Nonreciprocal transmission and fast-slow light effects in a cavity optomechanical system

Jun-Hao Liu, Ya-Fei Yu, and Zhi-Ming Zhang

1 Guangdong Provincial Key Laboratory of Nanophotonic Functional Materials and Devices (School of Information and Optoelectronic Science and Engineering), and Guangdong Provincial Key Laboratory of Quantum Engineering and Quantum Materials, South China Normal University, Guangzhou 510006, China

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1. Introduction

In recent years, optical nonreciprocity has got a lot of attentions for its important applications in photonic networking, signal processing, and one-way optical communication protocols. In the common nonreciprocal devices, such as, isolator, circulator, nonreciprocal phase shifter, the transmission of the information is not symmetric. At present, the researches about the optical nonreciprocity mainly focused on two aspects: one is the transmission properties of the signal fields, another is the photonic statistical properties of the signal fields.

For the first aspect, scientists have demonstrated that many physical effects and physical systems, such as Faraday rotation effect in the magneto-optical crystals [1-2], optical nonlinearity [4], spatial-symmetry-breaking structures [3, 6], optoacoustic effects [7, 8], the parity-time-symmetric structures [9-12], can be used to realize the optical nonreciprocal transmission. Efforts have also been made to study the nonreciprocal transmission in cavity optomechanical systems [13-17]. Mani-patrani et al. demonstrated that the optical nonreciprocal transmission was based on the momentum difference between the forward and backward-moving light beams in a Fabry-Perot cavity with one moveable mirror [18]. Hafezi et al. proposed a scheme to achieve the nonreciprocal transmission in a microring resonator by using an unidirectional optical pump [19]. Metelmann and Clerk discussed a general method for nonreciprocal photon transmission and amplification via reservoir engineering [20]. Peterson et al. demonstrated an efficient frequency-converting microwave isolator based on the optomechanical interactions [21]. Mirza et al. studied the optical nonreciprocity and slow light propagation in coupled spinning optomechanical resonators [22].

For the second aspect, the researches on the photonic statistic properties of the transmitted fields in nonreciprocal devices are fewer. At present, the relevant theoretical works include the nonreciprocal photon blockade [23], the authors discussed how to create and manipulate nonclassical light via photon blockade in rotating nonlinear devices. They found that the light with sub-Poissonian or super-Poissonian photon-number statistics can emerge when driving the resonator from its left or right side. Subsequently, Xu et al. proposed a scheme to manipulate the statistic properties of the photons transport nonreciprocally via quadratic optomechanical coupling [24].

In this paper, we study the nonreciprocal transmission and the fast-slow light effects in a cavity optomechanical system, as shown in Fig. 1. We show that when the intrinsic photon loss of the cavity equals the external coupling loss of the cavity, we can achieve the nonreciprocal transmission of the signal fields with the red-sideband pumping or the blue-sideband pumping. We also show that when the intrinsic photon loss is much less than the...
external coupling loss, the nonreciprocity of the system about the optical transmission properties almost disappears, now the system exhibits a nonreciprocal fast-slow light propagation phenomenon, i.e., the group velocity of the right-moving signal field will be speed up (fast light), while the group velocity of the left-moving signal field will be slowed down (slow light), or vice versa.

2. Model and Hamiltonian

Our system model is shown in Fig. 1(a). We consider an optomechanical microtoroid cavity, which supports a clockwise circulating mode (\(\hat{a}\)) and a counter-clockwise circulating mode (\(\hat{c}\)), both the two cavity modes couple with the mechanical mode (\(\hat{b}\)) via the radiation pressure. The cavity, and the signal field of amplitude \(\varepsilon_{as}\) respectively, in which \(\varepsilon_{as}\) and the cavity modes with frequency \(\omega_{as}\), respectively, in which \(\omega_{as}\) and the signal field of amplitude \(\varepsilon_{as}\) couple with the cavity modes by an optical fiber. (b) The nonreciprocal transmission: the right-moving signal field is completely transmitted \((T_a = 1)\), while the left-moving signal field is blocking-up \((T_c = 0)\). (c) The nonreciprocal fast-slow light: both the right-moving field and the left-moving signal field are transmitted \((T_a = T_c = 1)\). However, the group delay of the right-moving signal field is negative \((\tau_a < 0)\), that corresponds to the fast light. The group delay of the left-moving signal field is positive \((\tau_c > 0)\), that corresponds to the slow light.

