Tunable multiwindow magnomechanically induced transparency, Fano resonances, and slow-to-fast light conversion

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ABSTRACT

We investigate the absorption and transmission properties of a weak probe field under the influence of a strong control field in a cavity magnomechanical system. The system consists of two ferromagnetic-material yttrium iron garnet (YIG) spheres coupled to a single cavity mode. In addition to two magnon-induced transparencies (MITs) that arise due to magnon-photon interactions, we observe a magnomechanically induced transparency (MMIT) due to the presence of nonlinear magnon-phonon interaction. We discuss the emergence of Fano resonances and explain the splitting of a single Fano profile to double and triple Fano profiles due to additional couplings in the proposed system. Moreover, by considering a two-YIG system, the group delay of the probe field can be enhanced by one order of magnitude as compared with a single-YIG magnomechanical system. Furthermore, we show that the group delay depends on the tunability of the coupling strength of the first YIG with respect to the coupling frequency of the second YIG, and vice versa. This helps to achieve larger group delays for weak magnon-photon coupling strength.

Introduction:

A hybrid cavity magnomechanical system is shown in Fig. 1. It consists of two ferromagnetic yttrium iron garnet (YIG) spheres placed inside a microwave cavity. A bias magnetic field is applied in the *z* direction on each sphere, which excites the magnon modes, and these modes are strongly coupled with the cavity field. The bias magnetic field activates the magnetostrictive (magnon-phonon) interaction in both YIGs. The single-magnon magnomechanical coupling strength is very weak [6], and it depends on the sphere diameters and the external bias field direction. Either by considering a larger YIG1 sphere or by adjusting the direction of the bias field on it, the magnomechanical coupling of this sphere can be ignored. Here, we assume that the direction of the bias field at YIG1 is such that the single magnon magnomechanical interaction becomes very weak and can be ignored [14]. However, the magnomechanical interaction of YIG2 is enhanced by directly driving its magnon mode via a microwave drive (*y* direction). This microwave drive plays the role of a control field in our model. Cavity, phonon, and magnon modes are labeled *a*, *b*, and *mi* (*i* = 1, 2), respective`

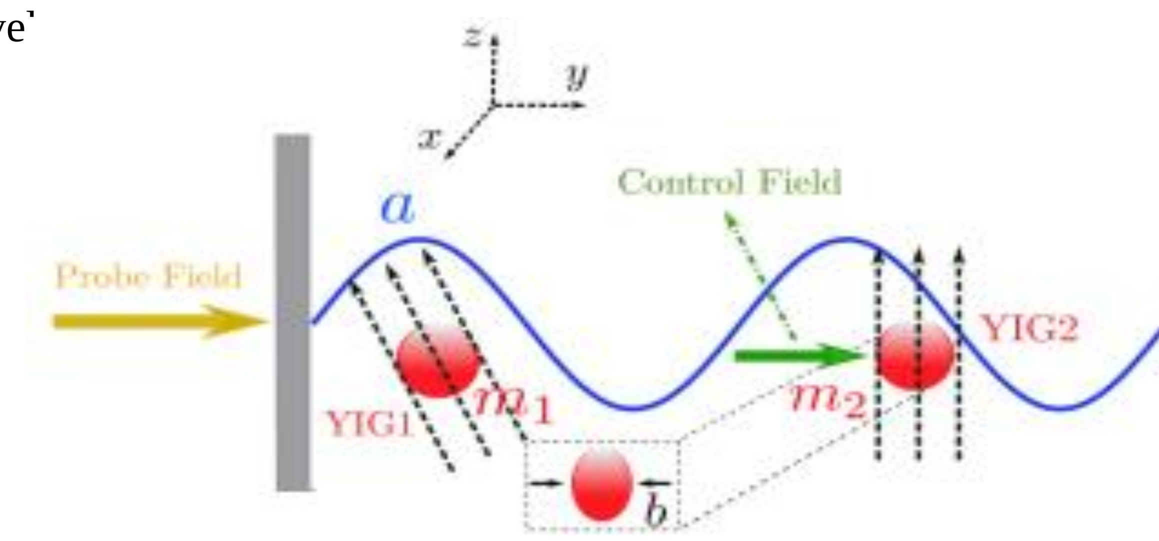


Fig.1. A schematic model of a hybrid magnomechanical system.

