Оптический журнал

Лазерная физика и техника

DOI: 10.17586/1023-5086-2022-89-12-38-45

Quantum properties of triple-coupled optical cavity with injection of a squeezed vacuum field

Ke Di[1], Jie Ren[2], Wei Cui[3], RenPu Li[4], YongLe Lu[5], JunQi Guo[6], Yu Liu[7], JiaJia Du[8]✉

[1, 2, 3, 4, 5, 6, 7, 8]Department of Electronic Engineering, Chongqing University of Post and Telecommunications, Chongqing 400065, China

[1, 2, 3, 4, 5, 6, 7, 8]Chongqing Key Laboratory of Autonomous Navigation and Microsystem, Chongqing University of Post and Telecommunications, Chongqing 400065, China

[1]dike@cqupt.edu.cn https://orcid.org/0000-0001-6339-923X
[2]836537144@qq.com https://orcid.org/0000-0002-1351-4743
[3]cuiwei@cqupt.edu.cn https://orcid.org/0000-0002-5675-6910
[4]lirp@cqupt.edu.cn https://orcid.org/0000-0002-0426-296X
[5]luyl@cqupt.edu.cn https://orcid.org/0000-0002-5958-2629
[6]guojq@cqupt.edu.cn https://orcid.org/0000-0001-9570-530X
[7]liuyu@cqupt.edu.cn https://orcid.org/0000-0001-6929-1481
[8]dujj@cqupt.edu.cn https://orcid.org/0000-0002-0051-6846

Abstract

Subject of Study. A scheme of quantum manipulation in coupled optical cavity system composed of triple-coupled optical cavity with injection of a squeezed vacuum field is proposed. **Method.** The scheme of quantum manipulation in coupled optical cavity system is based on analysis of the absorption and dispersion characteristics of the reflection in classical filed and quantum field. **Main Results.** It was established that the absorption and dispersion of the reflection field with different coupled intensities under the classical field show different characteristics. The Electromagnetic induction transparency like effect is observed as the couple dintensities increases, and becomes more and more obvious as the coupled intensities increases, until the absorption curve becomes completely independent due to the strong coupled. And the quantum noise fluctuation corresponding to the amplitude and phase of the reflection field in the quantum field also presented different characteristics. With the increase of couple dintensities, the quantum noise fluctuation curve begins to split. And at the same time, the splitting of the quantum noise fluctuation curve changes from one to three, and it completely splits into three Lorentz curves finally. **Practical significance.** The theoretical results of scheme demonstrated that multiple (three times) quantum manipulation can be implemented simultaneously in a device, which provides method for the quantum dense coding.

Keywords: quantum manipulation, quantum coding, triple-coupled optical cavity, squeezed vacuum field

Acknowledges: the National Natural Science Foundation of China (Nos. 11704053, 52175531); the Science and Technology Research Program of Chongqing Municipal Education Commission (KJQN201800629); the Innovation Leader Talent Project of Chongqing Science and Technology (No. CSTC-CXLJRC201711).

For citation: Ke Di, Jie Ren, Wei Cui, RenPu Li, YongLe Lu, JunQi Guo, Yu Liu, JiaJia Du. Quantum properties of triple-coupled optical cavity with injection of a squeezed vacuum field // Оптический журнал. 2022. Т. 89. № 12. С. 38–45. http://doi.org/ 10.17586/1023-5086-2022-89-12-38-45

OCIS codes: 270.5585, 190.4970.

Квантовые свойства оптического резонатора с тройной связью и инжекцией сжатого вакуумного поля