For simplicity, we assume that the two pump fields have the same frequency, i.e., \(\omega_{ap} = \omega_{cp} = \omega_p\). In the frame with \(H_r = \omega_p (\hat{a}^\dagger \hat{c} + \hat{c}^\dagger \hat{a})\), the system Hamiltonian can be written as

\[
H = \hbar \Delta \hat{a}^\dagger \hat{a} + \hbar \Delta \hat{c}^\dagger \hat{c} + \hbar \omega_p \hat{b}^\dagger \hat{b} + \hbar g (\hat{a}^\dagger \hat{a} + \hat{c}^\dagger \hat{c}) (\hat{b}^\dagger \hat{b} + \hat{b}^\dagger \hat{b})
\]

\[
\text{total Hamiltonian can be expressed as}
\]

\[
H_{total} = H_{om} + H_{aps} + H_{cps} + H_{ac},
\]

where \(H_{om} = \hbar \omega_0 \hat{a}^\dagger \hat{a} + \hbar \omega_0 \hat{c}^\dagger \hat{c} + \hbar \omega_m \hat{b}^\dagger \hat{b} + \hbar g (\hat{a}^\dagger \hat{a} + \hat{c}^\dagger \hat{c}) (\hat{b}^\dagger \hat{b} + \hat{b}^\dagger \hat{b})\) is the Hamiltonian of the cavity optomechanical system. \(\hat{a}(\hat{c})\) and \(\hat{b}\) are the annihilation operators of the clockwise (counter clockwise) circulating cavity mode and the mechanical mode with frequency \(\omega_0\) and \(\omega_m\), respectively. \(g\) is the optomechanical coupling strength between the cavity modes and the mechanical mode. \(H_{aps} = i \hbar \varepsilon_{as} (\hat{a}^\dagger e^{-i \omega_{as} t} - H.c.) + i \hbar \varepsilon_{as} (\hat{a} e^{-i \omega_{as} t} - H.c.)\) describes the interactions of the cavity mode \(\hat{a}\) with the pump field of amplitude \(\varepsilon_{ap} = \sqrt{2 \kappa P_{ap}/\hbar \omega_{ap}}\) and the signal field of amplitude \(\varepsilon_{as} = \sqrt{2 \kappa P_{as}/\hbar \omega_{as}}\), respectively, in which \(\kappa\) is the coupling decay rate of the cavity, and \(P_{ap}\) (\(P_{as}\)) is the laser power. Similarly, \(H_{cps} = i \hbar \varepsilon_{cp} (\hat{c}^\dagger e^{-i \omega_{cp} t} - H.c.) + i \hbar \varepsilon_{cs} (\hat{c} e^{-i \omega_{cs} t} - H.c.)\) describes the interaction Hamiltonian of cavity mode \(\hat{c}\) with the pump field of amplitude \(\varepsilon_{cp} = \sqrt{2 \kappa P_{cp}/\hbar \omega_{cp}}\) and the signal field of amplitude \(\varepsilon_{cs} = \sqrt{2 \kappa P_{cs}/\hbar \omega_{cs}}\), respectively. The last term \(H_{ac} = \hbar J (\hat{a}^\dagger \hat{c} + \hat{c}^\dagger \hat{a})\) represents the interaction between the two cavity modes with the strength \(J\).