Hamiltonian of the system:

$$H = \hbar\, \Delta_a\, \hat{a}^\dagger\, \hat{a} + \hbar\omega_b \hat{b}^\dagger\, \hat{b} + \hbar \sum_{j=1}^{2}(\Delta_{mj} \widehat{m}_j^\dagger m_j + \hbar g_j(\widehat{m}_j^\dagger \hat{a} + \widehat{m}_j\, \hat{a}^\dagger)) - \hbar g_{mb} \widehat{m}_2^\dagger \widehat{m}_2(\hat{b}^\dagger + \hat{b}) + i\hbar\Omega_d(\widehat{m}_2^\dagger - \widehat{m}_2) + \hbar\mathcal{E}_p(\hat{a}^\dagger e^{-i\delta t} - \hat{a} e^{+i\delta t}).$$

Where $a^\dagger(a)$ is the creation(annihilation) operator of the microwave field with $[a, a^\dagger]=1$. The resonance frequencies of the cavity, phonon, and magnon modes are denoted, Δ_a, ω_b , and Δ_{mj}, respectively. Where $\Delta_a=\omega_a$-ω_d, $\Delta_{mj}=\omega_j$-ω_d, and $\delta=\omega_p$-ω_d. $\Omega_d=\frac{\sqrt{5}}{4}\gamma\sqrt{N}\ B_0$, $\mathcal{E}_p=\sqrt{^{2P_p\kappa_a}/_{\hbar\omega_p}}$.

We ignore the nonlinear term, we must have $K|\langle m_2\rangle|^3 << \Omega_d$ and for the system parameters we consider in this work, this condition is always satisfied.

The quantum Heisenberg- Langevin equations of motion

$$\dot{m}_1 = -\Delta_{m1}\ m_1 - k_{m1}\, m_1 - ig_1 a + \sqrt{2k}_{m1}\ m_{1in}\,(t),$$
$$\dot{m}_2 = -\Delta_{m2}\ m_2 - ig_2\, a - k_{m2}\, m_2 - ig_{mb} m_2(\hat{b}^\dagger + \hat{b}) + \Omega_d + \sqrt{2k_{m2}}\, m_{2in}\,(t),$$
$$\dot{a} = -i\,\Delta_a\, a - ig_1\, m_1 - ig_2\, m_2 - \kappa_a a + \mathcal{E}_p e^{-i\delta t} + \sqrt{2\kappa}\, a_{in}(\text{t}),$$
$$\dot{b} = -i\omega_b b - k_b b - ig_{mb} \widehat{m}_2^\dagger \widehat{m}_2 + \sqrt{2k_b}\, b_{in}(\text{t}),$$

where $\hbar$=1

Using steady-state approach of an operator $\langle A\rangle=A_s+A_+e^{+i\delta t}+A_-e^{-i\delta t}$ and considering only the first order perturbation that comes from the contribution of the probe field. The absorption and transmission of the probe field, the perturbed solutions of the cavity photon can be found as:

$$a_- = \mathcal{E}_p[\ (A' + C_1' + \frac{g_2^2}{\beta'} + \frac{\alpha\, \alpha'}{\beta\, \beta' + A^* - C_1^* + g_2^2/\beta^*})]\hat{}-1$$