Ke Di, Jie Ren, Wei Cui, RenPu Li, YongLe Lu, JunQi Guo, Yu Liu, JiaJia Du

Аннотация

Предмет исследования. Предложена схема квантовой манипуляции в системе связанных оптических резонаторов, включающей оптический резонатор с тройной связью и инжекцией сжатого вакуумного поля. **Метод.** Схема квантовой манипуляции в системе со связанными оптическими резонаторами основана на анализе характеристик поглощения и дисперсии отражения в классическом поле и квантовом поле. **Основные результаты.** Было установлено, что поглощение и дисперсия поля отражения с различными связанными интенсивностями в условиях классического поля проявляют разные характеристики. Эффект прозрачности электромагнитной индукции наблюдается по мере увеличения связанных интенсивностей и становится всё более очевидным по мере увеличения связанных интенсивностей, пока кривая поглощения не станет полностью независимой из-за сильной связи. И флуктуация квантового шума, соответствующая амплитуде и фазе поля отражения в квантовом поле, также представляла различные характеристики. С увеличением связанных интенсивностей кривая флуктуации квантового шума начинает расщепляться. И в то же время наблюдается тенденция расщепления единой кривой флуктуации квантового шума на три части, пока, наконец, она полностью не распадается на три отдельные кривые Лоренца. **Практическая значимость.** Теоретические результаты рассмотренной схемы продемонстрировали, что многократная (трёхкратная) квантовая манипуляция может быть реализована в предлагаемом устройстве, что обеспечивает метод кодирования квантовой плотности.

Ключевые слова: квантовая манипуляция, квантовое кодирование, оптический резонатор с тройной связью, сжатое вакуумное поле

INTRODUCTION

Quantum information science [1, 2] has attracted much attention, which mainly includes two themes: quantum computation [3–5] and quantum communication [6–9]. Quantum computing utilizes the characteristics of quantum states such as coherence, entanglement and non-cloning [10] to achieve computational tasks such as evolutionally-coded quantum states. Because quantum states have many properties such as coherent superposition, the parallel scale of quantum computing is not limited, which is also impossible for many classical computing. Quantum communication mainly uses the properties of quantum mechanics to store and transmit information. The classical quantum communication includes quantum teleportation, quantum key distribution and quantum dense coding.

The manipulation [11–13] of quantum systems is a crucial link in the research of these fields. Ranging from quantum information science to quantum simulation, to quantum sensing, accurate control of quantum systems is a fundamental goal in many fields of quantum science. Controlling the quantum state of a system is critical because it is a preparatory step for subsequent calculations or simulations, or as a target in itself, such as adiabatic quantum computing.

The basic unit of quantum information processing [14, 15] is the quantum bit [16], which can exist in any system of double quantum states, such as photons, phonons and atoms. As a consequence of the strong stability and fast speed of photon, optical system [17–19] has become one of the ideal carriers for quantum information processing. In addition, in the traditional optoelectronic field, light as a carrier has been relatively mature applications. These results would seem to suggest that we may need the quantum optical devices which can be applied to quantum information processing by light. In these quantum devices, the transmission or storage of light can be controlled, which makes the encoded light signal insensitive to environmental disturbances. It is precisely because of this that people's research on the quantum control of optical system has become one of the main directions of quantum physics and quantum information research in recently.

Quantum entanglement is the focus of quantum information science, and it has very important applications in quantum communication, quantum teleportation [20], quantum coding and other fields. In quantum communication, in order to ensure the security of the process, the communication parties need to share the pure maximum entangled state in advance to establish their quantum channels. Based on the optical coupled cavity system [21, 22] and the related input and output processes of it, the effective quantum entanglement scheme can be developed to form the maximum entanglement state. Furthermore, the main problem of quantum coding is that it can only be used for separate variables and its encoding efficiency is low, which is also the main reason that limits its practical application.

In this paper, the quantum characteristics of the reflection field in triple-coupled optical cavity with injection of squeezed vacuum field were studied. We realized the manipulation of continuous variable in the quantum field. With the increase of the coupled strength of the cavity, the Electromagnetic Induction Transparency (EIT)-like effects appear in the coupled cavity. Since the quantum properties of triple-coupled optical cavity under different coupled intensities are studied, the results show that due to the different coupled intensities, the reflection spectra of the coupled optical cavity also show completely different structures. The results also demonstrated that it is possible to perform multiple quantum manipulation in a single device simultaneously.