\[
\frac{d\hat{a}}{dt} = -(i \Delta + \kappa t)\hat{a} - i g \hat{a} \hat{b} + \hat{b} + i \varepsilon_{as} e^{-i \omega_{as} t} + \sqrt{2 \kappa} \hat{a},
\]

\[
\frac{d\hat{b}}{dt} = -(i \Delta + \kappa t) \hat{b} - i g \hat{a} \hat{b} + \hat{b} + i \varepsilon_{as} e^{-i \omega_{as} t} + \sqrt{2 \kappa} \hat{b},
\]

\[
\frac{d\hat{c}}{dt} = -(i \Delta + \kappa t) \hat{c} - i g \hat{c} \hat{b} + \hat{b} + i \varepsilon_{cs} e^{-i \omega_{cs} t} + \sqrt{2 \kappa} \hat{c},
\]

\[
\frac{d\hat{b}}{dt} = -(i \omega_m + \gamma) \hat{b} - i g (\hat{a}^\dagger \hat{a} + \hat{c}^\dagger \hat{c}) + \sqrt{2 \gamma} \hat{b}.
\]
where the cavity has the damping rate $\kappa_t = \kappa_{in} + \kappa$, which are assumed to be due to the intrinsic photon loss and external coupling loss, respectively, and the mechanical mode has the damping rate $\gamma$. $\delta_{in}$, $\hat{\xi}_{in}$, and $\hat{b}_{in}$ are the $\delta$-correlated operators of the input noises for the cavity mode $\hat{\alpha}$ ($\hat{c}$) and the mechanical mode $\hat{b}$, respectively. These noise operators satisfy $\langle \delta_{in} \rangle = \langle \dot{\xi}_{in} \rangle = \langle \dot{b}_{in} \rangle = 0$.

In this model, we are interested in the mean response of the system. Thus, in the following, we turn to calculate the evolutions of the expectation values of $\hat{\alpha}$, $\hat{c}$, $\hat{b}$, and we denote $\langle \hat{a} \rangle = A$, $\langle \hat{\xi} \rangle = C$, $\langle \hat{b} \rangle = B$, $\langle \dot{\hat{a}} \rangle = A^*$, $\langle \dot{\hat{\xi}} \rangle = C^*$, $\langle \dot{\hat{b}} \rangle = B^*$. By using the mean-field assumption $\langle \hat{abc} \rangle = \langle \hat{a} \rangle \langle \hat{b} \rangle \langle \hat{c} \rangle$, we can write the equations for the mean values as

$$
\frac{dA}{dt} = -(i\Delta + \kappa_t)A - i\gamma A(B + B^*) - iJC + \varepsilon_{ap} + \varepsilon_{as} e^{-i\delta_{as}t},
$$

$$
\frac{dC}{dt} = -(i\Delta + \kappa_t)C - i\gamma C(B + B^*) - iJA + \varepsilon_{cp} + \varepsilon_{cs} e^{-i\delta_{cs}t},
$$

$$
\frac{dB}{dt} = -(i\omega_m + \gamma)B - i\gamma(|A|^2 + |C|^2).
$$

Equations (4) can be solved by using the perturbation method in the limit of the strong pump fields, while taking the signal fields to be weak. Using the linearization approximation, we make the following ansatz [25]

$$
X = X_0 + X_a e^{-i\delta_{as}t} + X_{a*} e^{i\delta_{as}t} + X_c e^{-i\delta_{cs}t} + X_{c*} e^{i\delta_{cs}t},
$$

where $X$ can be any one of the quantities $A$, $B$, $C$, or their complex conjugates $A^*$, $C^*$, $B^*$. $X_0$ represents the steady-state mean value of the corresponding system mode, and $X_a$, $X_{a*}$, $X_c$, $X_{c*}$ are the additional fluctuations. By substituting Eq. (5) into Eqs. (4), and keeping only the first-order in the small quantities and neglecting the nonlinear terms like $A_a + C_{a*} + A_{a*} + B_c$, $B_{c*} - C_{a+} + \cdots$, we can obtain the steady-state mean value equations, and the fluctuation equations for the cavity mode components $A_a$ and $C_{a+}$ (see the appendix). By solving these equations, we find that $A_{a+} = \eta(\delta_{as}) \varepsilon_{as}$, $C_{a+} = \xi(\delta_{cs}) \varepsilon_{cs}$, the concrete forms of the coefficients $\eta(\delta_{as})$ and $\xi(\delta_{cs})$ are tedious long, and we will not write them out here.