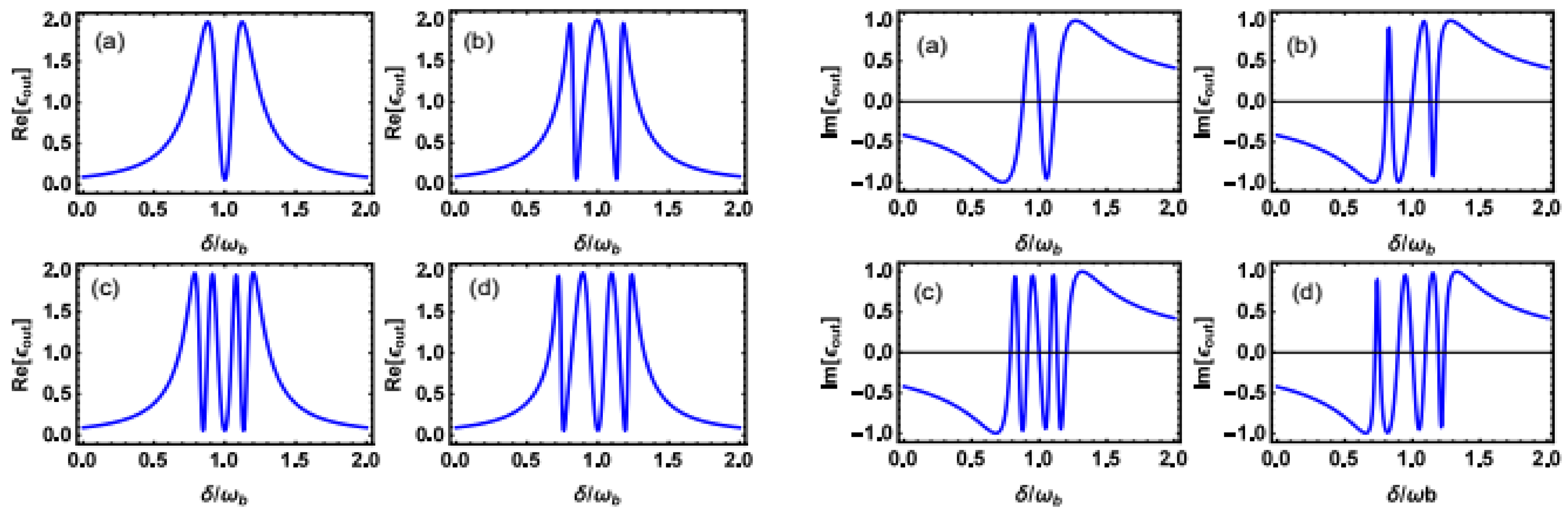
$$A = \kappa_a + i(\Delta_a + \delta), \quad B = \frac{G_{mb}^2\omega_b}{\omega_b^2 - \delta^2 + i\delta\kappa_b},$$
$$C_1 = \frac{g_1^2}{\kappa_{m1} + i(\Delta_{m1} + \delta)}, \quad C_2 = \frac{g_2^2}{\kappa_{m2} + i(\bar{\Delta}_{m2} + \delta)},$$
$$A' = \kappa_a + i(\Delta_a - \delta), \quad B' = \frac{G_{mb}^2\omega_b}{\omega_b^2 - \delta^2 - i\delta\kappa_b},$$
$$C_1' = \frac{g_1^2}{\kappa_{m1} + i(\Delta_{m1} - \delta)}, \quad C_2' = \frac{g_2^2}{\kappa_{m2} + i(\bar{\Delta}_{m2} - \delta)},$$
$$\alpha = \frac{g_2^2 B}{C_2 + iB}, \quad \alpha' = \frac{g_2^2 B'}{C_2' + iB'},$$
$$\beta = C_2 - i\frac{C_2^{\prime *} B}{C_2^{\prime *} + iB}, \quad \beta' = C_2' - i\frac{C_2^* B'}{C_2^* + iB'}.$$

Input-output relation

$a_{out} = \sqrt{2\kappa_a}\ a - a_{in}$, the rescaled output field correspond to probe field is given by $a_{out} = \frac{\sqrt{2\kappa_a}}{\mathcal{E}_p} a_-$.

