Research article

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Magnons scattering induced photonic chaos in the optomagnonic resonators

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Abstract: Along with the studies of the properties of optical microcavities, the optical nonlinear effects of the material and the interaction between light and matter are becoming important topics. For example, the chaotic effect of the optical field may appear under the strong laser pumping due to the nonlinear effects. In this study, the chaotic phenomenon of photonic superposed states is investigated in an optomagnonic cavity. Through the dynamic evolution of two-mode photons in the cavity, we found that the energy of the system could be transferred between different modes, and the chaotic behaviour can be tuned by the coupling and the dissipation.

Keywords: microcavity; chaos; optomagnonic resonators.

1 Introduction

Cavity optomagnonics describes the hybrid interaction between the optical field and the magnetic field in microresonators. It is expected to show great potential for future applications in the field of nanophotonics and quantum information science [1–6]. Owing to the magneto-optical effect, the electromagnetic field could be strongly coupled with the magnetic polarisation field in the microresonators

[7–11]. The study of optomagnonics extends the applications of magneto-optical effect from the manipulation of the optical field using magnetic control [12–14] to the more complex process caused by the magnetic–optical interactions [15–20]. Recently, for example, the coupling between the optical mode and the magnetic mode is realised in an optical whispering-gallery mode (WGM) microcavity, which is made by the magnetic material. During the past decades, various theoretical and experimental progress has been made, such as the topics of topological features [19, 21–23], chaos [24–27], and the quantum optical effects [28–31].

On the other hand, the quantum dynamic behaviours of the photons are an important issue in the study of optical microresonators [32–35]. Among them, the researches of photonic dynamics in the deformed cavity attract much attention on the topic of cavity quantum chaos [36–41]. The phenomenon of quantum chaos was first studied in the asymmetric resonator cavity [38] in 1997. The phenomenon of quantum chaos has several novel features, such as dynamic tunnelling [42–44], quality factor spoiling [45–47], and so on. Besides the influence of the shape of the cavity [48–51], Goos–Hänchen shift and Fresnel filtering [52–54] will also influence the generation of quantum chaos in the microcavities. In recent studies, chaos has been investigated to achieve the fast excitation of whispering gallery mode and photon transportation in mixed phase space [36, 55]. Different from a highly symmetrical circular cavity [56–59], the path of reflected light in the deformed cavity will be affected by the properties of asymmetry. In case there is still much symmetry in the system, it may generate dynamic chaos [36, 38, 43, 46, 48, 60, 61]. In fact, different degrees of freedom of the system may also show the symmetry. For example, not only the propagation of the photon in the optical microcavity has a high degree of symmetry, but also other behaviours, such as the Rabi oscillation of the photon, which can also have similar symmetry. Specifically, in the optomagnonic system, the photon can strongly couple with the magnons, which means that the energy could be transferred between them.

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It provides us with a method to break the symmetry of the photons evolution in the photonic Rabi oscillation process.

In this study, we study the dynamic evolution behaviour of two-mode photons in an optomagnonic cavity. Under the condition of elastic scattering, it is found that the energy flow of the system is periodically oscillated between the two modes to form a Rabi cycle. However, because of the existence of magneto-optical coupling, there is inelastic scattering in the system. The symmetry of the Rabi cycle could be broken because of the existence of the nonlinear interaction. Similar with the deformation cavity, the field of the system shows chaotic behaviour. Moreover, the energy transfer between the photons and the magnons could be enhanced by the increment of the coupling, which is similar to the condition that the increase in the incident angle of the deformed cavity will also enhance the optical field in the cavity. Thus, the coupling and dissipation would influence the generation process of chaos in the system. Besides, the Rabi cycle of photons corresponds

to the evolution of the superposition state of the system, which can be used for random quantum states preparation.

