, microwave photon, and optical photons.

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1. A. V. Chumak, V. I. Vasyuchka, A. A. Serga, and B. Hilbrandts, Nature Phys. 11, 453 (2015).
2. Y. Tabuchi, S. Ishino, A. Noguchi, T. Ishikawa, R. Yamazaki, K. Usami, and Y. Nakamura, Science 349, 405 (2015).
3. C.-M. Hu, arXiv:1508.01966 (2015).
4. Y. Tabuchi, S. Ishino, T. Ishikara, R. Yamazaki, K. Usami, and Y. Nakamura, Phys. Rev. Lett. 113, 083603 (2014).
5. X. Zhang, C.-L. Zou, L. Jiang, and H. X. Tang, Phys. Rev. Lett. 113, 156401 (2014).
6. M. Goryachev, W. G. Farr, D. L. Creedon, Y. Fan, M. Kostylev, and M. E. Tobar, Phys. Rev. Appl. 2, 054002 (2014).
7. L. Bai, M. Harder, Y. P. Chen, X. Fan, J. Q. Xiao, and C.-M. Hu, Phys. Rev. Lett. 114, 227201 (2015).
8 H. Huebl, C. W. Zollitsch, J. Lotze, F. Hocke, M. Greifenstein, A. Marx, R. Gross, and S. T. B. Goennenwein, Phys. Rev. Lett. 111, 127003 (2013).
9 X. Zhang, C.-L. Zou, N. Zhu, F. Marquardt, L. Jiang, and H. X. Tang, arXiv 1507.02791 (2015).
10 A. A. Serga, A. V. Chumak, and B. Hillebrands, J. Phys. D. Appl. Phys. 43, 264002 (2010).
11 B. Lenk, H. Ulrichs, F. Garbs, and M. Münzenberg, Phys. Rep. 507, 107 (2011).
12 C. Kittel, Phys. Rev. 110, 836 (1958).
13 K. Sinha and U. Upadhyaya, Phys. Rev. 127, 432 (1962).
14 Y. Shen and N. Bloembergen, Phys. Rev. 143, 372 (1966).
15 S. Demokritov, B. Hillebrands, and A. Slavin, Phys. Rep. 348, 441 (2001).
16 M. Freiser, IEEE Trans. Magn. 4, 152 (1968).
17 Magneto-Optics, edited by S. Sugano and N. Kojima (Springer, Boston, MA, 1999).
18 L. Bi, J. Hu, P. Jiang, D. H. Kim, G. F. Dionne, L. C. Kimerling, and C. A. Ross, Nature Photon. 5, 758 (2011).
19 A. Kirilyuk, A. V. Kimel, and T. Rasing, Rev. Mod. Phys. 82, 2731 (2010).
20 A. V. Kimel, A. Kirilyuk, P. A. Usachev, R. V. Pisarev, A. M. Balbashov, and T. Rasing, Nature 435, 655 (2005).
21 T. Saitoh, Y. Terui, R. Moriya, B. A. Ivanov, K. Ando, and E. Saitoh, Nature Photon. 6, 662 (2012).
22 J. V. der Ziel, P. Pershan, and L. Malmstrom, Phys. Rev. Lett. 15, 190 (1965).
23 P. A. Fleury and R. Loudon, Phys. Rev. 166, 514 (1968).
24 D. D. Stancil and A. Prabhakar, Spin Waves - Theory and Applications (Springer US, Boston, MA, 2009).
25 H. Le Gall, J. Phys. Colloq. 32, C1 (1971).
26 A. Borovik-Romanov and N. Kreines, Phys. Rep. 81, 351 (1982).
27 V. Braginsky, M. Gorodetsky, and V. Ilchenko, Phys. Lett. A 137, 393 (1989).
28 A. Chiasera et al., Laser Photon. Rev. 4, 457 (2010).
29 C. Junge, D. O’Shea, J. Volz, and A. Rauschenbeutel, Phys. Rev. Lett. 110, 213604 (2013).
30 J. Petersen, J. Volz, and A. Rauschenbeutel, Science 346, 67 (2014).
31 I. Shomroni, S. Rosenblum, Y. Lovsky, O. Bechler, G. Guendelman, and B. Dayan, Science 345, 903 (2014).
32 P. Röchmann and H. Dösch, Phys. Stat. Sol. 82, 11 (1977).
33 D. L. Wood and J. P. Remeika, J. Appl. Phys. 38, 1038 (1967).
34 C.-L. Zou, Y. Yang, C.-H. Dong, Y.-F. Xiao, X.-W. Wu, Z.-F. Han, and G.-C. Guo, J. Opt. Soc. Am. B 25, 1895 (2008).
35 C.-H. Dong, Z. Shen, C.-L. Zou, Y.-L. Zhang, W. Fu, and G.-C. Guo, Nat. Commun. 6, 6193 (2015).
36 J. Kim, M. C. Kuzyk, K. Han, H. Wang, and G. Bahl, Nature Phys. 11, 275 (2015).