Optomagnonically tunable whispering gallery cavity laser wavelength conversion

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We achieve laser wavelength conversion in an optomagnonical whispering gallery cavity by adjusting the strength of the applied static magnetic field. Numerical simulations are carried out on a yttrium iron garnet (YIG) sphere under different cavity quality factors or coupling strength. It is found that a high cavity quality factor will not always mean a high cavity excitation field for Gaussian lasers with finite linewidth. On state of the art, the high cavity quality factor will always mean the higher lightwave conversion rate. In addition, we also find that increasing the mode coupling strength is beneficial to the conversion of the laser. Our study provides new insights into generation of highly precise tunable coherent light.

Keywords: cavity optomagnonics, YIG sphere, laser modulation

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1. Introduction

Magnon, firstly introduced by Bloch,[1] is the collective spin wave excitation carrying quantized energy in a magnetically ordered ground state. In practice, magnons can couple with various subjects, such as microwaves,[2–4] phonons,[5–7] and photons.[8–10] Among these interactions, the magnon–photon interaction, or optomagnonics, communicates the two most widely used wavebands in the field of communication today, microwave and optical communication waves. In this prospect, magnons have drawn significant research interests over the past decades.

With the rapid growth of quantum research and progress of high precision micro-fabrication technologies, optomagnonic microcavity has emerged as a novel research field.[9–14] Yutaka *et al.* firstly observed the strong coupling between photons and magnons in the quantum regime below 1 K.[4] Zhang *et al.* demonstrated an enhanced Brillouin scattering process through triply resonant magnon, pump, and signal photon modes inside a yttrium iron garnet (YIG) cavity,[15] because the YIG has large gyromagnetic ratio and low magnetic dissipation rate. Recently, researchers have begun to pay attention to applications of optomagnonics, such as photon blockades and frequency combs.[15–23]

In this work, we propose a laser wavelength conversion method based on optomagnonics, which converts the incoming photons to the orthogonal polarization direction in different wavelengths. The setup is shown in Fig. 1, following an attested model developed by Tang *et al.*[10] In whispering gallery mode cavities, the Faraday effect changes the polarization direction of EM waves to its orthogonal direction. Therefore, an input of TE mode laser gives out an output of TM mode. The optical TE and TM modes are inelastically scattered by magnons. Due to the conservation of the energy, the difference in the wavelength between the two optical modes is the same as the static magnetic field adjustable frequency of the magnons. We give the energy conversion features of the system for the gaussian laser. The result will benefit the wide range, continuous modulation of the coherent light.

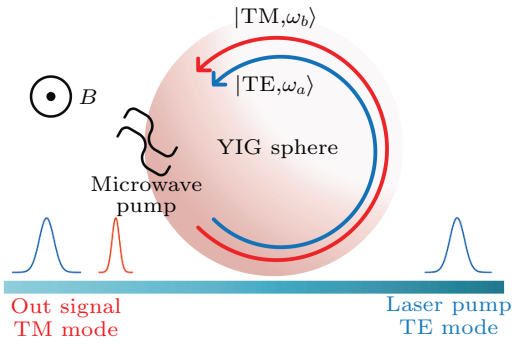


Fig. 1. The schematic diagram of the proposed modulation configuration. Two inner modes, TE (TM) polarized with frequency ω_a (ω_b), reside in the YIG sphere. TE polarized photon centered at ω_L is coupled into the YIG sphere by a fiber laser. A microwave pump is also applied whose frequency is ω_{mw}. The whole setup is under a static magnetic field B.

2. Theory

The Hamiltonian of the studied system incorporates three parts: the Hamiltonian of free optical and magnetic mode, the photon-magnon interaction, and the bath. We use operators a, b, m to denote the annihilation operator of the optical transverse electric (TE) mode, optical transverse magnetic (TM) mode, and the magnon, and use ω_a, ω_b, ω_m as the respective

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eigen-frequencies; g stands for the coupling factor. The system is laser and microwave pumped, and the pump frequencies are $\omega_{\rm L}$, $\omega_{\rm mw}$ respectively. We use $\kappa_{a,\rm ex}$ and $\kappa_{m,\rm ex}$ to denote the external coupling rate to laser and microwave pumps. Therefore, the Hamiltonian can be written as

$$\begin{aligned} H &= \omega_a a^\dagger a + \omega_m m^\dagger m + \omega_b b^\dagger b + g(ab^\dagger m + a^\dagger b m^\dagger) \\ &+ \sqrt{2\kappa_{m,\rm ex}}\sqrt{\frac{P_{\rm mw}}{\hbar\omega_{\rm mw}}}(m\,{\rm e}^{{\rm i}\omega_{\rm mw}t} + m^\dagger\,{\rm e}^{-{\rm i}\omega_{\rm mw}t}) \\ &+ \sqrt{2\kappa_{a,\rm ex}}\sqrt{\frac{P_{\rm L}}{\hbar\omega_{\rm L}}}(a\,{\rm e}^{{\rm i}\omega_{\rm L}t} + a^\dagger\,{\rm e}^{-{\rm i}\omega_{\rm L}t}). \end{aligned} \tag{1}$$