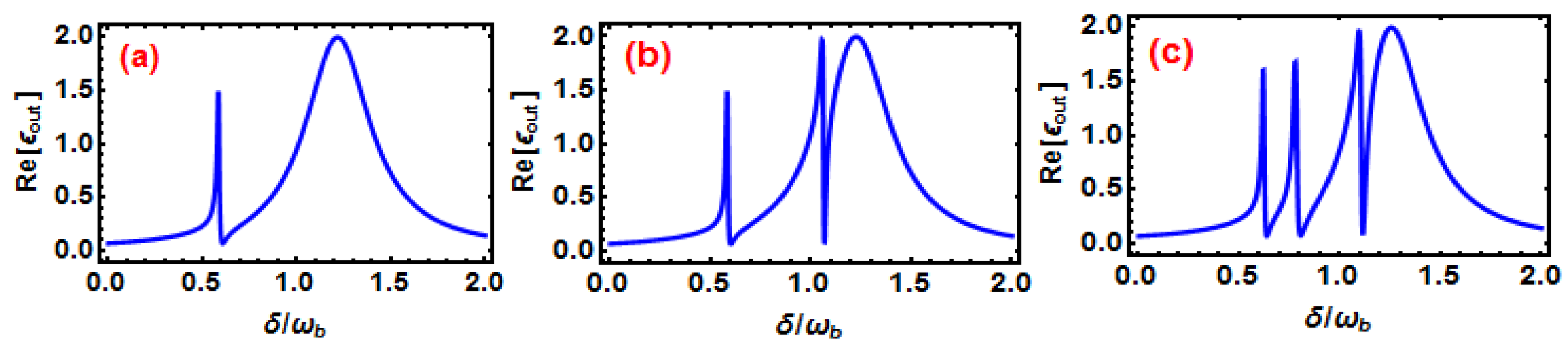
The real part $Re[\ a_{out}] = \frac{\sqrt{2\kappa_a}}{\mathcal{E}_p}(a_- + a_-^*)/\mathcal{E}_p$ and imaginary part $Im[\ a_{out}] = \frac{\sqrt{2\kappa_a}}{\mathcal{E}_p}(a_- - a_-^*)/i\mathcal{E}_p$ represent the absorption and dispersion of the output field.

Results;



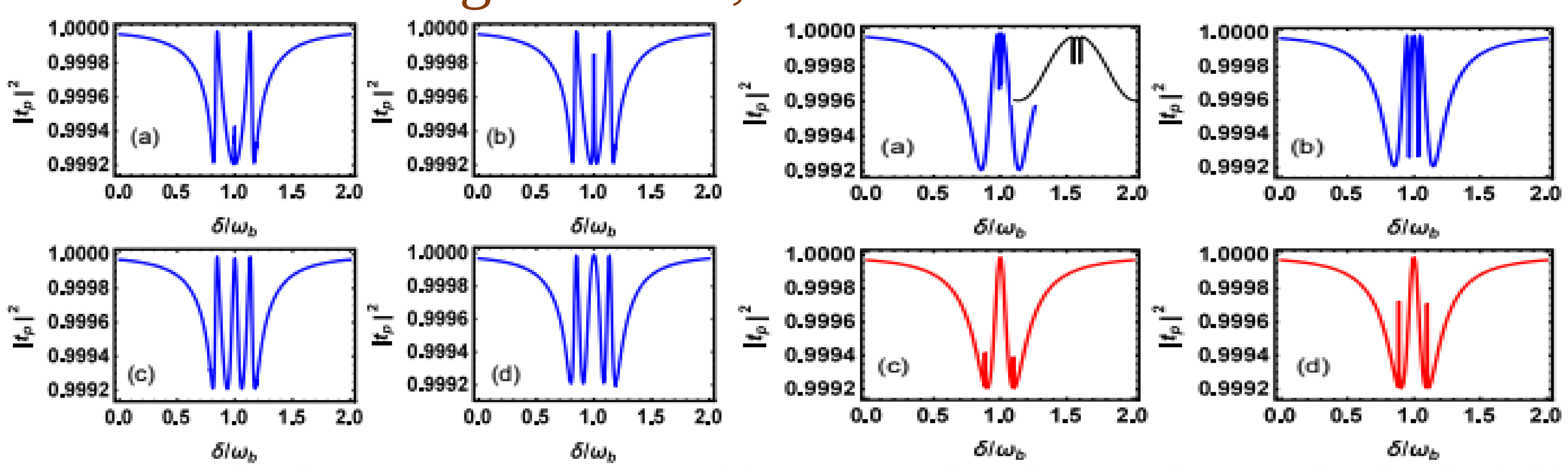
In Fig.2, a, b, c, d show a pattern of the transparency windows for files are shown against the normalized probe field detuning $\delta/\omega b$. (a) $g1 = gmb = 0$, $g2/2\pi = 1.2$ MHz and (b) $g1 = 0$, $g2/2\pi = 1.2$ MHz, $Gmb/2\pi = 2.0$ MHz, (c) $g1/2\pi = g2/2\pi = 1.2$ MHz, $Gmb/2\pi = 2$ MHz and (d) $g1/2\pi = g2/2\pi = 1.2$ MHz, $Gmb/2\pi = 3.5$ MHz. For detailed parameters see Phys. Rev. A 102, 033721 (2020).