THEORETICAL MODEL

The theoretical model is shown in Fig. 1. Firstly, a concentric optical cavity is formed by two plano-concave mirrors (M1 and M4), and then two plane mirrors M2 and M3 are inserted into this cavity, thus forming three Optical cavities C1, C2 and C3, which are mutually coupled. These three cavities constitute the entire coupled optical cavity system, and the coupled strength of the entire optical cavity system is determined by the reflectivity of the two intermediate cavity mirrors M2 and M3.

The Hamiltonian of the system [23] is:

$$H = -\delta a^* a + i\left(\alpha_{in}^1\sqrt{\frac{\kappa_\tau}{\tau}} + \alpha_{in}^2\sqrt{\frac{\kappa_l}{\tau}} + \ldots\right)\left(a^* - a\right), \quad (1)$$

where, α is the annihilation operator of cavity film, δ is the detuning of laser frequency and cavity frequency, the relationship between the dissipation rate of the mirror, the transmission coefficient of the mirror, and the round-trip time of the photon in the cavity is: $\kappa i = Ti/\tau$.

Suppose that the light field at any point in the cavity is a, the langevin equation of the light field in the cavity [24] can be obtained:

$$\tau\frac{da}{dt} = -i\Delta\tau a - \gamma a + \sqrt{2\gamma_{in}^a}\,a_{in} + \sqrt{2\rho}\,a_v, \quad (2)$$

where $\tau = 2l/c$ represents the round-trip time of the signal light in the cavity, $\gamma = \gamma_{in}^a + \rho$ represents the total loss of the cavity, γ_{in}^a represents the loss of the input cavity mirror M4, ρ represents the sum of the loss in the cavity and the loss of the output cavity mirror, and Δ represents the detuning amount between the resonance frequency of the cavity and the input optical frequency. The left term of the formula represents the change of signal light in the round trip of the cavity, the first term on the right represents the influence of the detuning of signal light in the round trip of the cavity, the second term on the right represents the change of the light field in the cavity caused by the total loss, the third term on the right is the input term brought by the front cavity mirror, and the last term is the vacuum compensation term of the back cavity mirror.

Conjugate of Equation (2):

$$\tau\frac{da^*}{dt} = i\Delta\tau a^* - \gamma a^* + \sqrt{2\gamma_{in}^a}\,a_{in}^* + \sqrt{2\rho}\,a_v^*. \quad (3)$$

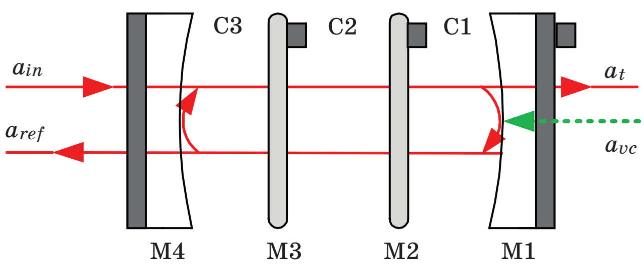

Fig. 1. Schematic diagram of coupled optical cavity

Fourier transformation and linearization of Equation (3) can be obtained:

$$\delta a(\omega)=\frac{\sqrt{2\gamma_{in}^{a}}\delta a_{in}(\omega)+\sqrt{2\rho}\delta a_{v}(\omega)}{\gamma+i(\omega+\Delta)\tau}, \tag{4}$$

$$\delta a^{*}(-\omega)=\frac{\sqrt{2\gamma_{in}^{a}}\delta a_{in}^{*}(-\omega)+\sqrt{2\rho}\delta a_{v}^{*}(-\omega)}{\gamma+i(\omega-\Delta)\tau}. \tag{5}$$

According to the correlating theory of classical field, we can get the reflection coefficient R_1 of cavity C_1 as:

$$R_1(\phi_1)=\frac{r_2-r_1{\alpha_1}^2\exp(i\phi_1)}{1-r_2r_1{\alpha_1}^2\exp(i\phi_1)}. \tag{6}$$

The reflection coefficient R_2 of the coupled cavity composed of M1, M2 and M3 can be obtained by the iterative formula:

$$R_2(\phi_2)=\frac{r_3-R_1{\alpha_2}^2\exp(i\phi_2)}{1-R_1r_3{\alpha_2}^2\exp(i\phi_2)}. \tag{7}$$