2 Model and the Hamiltonian

As shown in Figure 1A, the microcavity supports both the optical mode and the magnetic mode. And the photons and the magnons are coupled because of the magnetic-optical interaction in the resonator. Here we choose $\hat{a}_r$ and $\hat{a}_l$ to denote the clockwise and counterclockwise WGM modes, which can be excited simultaneously in the cavity. These two optical modes are coupled by the magnetic modes through elastic and inelastic scattering. Then, the superposition between the right and left rotation photons will be chaotic. The right and left rotated photons can be divided by the polarisation beamsplitter at the output port of the fibre tapers and then detected by the photon detector. As shown in Figure 1C, the state evolution is limited

Figure 1: Schematic diagram of the model.

(A) The cavity optomagnonic system. Here the frequency and dissipation of the optical whispering-gallery mode (WGM) are denoted as ω and γ , respectively. The frequency and dissipation of the magnons are denoted as ω_m and γ_m , respectively. The coupling strength between the magnons and the optical WGM mode is G . (B) The trajectory of the light that is trapped in a deformed cavity. (C) The evolution of the states that is limited to a certain region.

to the elliptical area just as the deformed cavity shown in Figure 1B. The main difference of the deformation cavity is the propagation of photons along a straight line before being reflected, whereas the evolution of the system in the phase space is curved.

The Hamiltonian of the system can be written as [2]

$$\begin{aligned}\hat{H}_M &= \hbar\omega_m \hat{S}_z, \\ \hat{H}_O &= \hbar\omega_L \hat{a}_L^\dagger \hat{a}_L + \hbar\omega_R \hat{a}_R^\dagger \hat{a}_R, \\ \hat{H}_{MO} &= \hbar G \hat{S}_x (\hat{a}_L^\dagger \hat{a}_L - \hat{a}_R^\dagger \hat{a}_R), \\ \hat{H}_{LR} &= \hbar g (\hat{a}_R^\dagger \hat{a}_L + \hat{a}_R \hat{a}_L^\dagger).\end{aligned}$$

Here $\hat{H}_M$ represents the Hamiltonian of the magnon with the frequency ω_m . S_z is the spin operator along the z direction. The right (left)-hand rotated photon $\hat{a}_R$ ($\hat{a}_L$) has the frequency ω_R (ω_L). The coupling strength between the magnons and photons is denoted as G shown in the Hamiltonian $\hat{H}_{MO}$. It should be noticed that the magnon-induced coupling between the right and left rotation photon is not included [62], which is also very important in the study of optomagnonics. Here we choose only the single-mode photon–magnon coupling in the study [2]. In addition, there is an elastic scattering between the left-hand rotated photon and the right-hand rotated photon with the strength g . Here we assume that there is only a single-photon excitation in the system under weak coupling driven as

$$|\phi\rangle = \sum_{n_R, n_L, m} C_{n_R, n_L, m} |n_R, n_L, m\rangle, \quad n_R, n_L, m \geq 0. \quad (1)$$

From the above expression, we found the total photon number of the system is conserved. So, we focus only on

Here, $C_{m,1}$ denotes the superposed coefficient of the state $|1, 0, m\rangle$, whereas $|0, 1, m\rangle$ has a superposition coefficient as $C_{m,2}$. γ stands for the damping of the photons, whereas P_1 and P_2 are the pumping power on the right-hand and left-hand rotating photon modes. $\delta(m)$ is the Dirac delta function.

3 Rabi oscillation under the nondissipative and dissipative conditions

To further investigate the performance of magnons in the microresonator, here we first present the results without the magnons. On condition with only the optical modes in the system, there is only the coupling between the clockwise and counterclockwise modes of the photons in the system. We assume the two modes with the same frequencies, and the system is initialised to the state $|\hat{a}_R, \hat{a}_L\rangle = |1, 0\rangle$, and then the time evolution of the probability amplitude can be written as

$$\begin{aligned}C_{0,1}(t) &= \frac{1}{2}(1 + e^{2igt})e^{-it(g+\omega)}, \\ C_{0,2}(t) &= \frac{1}{2}(-1 + e^{2igt})e^{-it(g+\omega)}.\end{aligned} \quad (3)$$