Fano resonances

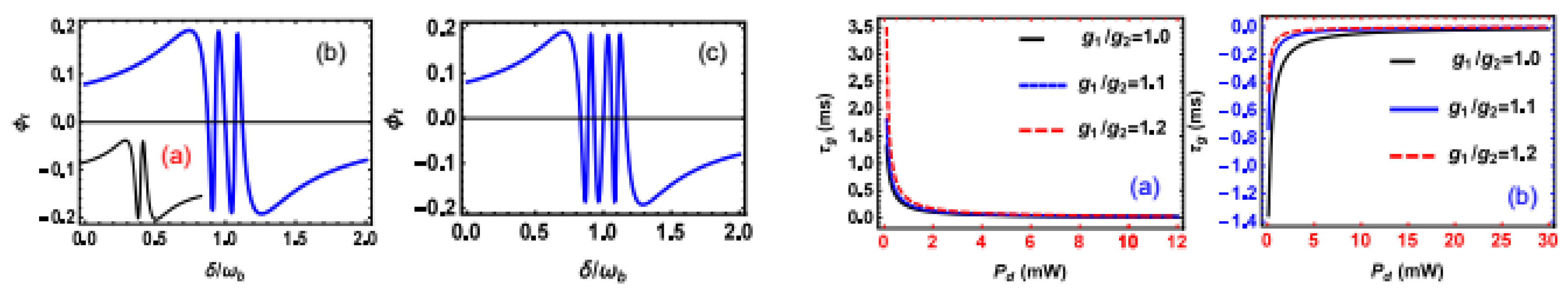


In Fig.3, single, double and triple Fano resonances are given in subfigures a, b and c. The detailed explanation and parameters feasibility are given in Phys. Rev. A 102, 033721 (2020).

Slow and fast light effects;



In Fig.4 and 5, the transmission spectrum of the output is plotted against the normalized probe field detuning. For further detail see Phys. Rev. A 102, 033721 (2020).



In Fig. 6, the phase of the output field is shown. In the next pattern, slow and fast effects of the transmitted field are shown. A detailed analysis of these plots is given in Phys. Rev. A 102, 033721 (2020).

CONCLUSION

We have investigated the transmission and absorption spectrum of a weak probe field under a strong control field in a hybrid magnomechanical system in the microwave regime. Due to the presence of a nonlinear phonon-magnon interaction, we observed magnomechanically induced transparency (MMIT), and the photon-magnon interactions lead to magnon-induced transparency (MIT). We found single MMIT, a result of the single-phonon process, and found two MIT windows in the output probe spectra due to the presence of two magnon-photon interactions. This is demonstrated by plotting the absorption, dispersion, and transmission of the output field. We discussed the emergence of Fano resonances in the output field spectrum of the probe field. These asymmetric lineshapes appeared due to the presence of anti-Stokes processes in the system. We examined conditions of slow and fast light propagation in our system, which can be controlled by different system parameters. It was shown that, in a two-YIG magnomechanical system, the tunability of the first coupling strength (YIG1) corresponding to the coupling of the second YIG (YIG2) has an immense effect on the slow and fast light and vice versa. This not only helped to investigate larger group delays at a weak magnon-photon coupling but also enhanced the group delay of the transmitted probe field, which is not possible in a single-YIG system. Our results suggest that this system may find applications to implement multiband quantum memories [6].

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