Under the rotating wave approximation, we obtain the reduced Hamiltonian

$$\begin{aligned} H_{\rm eff} &= (\omega_a - \omega_{\rm L})a^\dagger a + (\omega_m - \omega_{\rm mw})m^\dagger m \\ &+ (\omega_b - \omega_{\rm L} - \omega_{\rm mw})b^\dagger b + g(ab^\dagger m + a^\dagger b m^\dagger) \\ &+ \sqrt{2\kappa_{m,\rm ex}}\sqrt{\frac{P_{\rm mw}}{\hbar\omega_{\rm mw}}}(m + m^\dagger) \\ &+ \sqrt{2\kappa_{a,\rm ex}}\sqrt{\frac{P_{\rm L}}{\hbar\omega_{\rm L}}}(a + a^\dagger). \end{aligned} \tag{2}$$

When introduce the unavoidable damping term, the Langevin equations can be written as

$$\begin{aligned} \frac{{\rm d}\hat{a}}{{\rm d}t} &= -[{\rm i}(\omega_a - \omega_{\rm L}) + \kappa_a]\hat{a} + g\hat{b}\hat{m}^\dagger + 2\sqrt{\kappa_{a,\rm ex}}\sqrt{\frac{P_{\rm L}}{\hbar\omega_{\rm L}}}, \\ \frac{{\rm d}\hat{b}}{{\rm d}t} &= -[{\rm i}(\omega_b - \omega_{\rm L} - \omega_{\rm mw}) + \kappa_b]\hat{b} + g\hat{a}\hat{m}, \\ \frac{{\rm d}\hat{m}}{{\rm d}t} &= -[{\rm i}(\omega_m - \omega_{\rm mw}) + \kappa_m]\hat{b} + g\hat{a}^\dagger\hat{b} + 2\sqrt{\kappa_{m,\rm ex}}\sqrt{\frac{P_{\rm mw}}{\hbar\omega_{\rm mw}}}, \end{aligned} \tag{3}$$

where κ_a and κ_b denote the dissipation rate of the first TE and TM modes, respectively. As the optomagnonic coupling is much weaker than the cavity dissipation ($g \ll \kappa_a$), the steady state of the cavity TE field reduces to

$$\langle a\rangle = \frac{-{\rm i}\sqrt{2\kappa_{a,\rm ex}}\sqrt{\frac{P_{\rm L}}{\hbar\omega_{\rm L}}}}{-{\rm i}(\omega_a - \omega_{\rm L}) - \kappa_a}. \tag{4}$$

Substituting the steady state value of a into the original Hamiltonian, we can obtain the steady state solution of b and m:

$$\langle b\rangle = \frac{{\rm i}G}{-{\rm i}(\omega_b - \omega_{\rm L} - \omega_{\rm mw}) - \kappa_b}\langle m\rangle, \tag{5}$$

$$\langle m\rangle = \frac{{\rm i}\sqrt{2\kappa_{m,\rm ex}}\sqrt{\frac{P_{\rm mw}}{\hbar\omega_{\rm mw}}}}{-{\rm i}(\omega_m - \omega_{\rm mw}) - \kappa_m + \frac{|G|^2}{-{\rm i}(\omega_b - \omega_{\rm L} - \omega_{\rm mw}) - \kappa_b}}. \tag{6}$$

Here, G is the effective coupling strength, and $G = g\langle a\rangle$. The output profile of the TM mode can therefore be written as

$$\begin{aligned} \frac{P_{\rm out}}{\hbar\omega_b} &= 2\kappa_{b,\rm ex}|\langle b\rangle|^2 \\ &= 2\kappa_{b,\rm ex}\frac{\kappa_b\kappa_m}{(\omega_b - \omega_{\rm L})^2 + \kappa_b^2}\frac{g^2|\langle a\rangle|^2}{\kappa_b\kappa_m} \\ &\times \frac{2\kappa_{m,\rm ex}}{|-{\rm i}(\omega_m - \omega_{\rm mw}) - \kappa_m + \frac{|G|^2}{-{\rm i}(\omega_b - \omega_{\rm L} - \omega_{\rm mw}) - \kappa_b}|} \\ &\times \frac{P_{\rm mw}}{\hbar\omega_{\rm mw}}. \end{aligned} \tag{7}$$