The initial state of the system is set as a vacuum state. Then, (2) could be solved with the optical pumping power P as

$$\begin{aligned}C_{0,1}(t) &= \frac{Pe^{-\frac{1}{2}t(\gamma+2ig+2i\omega)} \left(-(\gamma+2i\omega) \left(-2e^{\frac{1}{2}t(\gamma+2ig+2i\omega)} + e^{2igt} + 1 \right) - 2ig(-1 + e^{2igt}) \right)}{(i\gamma+2g-2\omega)(\gamma+2ig+2i\omega)}, \\ C_{0,2}(t) &= \frac{Pe^{-\frac{1}{2}t(\gamma+2ig+2i\omega)} \left(i(\gamma+2i\omega)(-1 + e^{2igt}) - 2g \left(-2e^{\frac{1}{2}t(\gamma+2ig+2i\omega)} + e^{2igt} + 1 \right) \right)}{4g^2 + (\gamma+2i\omega)^2}.\end{aligned} \quad (4)$$

the evolution of state $|0, 1, m\rangle$ and $|1, 0, m\rangle$ and the superposed form. As only the single-photon dynamics is considered, the time evolution equation of the superposition coefficients could be written as

$$\begin{aligned}i\hbar\dot{C}_{m,1} &= \hbar(m\omega_m + \omega_R - \frac{\gamma}{2})C_{m,1} + \hbar g C_{m,2} \\ &\quad + \hbar G(\omega_R)(\sqrt{m+1}C_{m+1,1} + \sqrt{m}C_{m-1,1}) + P_1\delta(m), \\ i\hbar\dot{C}_{m,2} &= \hbar(m\omega_m + \omega_L - \frac{\gamma}{2})C_{m,2} + \hbar g C_{m,1} \\ &\quad + \hbar G(-\omega_L)(\sqrt{m+1}C_{m+1,2} + \sqrt{m}C_{m-1,2}) + P_2\delta(m),\end{aligned} \quad m \geq 0. \quad (2)$$

It is obvious that there will be no magnon excitation without the optomagnonic coupling. Thus, we can get the analytical solutions for both the isolated system and the open system condition as shown in (3) and (4), respectively.

In the following, the dynamic evolution of the probability amplitudes of the state $|0, 1, 0\rangle$ and $|1, 0, 0\rangle$ is numerically studied in Figure 2. Here the frequency of the photons is set as 1 unit, and the dissipation rate of the cavity modes is chosen as $\gamma=0.001$ for the open system. The coupling strength is denoted as $g=0.1$ for both of them. Usually, the

frequency of magnons is proportional to the applied static magnetic field, and then its frequency can be increased by simply increasing the power of the field. Meanwhile, the coupling strength between the magnons and photons can be enhanced by the pumping probe scheme [4]. It is worth noting that the dissipation rate is relatively high, which made the system reach the steady state faster, so the optical frequency could be considered as the frequency in the rotating frame. Here Figure 2A and B represent the isolated system conditions, where the Rabi oscillation behaviour could be clearly seen in Figure 2A. Under the isolated system condition, the energy is transferred between the two modes in the cavity. We can also find that the total photon number is conserved, which is undoubtedly in line with our expectations. In Figure 2B, we show the real part of the parameters $C_{0,1}$ and $C_{0,2}$ in the phase space, in which the orbits in the phase space are regular.

Figure 2: The time evolution of the probability of two-mode photons and the phase diagram.

Here the frequency of the optical mode is set as 1 unit, and the frequency of the magnon is denoted as 0.01. The initial state could be expressed as $|C_1, C_2\rangle = |0, 1\rangle$. A and B represent the isolated system with the coupling strength $g = 0.1$. C and D represent the open system with the coupling strength $g = 0.1$; the optical modes have the dissipation rate $\gamma = 0.0001$, and the pumping strength is 0.2 on C_1 port. The initial state could be expressed in the form $|C_1, C_2\rangle = |0, 0\rangle$. In E and F, all the parameters are the same with C and D except that the system is pumped both on the C_1 port and C_2 port.