The relation among the input, internal, and output fields is given as [20] $X_{out} = X_{in} - 2\kappa X$. By using the ansatz again, we write the output field $X_{out}$ as $X_{out} = X_{a+} e^{-i\delta_{as}t} + X_{a*} e^{i\delta_{as}t} + X_{c+} e^{-i\delta_{cs}t} + X_{c*} e^{i\delta_{cs}t}$. Then we can obtain the output field components $A_{out} = \varepsilon_{as} - 2\kappa A_{a+}$ and $C_{out} = \varepsilon_{cs} - 2\kappa C_{a+}$. The transmissivities can be written as $t_a(\delta_{as}) = A_{out} / \varepsilon_{as}$, $t_c(\delta_{cs}) = C_{out} / \varepsilon_{cs}$. The nonreciprocal transmission is then described by the normalized transmissivities (transmission spectra)

$$
T_a = |t_a(\delta_{as})|^2 = |1 - 2\kappa \eta(\delta_{as})|^2,
$$

$$
T_c = |t_c(\delta_{cs})|^2 = |1 - 2\kappa \xi(\delta_{cs})|^2.
$$

What’s more, in the resonant region of the transmission spectra, the output signal fields have the phase dispersions $\phi_a(\omega_{as}) = \arg[T_a(\omega_{as})]$ and $\phi_c(\omega_{cs}) = \arg[T_c(\omega_{cs})]$, which can cause the group delay [27]

$$
\tau_a = \frac{d\phi_a(\omega_{as})}{d\omega_{as}}, \quad \tau_c = \frac{d\phi_c(\omega_{cs})}{d\omega_{cs}}.
$$

The group delay $\tau_a$ ($\tau_c$) > 0 corresponds to the slow light propagation of the signal field, and the group delay $\tau_a$ ($\tau_c$) < 0 corresponds to the fast light propagation of the signal field. In the following, we will discuss the nonreciprocal transmission ($\tau_a = 1$, $\tau_c = 0$ or $\tau_a = 0$, $\tau_c = 1$) and the nonreciprocal fast-slow light effects ($\tau_a > 0$, $\tau_c < 0$ or $\tau_a < 0$, $\tau_c > 0$), respectively.

In this paper, the parameters are chosen based on the recently experiment [28, 29]: $\omega_m = 2\pi \times 10$ MHz and $\gamma = 2\pi \times 10^2$ Hz (quality factor $Q_m = 10^6$), the equivalent mass of the mechanical resonance $m = 5$ ng, and the equivalent cavity length $l = 1$ mm. The damping rate of the optical cavity $\kappa = 2\pi \times 1$ MHz, the wavelength of the pump laser $\lambda = 1064$ nm. The other parameters are $J = 2\pi \times 10^3$ Hz, $\kappa_{in} = 2\pi \times 1$ MHz.

3. Nonreciprocal transmission

In this section, we numerically evaluate the transmission spectra $T_a$ and $T_c$ to show the possibility of achieving the nonreciprocal transmission of the signal fields.