For the maximal conversion, we need to align the frequency of the microwave pump to the frequency of the excited magnon to induce the triple resonance, $\omega_m = \omega_{\rm mw}$, in that case the TM transmission can be simplified to

$$\frac{P_{\rm out}}{\hbar\omega_b} = \frac{4\kappa_{b,\rm ex}\kappa_{m,\rm ex}}{\kappa_b^2}\frac{g^2|\langle a\rangle||^2}{(\kappa_m + \frac{|G|^2}{\kappa_b})^2}\frac{P_{\rm mw}}{\hbar\omega_m}. \tag{8}$$

In practice, the linewidth of the laser pump is usually in the sub-picometer regime and the experimental cavity quality factor of the YIG sphere is below 10^7. Therefore, we can safely assume that the linewidth of the laser is far less than that of the cavity, that is $\Delta\lambda_{\rm in} \ll \Delta\lambda_{\rm cav}$. Under this approximation, we obtain

$$\frac{P_{\rm out}}{\hbar\omega_b} = \frac{\mathbb{A}}{\kappa_m^2}, \tag{9}$$

where $\mathbb{A}$ is the amplitude of the output spectrum:

$$\mathbb{A} = 4\kappa_{b,\rm ex}\kappa_{m,\rm ex}\frac{g^2|\langle a\rangle|^2}{\kappa_b^2}\frac{P_{\rm mw}}{\hbar\omega_{\rm mw}}. \tag{10}$$

3. Results and discussion

In the following we discuss the performance of the laser tuning process. We set the eigen-frequency of the cavity TE mode to match the central frequency of the laser pump, that is, $\omega_a = \omega_{\rm L}$.

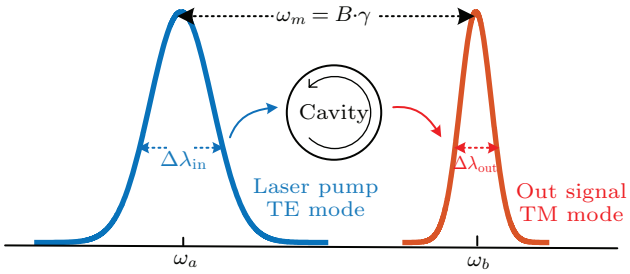


Fig. 2. The frequency modulation scheme. The input TE polarized photon centered at ω_a are scattered to TM polarized photon centered at ω_b. The frequency difference is determined by $\omega_m = B \cdot \gamma$, which can be adjusted by the static field strength.

As shown in Fig. 2, during the inelastic collision of optomagnonics, the output TM mode frequency ω_b is the sum of the pump field frequency ω_a and the magnon frequency ω_m subjected to the conservation of energy. Moreover, the magnon frequency solely depends on the magnetic field intensity, $\omega_m = B \cdot \gamma$. Therefore, the frequency difference of the input and output field is proportional to the applied magnetic field. Thus, the output frequency can be tuned by the applied magnetic field. For wavelength modulation, another issue we need to pay attention to is the conversion rate of energy. We

assume a fixed applied magnetic field as 2410 Oe. Considering the YIG sphere's gyromagnetic ratio $2\pi \cdot 2.8$ MHz/Oe, this amounts to a magnon frequency of 6.75 GHz.

One key factor impacting the conversion efficiency is the optical and magnetic quality factor of the cavity. The optical dissipation ratio scales with cavity optical quality factor by the relation $\delta\lambda_a = \kappa_a = \omega_a/Q$, where ω_a is the eigen-frequency of the cavity TM mode. As shown in Eq. (8), the optical dissipation ratio impacts the laser pump coupling strength and the output power directly, therefore we ramp the quality factor of the cavity and observe the output signal bandwidth, the inner field strength, and the output power, respectively. The frequency of the Gaussian profile pump laser is centered at 1550 nm with 0.03 mW power. The bandwidth of the laser pump varies from 0.04 pm to 2 pm to investigate the relation between the laser bandwidth and the cavity optical quality factor.