On condition that the system is an open system, its properties will undoubtedly change compared with the isolated system. The evolution of the probabilities is shown in Figure 2C–F under different driven methods. At first, the system is driven on the single mode a_R in Figure 2C and D using single-photon sources with the strength $P = 0.1$, while both the a_L and a_R components are driven under the same amplitude $P = 0.1$ in Figure 2E and F. When the system is single mode driven, we can find that the oscillation of photons shows a certain beat frequency. If we compared the results with the open system condition, the frequency of the beat is similar to the Rabi frequency as the dissipation brings the nonlinearity to the system. In the region of Rabi oscillation, the dissipation is large when all the energy is stored in one mode, whereas when the energy is separated into two modes, the dissipation could be smaller. The total energy is oscillated with the Rabi frequency. When the two modes are driven with the same power, the system will be symmetric. As shown in Figure 2E–F, we can find the two modes are synchronised. From the above analysis, both the open and isolated systems will have quite different dynamic behaviours under the same situation. Even for the isolated system, different driven methods induce different dynamic behaviours.

4 Chaos generation in the cavity optomagnonic system

As discussed above, our system is similar to the deformed cavity situation, while the trajectory is different. It is

Figure 3: (A) The evolution of the two state probability amplitudes over time. The solid red line corresponds to the state $|1, 0, 0\rangle$ and blue dashed line corresponds to the state $|1, 0, 0\rangle$. (B) The Poincaré section of the two states.

Here we set the resonant frequency of the microcavity as 1 unit. The frequency of the magnons is set as $\omega_m = 0.001$ and the dissipation rate of the microcavity is set as $\gamma = 0.0001$, also the dissipation rate of the magnons is $\gamma = 0.00002$. The coupling strength between the two optical modes is $g = 0.01$, whereas the coupling between the optical and magnetic mode is $g_m = 0.1$. The system is pumped with the single photon under the power of 2 units on the C_1 mode.

required to remove such difference to make our system more similar to the deformed microcavity. The Poincare section method commonly used in the study of deformed cavities provides us a way to achieve this purpose. During the process of magneto–photon energy exchange, there is an extreme value of the energy of the photon. We choose these extreme points as the boundary of the Poincare section of the system by comparing it to the case where the light is reflected by the deformed microcavity. Similarly, the chaotic properties of the Poincare section could be investigated as the case of the deformation cavity. At first, the time evolution of total energy of the nonmagnon state could be calculated as follows:

$$i\hbar \frac{dE_{\text{Rabi}}}{dt} = 2\hbar g (C_{0,L} C_{0,R}^* - c.c.) + \hbar G \omega_R (C_{1,L} C_{0,R}^* - c.c.) - \hbar G \omega_L (C_{1,R} C_{0,L}^* - c.c.). \quad (5)$$

Here, $E_{\text{Rabi}} = |C_{0,R}|^2 \omega_R + |C_{0,L}|^2 \omega_L$ is the total energy of the photons when no magnons are excited. Undoubtedly, the extreme point of the system is the point where its derivation is zero. Then, the equation of the Poincare section could be expressed as

$$0 = 2\hbar g (C_{0,L} C_{0,R}^* - c.c.) + \hbar G \omega_R (C_{1,L} C_{0,R}^* - c.c.) - \hbar G \omega_L (C_{1,R} C_{0,L}^* - c.c.). \quad (6)$$

In order to analyse the dynamic features in detail, the time evolution of the probability amplitude of the two coupled modes are plotted in Figure 3. As shown in the figure, both modes exhibit a beat frequency. However, if we pay attention to the nodes of the wave, the fluctuations in the waveforms of each wave are significantly different. Furthermore, we show the Poincare section of the system in Figure 3B. Here the frequency of the cavity modes is set as 1 unit. (It is worth noting that this frequency can be the frequency in rotating reference frame.) We can see that the state of the system is in a chaotic state. The frequency of the magnon is $\omega_m = 0.001$, and the dissipation rate of the cavity is $\gamma = 0.1\omega_m$, which means that the system working in the resolved sideband region. The coupling strength between the optical modes is $g = 0.01$; also, we set the coupling between the optical mode and magnetic mode as $g_m = 0.1$ in order to show strong nonlinearity of the system.