Firstly, we assume that the system works near the red sideband ($\Delta = \omega_m$). In Fig. 2 we plot $T_a$ and $T_c$ as a function of $\delta_{as}/\omega_m$ and $\delta_{cs}/\omega_m$, respectively. The system works near the red sideband ($\Delta = \omega_m$). The parameters are: (a) $P_a = P_c$, (b) $P_a = 10^2 P_c$, (c) $P_a = 10^3 P_c$, (d) $P_a = 10^4 P_c$. The other parameters are stated in the text.
gradually increase with the increase of $P_T$. In Fig. 3, we can see that the right-moving signal field (∆ = $-\omega_m$) is completely transmitted, while the left-moving signal field cannot be amplified. The other parameters are stated in the text.

Then we consider that the system works near the blue sideband ($\Delta = -\omega_m$), and we also choose $P_c = 100$ nW. For example, when $\Delta = -\omega_m$, $P_a = 100$ nW, and $P_c = 10^4 P_a$, now the left-moving signal field is completely transmitted while the right-moving signal field is blocking-up.

In addition, in our system, the transmissive direction of the signal field can be changed by adjusting the ratio of $P_a$ and $P_c$. For example, when $\Delta = -\omega_m$, $P_a = 100$ nW, and $P_c = 10^4 P_a$, now the left-moving signal field is completely transmitted while the right-moving signal field is blocking-up.

4. Nonreciprocal fast-slow light effects

In this section, we show how to realize the nonreciprocal fast-slow light propagation of the signal fields, i.e., both the right-moving and left-moving signal fields can be completely transmitted, while the group velocity of the right-moving signal field will be speed up and the left-moving signal field will be slowed down, or vice versa.

In Fig. 4, we plot $T_a$ and $T_c$ for different intrinsic photon loss rate $\kappa_{in}$ under the unbalanced-pumping condition ($P_a = 10^4 P_c$, $P_c = 100$ nW). We find that with the decrease of $\kappa_{in}$ the transmission of the left-moving signal field $T_c$ will gradually increase near $\delta_{cs} = -\omega_m$. However, the transmission of the right-moving signal field $T_a$ as a function of $\delta_{as}/\omega_m$ and $\delta_{cs}/\omega_m$, respectively. Here we hold the pump power $P_c$ constant, $P_c = 100$ nW.

Fig. 4. The transmission spectra $T_a$ (red solid lines) and $T_c$ (blue dashed lines) as a function of $\delta_{as}/\omega_m$ and $\delta_{cs}/\omega_m$, respectively, for different intrinsic photon loss rate $\kappa_{in}$. The parameters are: (a) $\kappa_{in} = \kappa$, (b) $\kappa_{in} = 10^{-1}\kappa$, (c) $\kappa_{in} = 10^{-2}\kappa$, (d) $\kappa_{in} = 10^{-3}\kappa$. The other parameters are stated in the text.
The other parameters are stated in the text. The parameters are: (a) have plotted the transmission spectra that in the range of the parameters we considered (we signal fields. In Fig. 5, we plot the system works near the blue sideband ($\Delta = -\omega_m$). The parameters are: (a) $P_a = 1 \times 10^4 P_c$, (b) $P_a = 5 \times 10^2 P_c$, (c) $P_a = 1 \times 10^3 P_c$, (d) $P_a = 2 \times 10^2 P_c$, (e) $P_a = 5 \times 10^2 P_c$. The other parameters are stated in the text.

$T_a \approx 1$ near $\delta_{as} = -\omega_m$. When $\kappa_{in} = 10^{-4} \kappa$, we have $T_a \approx 1$, $T_c \approx 0.7$, now the nonreciprocity of the system about the optical transmission is weakened. When $\kappa_{in} = 10^{-3} \kappa$, we have $T_a \approx 1.01$, $T_c \approx 0.996$, and the nonreciprocity of the system about the optical transmission almost disappears ($T_a \approx T_c$).