Figure 3(a) shows the inner TE mode strength $\langle a \rangle$ with respect to the cavity factor. As suggested by Eq. (4), the mode strength profile is determined by the mode dissipation ratio κ_a and the external coupling $\kappa_{a,\mathrm{ex}}$. Since the external coupling rate can be adjusted by the placement of the optical fiber and the physical configuration of the joint structure, we can safely set the external coupling rate to the critical point where $\kappa_{a,\mathrm{ex}} = 0.5\kappa_a$ to reach the maximum coupling efficiency. We can find that all except the laser with 2 pm linewidth show a monotonous increase as the cavity quality factor increases, because a higher quality factor means a higher optical storage capacity. However, the pump with 2 pm linewidth shows an increase followed by a steady decrease in the field strength. This is because, for the lower external coupling in the off-resonance region, it is difficult for a laser with large linewidth to be coupled in. It should also be noted that the maxima of this group indicate the optimal coupling of the Gaussian laser.

To generate the modulated signal, the purposed operation sequence should follow after.

Firstly, get the static magnetic field strength according to the gyromagnetic ratio of the cavity material and the desired modulation frequency. Then, apply the static magnetic field to the cavity to excite the magnons with a specified frequency.

In order to amplify the output TM signal by the triple resonance process, apply a microwave signal with a frequency equalling that of the magnons.

Apply the laser pump to couple into the cavity in the TE mode and collect the output TM signal.

To study this scheme, we set the frequency of the microwave to 6.75 GHz, the same as the magnon frequency inside the cavity, and the microwave pump power is fixed at 320 mW. All these parameters are experimentally achievable. We demonstrate the power of the output TM mode in Fig. 3(b). As the cavity quality factor increases, the output power grows monotonously. At the maximum cavity quality factor, the output power differences are evident for lasers with linewidth greater than 0.5 pm, whereas for laser pumps with a finer linewidth, the output power difference is negligible, which indicates the impact of laser linewidth vanishes when the relation $\Delta\lambda_{\mathrm{in}} \ll \Delta\lambda_{\mathrm{cav}}$ is satisfied. However, it should be noted that this result only holds for a relatively low quality factor, i.e., $Q \leq 10^7$. For cavities with a much higher quality factor, usually 10^8 or higher, an off-resonant term must be considered. Then the influence of the cavity quality factor will not be monotonous.

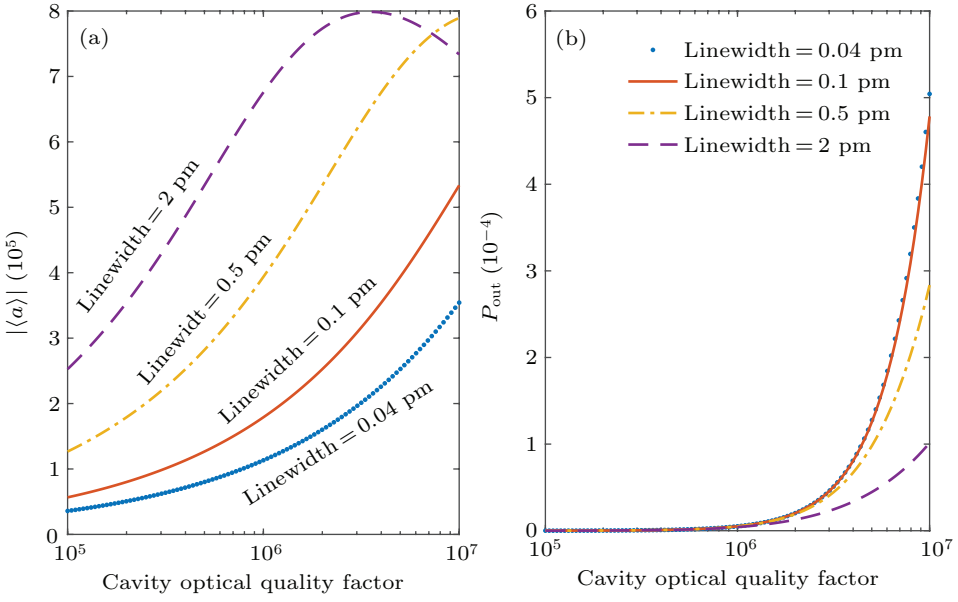


Fig. 3. (a) The cavity TE mode field strength, and (b) the output TM polarized power, P_{out} with respect to the cavity optical quality factor. The powers of the laser and microwave pump are 0.03 mW and 320 mW, respectively. The magnetic dissipation factor of the cavity is 5 MHz. The frequencies of cavity magnon and microwave pump are 6.75 GHz. The g coupling factor is set to 50 Hz.