In Figure 3B, these points are similar to the reflection points in the deformed microcavity. Considering the isolated system, the existence of the magnons causes the decreasing of the total energy. This changes the trajectory of the system in the C_1 – C_2 phase space. However, it should be within the closed boundary of the previous Rabi vibration space due to the conservation of energy. The Poincare

section of the system corresponds to the state with the maximal energy. When the system is an open system, the energy of the system is no longer conserved. But the energy exchange between the photon and the magnons in the system will still exist because of the balance of pump dissipation. For the isolated system, the system still have chaotic phenomena under the strong exchange of energy between photons and magnons.

4.1 Chaos generation under photon–magnon coupling modulation

Obviously, the dynamics of the system relies on the coupling strength between photons and magnons. In order to visually study the properties of the system at different coupling strengths, we show the performance of the dynamic evolution of the system and its Poincare section by continuously tuning the photon–magnon coupling strength at 0, 0.001, and 0.01 in the unit of the cavity resonant frequency. To numerically simulate the system, we set the frequency of the magnon as $\omega_m = 0.01$, the dissipation rate of the microcavity is $\gamma = 0.001$, and the dissipation rate of the magnon is $\gamma_m = 0$; the pump strength is 1 at C_1 port. The coupling strength between the two optical modes is denoted as $g = 0.01$. We assume that the initial state is in the vacuum state. When the photon–magnon coupling strength is 0, the system is not chaotic as shown in Figure 4A and B. But it has obvious beat frequency resonance, and the Poincare section is regular in this region, which means there are no magnons excited in this region. At this time, although the energy of the system is not conserved because of the existence of dissipation, the system is still stable and predictable. When there is weak coupling between the magnons and the photons, the system is still regular as shown in Figure 4C and D. The probability amplitude still resonant at a certain beat frequency, but Poincare section of the system is changed. The two traces are mixed in Figure 4D. It is because the magnon is excited in this region, as a feedback, the magnon will influence the behaviour of the photons. Then, the coupling strength is continuously increasing to 0.1. As shown in Figure 4, the beat disappears for the probability amplitude evaluation, and the Poincare section shows the chaotic features. The photons and magnons strongly coupled together and strongly broke the symmetry of the Rabi cycle. Although the system still has some symmetry, the state evolution of the system is already in a chaotic state. When the coupling is large, the energy of the photons in the system can be transferred to the magnons; that is to say, the evolution of the system in the phase space will greatly deviate from

Figure 4: The probability amplitude evolution of C_1 and the Poincare section under different coupling strengths. Here we set the resonant frequency of the microcavity as 1 unit. Then, we set the frequency of the magnons as $\omega_m = 0.01$ and the dissipation rate of the microcavity as $\gamma = 0.001$. The dissipation rate of the magnons is $\gamma_m = 0$, and the pump strength is 1 unit at C_1 port. The coupling strength between two optical modes is $g = 0.01$. The initial state is the vacuum state. In A and B, the optical-magnetic strength is 0; in C and D, the optical-magnetic strength is 0.001. In E and F, the optical-magnetic strength is 0.01.

the trajectory of the previous Rabi cycle. This is similar to the chaotic system when the incident angle of the light is greater than a certain angle in the deformed cavity.

4.2 Dissipation suppression of chaos

The excitation of photons and magnons would be affected by the dissipation of the system. Undoubtedly, the difference in dissipation will also influence the properties of the dynamic behaviour of the system. Here we focus on the performance of the dissipation during the generation of chaos in the system.