However, in this situation ($\kappa_{in} \ll \kappa$), the nonreciprocity of system is shown in the group delay properties of the signal fields. In Fig. 5, we plot $\tau_a$ and $\tau_c$ as a function of $\delta_{as}/\omega_m$ and $\delta_{cs}/\omega_m$, respectively. We can see that in the range of the parameters we considered (we have plotted the transmission spectra $T_a$ and $T_c$ and we can guarantee that $T_a \approx T_c \approx 1$ for all the parameters used in Fig. 5), the group delay of the right-moving signal field is negative near $\delta_{as} = -\omega_m$ (the group velocity will be speed up), that corresponds to the fast light propagation. While the group delay of the left-moving signal field is positive near $\delta_{cs} = -\omega_m$ (the group velocity will be slowed down), that corresponds to the slow light propagation. This shows that the system can exhibit a nonreciprocal fast-slow light propagation of the signal fields.

Furthermore, we can change the propagation direction of the fast-slow light by adjusting the ratio of of $P_a$ and $P_c$. For example, in Fig. 5(c), we have $\tau_a \approx -0.3 \mu s$ and $\tau_c \approx 0.3 \mu s$. However, if we choose $P_a = 100 \text{nW}$ and $P_c = 10^5 P_a$, then we have $\tau_a \approx 0.3 \mu s$ and $\tau_c \approx -0.3 \mu s$, now the right-moving signal field is slow light and the left-moving signal field is fast light.

5. Conclusion

In summary, we have studied the nonreciprocal transmission and the fast-slow light effects in a cavity optomechanical system. We have shown that for both the red-sideband pumping or the blue-sideband pumping, the system can act as an optical unidirectional isolator. We have also shown that if the intrinsic photon loss is much less than the external coupling loss, the nonreciprocity of the system on the optical transmission almost disappears, now the system reveals an interesting nonreciprocal fast-slow light propagation phenomenon. Our proposed model might have applications in the photonic network.

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Appendix

By substituting Eq. (5) into Eqs. (4), we can obtain the steady-state mean value equations

$$0 = -(i\Delta + \kappa_i) A_0 - ig A_0 (B_0 + B^*_0) - iJC_0 + \varepsilon_{ap},$$
$$0 = -(i\Delta + \kappa_i) C_0 - ig C_0 (B_0 + B^*_0) - iJA_0 + \varepsilon_{cp},$$
$$0 = -(i\omega_m + \gamma) B_0 - ig (|A_0|^2 + |C_0|^2).$$

(A1)

In this system, we are interested on the dynamics of the cavity mode components $A_{a+} e^{-i\delta_{as} t}$ and $C_{c+} e^{-i\delta_{cs} t}$ which are resonance with the corresponding signal fields $\varepsilon_{as} e^{-i\delta_{as} t}$ and $\varepsilon_{cs} e^{-i\delta_{cs} t}$, respectively. We can obtain

$$\Phi_{a+} B_{a+} = -ig (A_0 A_{a+} + A^*_{a+} A_0 + C_0^* C_{a+} + C^*_{a+} C_0),$$
$$\Omega_{a+} A_{a+} = -ig A_0 (B_{a+} + B^*_{a+}) - iJC_{a+} + \varepsilon_{as},$$
$$\Omega_{a+} C_{a+} = -ig C_0 (B_{a+} + B^*_{a+}) - iJA_{a+} + \varepsilon_{cs},$$

(A2)

$$\Phi_{c+} B_{c+} = -ig (A_0^* A_{c+} + A^*_{c+} A_0 + C_0^* C_{c+} + C^*_{c+} C_0),$$
$$\Omega_{c+} C_{c+} = -ig C_0 (B_{c+} + B^*_{c+}) - iJA_{c+} + \varepsilon_{cs},$$
$$\Omega_{c+} A_{c+} = -ig A_0 (B_{c+} + B^*_{c+}) - iJC_{c+},$$

(A3)

where $\Phi_k = i(\omega_m - \delta_{ks}) + \gamma$ and $\Omega_k = i[\Delta + g (B_0 + B^*_0) - \delta_{ks}] + \kappa_i$, $k = a, c$.

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