When the optical mode is modulated by the cavity, the power profile of the output signal may also be changed. Under the assumption that the input laser has a Gaussian profile in the frequency domain, the full width at half maximum (FWHM) is the input laser's linewidth $\Delta\lambda_{\text{in}}$. Figure 4 demonstrates one of the cavity's characteristics as a frequency filter by showing variation of the bandwidth ratio, $\Delta\lambda_{\text{in}}/\Delta\lambda_{\text{out}}$, with respect to the optical quality factor. Initially, the output profile is slightly affected and the ratio is close to 1 under the lowest cavity quality factor condition of $\Delta\lambda_{\text{in}} \ll \Delta\lambda_{\text{cav}}$. Thus, for laser pumps with small linewidth, a cavity with a quality factor less than 10^7 has little impact on the output bandwidth. It should be noted that for laser pumps with linewidth 0.5 pm and linewidth 2 pm, the bandwidth ratio decreases significantly as the cavity becomes finer when the cavity linewidth has the same magnitude as the laser. This shows a strong filter effect, and the output profiles become sharper in the frequency domain. Then the higher quality factor cavity can be used to convert the laser frequency and its linewidth. As suggested by Eq. (10), the magnetic quality factor seems to play similar roles as the optical quality factor. However, the magnetic quality factor's influence on the coupling and output power is limited. While the optical quality factor can be improved by decreasing the surface roughness, the adjustability of magnetic quality factors is limited, which is mainly determined by the material properties.

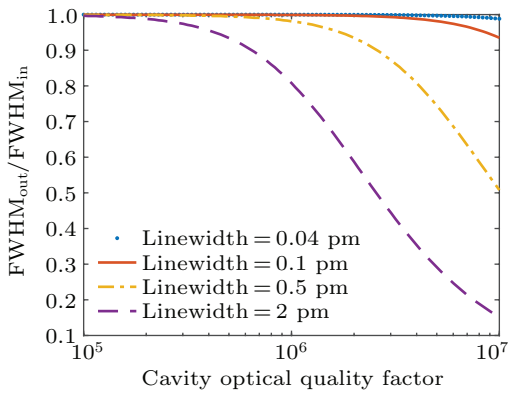


Fig. 4. The input–output bandwidth ratio, $\Delta\lambda_{\text{out}}/\Delta\lambda_{\text{in}}$, with respect to the cavity optical quality factor.

As a parameter describing the connection between the TE and TM mode, the coupling g factor will also impact the output TM mode. Therefore, we study the output TM power profile under different g coupling factors in Fig. 5. It can be found that the cavity with a higher g coupling factor has a better conversion performance, but the g factor does not influence the linewidth of the output TM mode because all these frequency spectra have the same linewidth. This means that we can increase the coupling factor to increase the energy conversion without the need to consider the effect on the laser frequency distribution.

The results indicate that the conversion efficiency of our purposed system is relatively low in the current stage. However, we only adopt parameters that are currently experimentally achievable, whereas remarkable improvement in the conversion efficiency is feasible with the advance in materials and coupling technologies. For instance, Kobayashi *et al.* purposed a metal-fluoride nanogranular film that can produce Faraday rotation 40 times larger than the BI-YIG material.[24] As suggested by Eq. (10), adopting such a material will lead to 1600 times increase in conversion efficiency, which will make the configuration practical.

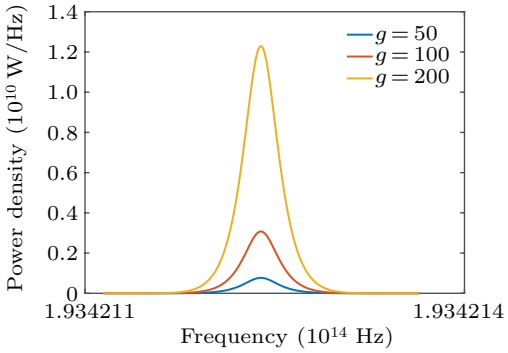


Fig. 5. The frequency spectrum of output TM polarized signal with different g coupling factors. The laser pump linewidth is 0.5 pm and the cavity optical quality factor is 10^7.

4. Conclusion

In summary, we have proposed a method to modulate a TE mode laser to get TM polarized output with the whispering-gallery mode cavity optomagnonics. Under the 320 mW pump, we can obtain a 600 μW output. By numerical simulation, the key parameters impacting the performance of the modulation are discussed. We find that the optical quality factor of the cavity and the coupling g factor are positively correlated to the quality factor of the cavity, and the output profile in the frequency domain is slightly compressed when $\Delta\lambda_{\text{in}} \ll \Delta\lambda_{\text{cav}}$. We find that, to reach the best conversion efficiency, the linewidth of the pump laser should match the cavity quality factor. The cavity with a higher g coupling factor means a higher output efficiency without affecting frequency distribution. Our scheme presents a new non-contact laser frequency modulation scheme that is different from previous ones that require mechanical modulation or applied voltage.

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