In Figure 5, the dynamic features of the state with various optical dissipation rates are shown. For clarity, we set the dissipation rate of the magnons as $\gamma_m = 0$. As discussed before, the eigenfrequency of the optical mode is treated as 1 unit, and then we set the frequency of the

Figure 5: The probability amplitude evolution and the Poincare section under different coupling strength. Here we set the frequency of the microcavity as 1 unit. The frequency of the magnons is $\omega_m = 0.001$; the magnetic–optical coupling strength is $G = 0.01$, and the dissipation rate of the magnons is $\gamma_m = 0$. The pumping strength is 2 units at C_1 port. The coupling strength between two optical modes is $g = 0.01$. The initial state is the vacuum state. In (A) and (B), we set the optical mode dissipation strength as $\gamma = 0.001$. In (C) and (D), we set the optical mode dissipation rate as $\gamma = 0.0001$.

magnons as $\omega_m = 0.001$, the magnetic–optical coupling strength is $G = 0.01$, and the pumping power is 2 units at the C_1 port. The initial state of the system is assumed in the vacuum state. In Figure 5A and B, we set the optical dissipation rate as 0.001. The probability amplitude of C_1 is obviously stronger than that of C_2 as the pumping is added on the C_1 port, while the dissipation is comparable to the coupling strength g . When the energy is transferred into the C_2 photons, it is quickly dissipated. At this time, the Poincare section of the system shows that the motion of the system has obvious regularity. When the dissipation rate is reduced to 0.0001 as shown in Figure 5C and D, the probability increases. On the other hand, the Poincare section shows that the system will be chaotic. When the dissipation is weak, the higher-order magnons can be easily excited, and then the dynamic behaviours of the system will also be chaotic.

As the dissipation of magnons plays a different role compared with the optical dissipation, we should also discuss the influence of the dissipation of magnons. For this purpose, the dynamic behaviours of the system under different magnetic dissipative rates are shown in Figure 6. In order to compare the results with the dissipation of photons, we set other parameters of the system exactly the same, and the dissipation rate of the photons

Figure 6: The evolution of the probability amplitude and the Poincaré section under different coupling strength.

Here we set the resonant frequency of the microcavity as 1 unit.

Then, we set the frequency of the magnons as $0.01 \omega_m = 0.001$, the magnetic–optical coupling strength is $G = 0.01$, and the dissipation rate of the photon is $\gamma = 0$. The pumping strength is 2 units at C_1 port. The coupling strength between two optical modes is $g = 0.01$. The initial state is the vacuum state. In A and B, we set the optical mode dissipation strength as $\gamma_m = 0.05$; in C and D, the optical mode dissipation rate is $\gamma_m = 0.001$.

is zero. Then, we set the dissipation rate of the magnons as $\gamma_m = 0.05$ in Figure 6A and B. In our system, the dissipation caused by the magnons increases as the number of magnons increases. When the magnon is in the strong dissipative state, the excitation of the magnons is weak, and the condition of the system is close to that of the two-photon coupling. So although the system is in a strong coupling state, the system still has no chaos. In order to make the system chaotic, we reduce the dissipation rate of the magnons to $\gamma_m = 0.001$. As shown in Figure 6, the system becomes chaotic again. In this case, the multimagnon state can be excited, and the system is in a dynamic mixed state of the multienergy state; the dynamic behaviours of the system become chaotic.

5 Summary

In summary, the dynamic behaviours of the superposed state of the photons in the optomagnonic cavity are theoretically studied. By comparing the symmetry broken of the Rabi cycle during the evolution with the ray dynamic of the deformed cavity, the generation and performance of chaos are analysed in the optomagnonic cavity. In further

in-depth study of the parameters of the system, we found that the generation process of chaos would be influenced by both the magnetic–optical coupling strength and the dissipation of the system. When the coupling is strong compared with the dissipation in the cavity, there is enhancement of the dynamic chaos, which is similar to the case when the incident angle of the light in the deformed cavity increases. Along with the increment of the coupling or the incident angle, the influence of symmetry breaking appears gradually, and the system becomes chaotic. On the other hand, both the performance of photon and magnon dissipation are studied during the chaos generation process. The excitation of the magnons would be suppressed when the dissipation is strong. On the contrary, when the dissipation is weak, the magnons in the system can be fully excited. The dynamic mixing of the energy states of the system will become complicated, and the system becomes chaos.

Moreover, the dynamic evolution of the photon superposed state in the cavity is also studied. The requirements of generation and production conditions of the superposition coefficients of the states are theoretically discussed. We believe the method of stochastic quantum state generation and manipulation has important implications for both quantum metrology and quantum computation.

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