Now considering the entire coupled cavity system, we only need to consider the following cavities C_1 and C_2 as an integral cavity mirror, and the reflection coefficient R_3 of the entire coupled optical cavity can be obtained as:

$$R_3(\phi_3)=\frac{r_4-R_2{\alpha_3}^2\exp(i\phi_3)}{1-R_2r_4{\alpha_3}^2\exp(i\phi_3)}. \tag{8}$$

where $\phi_i = 2\pi 2L_jn_j\omega/c$ represents the phase change in one cycle of the cavity, L_j represents the cavity length, ω represents the frequency of the signal light in the cavity, n_j represents the refractive index of the light in the cavity, α_j represents the round-trip loss in the cavity, $j = 1, 2, 3$ represents the corresponding optical cavity.

So in the amplitude space:

$$\begin{aligned}\delta X_{ai}=&\frac{\sqrt{2r_{in}^{a}}\left(\gamma_b^2+\Delta^2\tau^2\right)\gamma+i\sqrt{2r_{in}^{a}}\omega\tau}{\gamma^2+(\Delta^2-\omega^2)\tau^2+2i\omega\tau\gamma}\delta X_{ain}+\\&+\frac{\sqrt{2r_{in}^{a}}\Delta\tau}{\gamma^2+\left(\Delta^2-\omega^2\right)\tau^2+2i\omega\tau\gamma}\delta Y_{ain}+\\&+\frac{\left[\sqrt{2\rho}\gamma+i\sqrt{2\rho}\omega\tau\right]}{\gamma^2+\left(\Delta^2-\omega^2\right)\tau^2+2i\omega\tau\gamma}\delta X_{av}+\\&+\frac{+\sqrt{2\rho}\Delta\tau}{\gamma^2+\left(\Delta^2-\omega^2\right)\tau^2+2i\omega\tau\gamma}\delta Y_{av}.\end{aligned} \tag{9}$$

The mean square of noise in the amplitude space is:

$$\begin{aligned}\delta^2X_o=&\frac{\left[2r_{in}^{a}\gamma-\gamma^2-\left(\Delta^2-\omega^2\right)\tau^2\right]^2+4\omega^2\tau^2\left(r_{in}^{a}-\gamma\right)^2}{\left(\gamma^2+\left(\Delta^2-\omega^2\right)\tau^2\right)^2+4\omega^2\tau^2\gamma^2}\delta^2X_{ain}+\\&+\frac{4r_{in}^{a\,2}\Delta^2\tau^2}{\left(\gamma^2+\left(\Delta^2-\omega^2\right)\tau^2\right)^2+4\omega^2\tau^2\gamma^2}\delta^2Y_{ain}+\\&+\frac{4r_{in}^{a}\rho\left(\gamma^2+\omega^2\tau^2\right)}{\left(\gamma^2+\left(\Delta^2-\omega^2\right)\tau^2\right)^2+4\omega^2\tau^2\gamma^2}\delta^2X_{av}+\\&+\frac{4r_{in}^{a}\rho\Delta^2\tau^2}{\left(\gamma^2+\left(\Delta^2-\omega^2\right)\tau^2\right)^2+4\omega^2\tau^2\gamma^2}\delta^2Y_{av}.\end{aligned} \tag{10}$$

We can get the mean square of noise in the phase space with the same way:

$$\begin{aligned}\delta^2Y_o=&\frac{\left[2r_{in}^{a}\gamma-\gamma^2-\left(\Delta^2-\omega^2\right)\tau^2\right]^2+4\omega^2\tau^2\left(r_{in}^{a}-\gamma\right)^2}{\left[\gamma^2+\left(\Delta^2-\omega^2\right)\tau^2\right]^2+4\omega^2\tau^2\gamma^2}\delta^2Y_{ain}+\\&+\frac{4r_{in}^{a\,2}\Delta^2\tau^2}{\left[\gamma^2+\left(\Delta^2-\omega^2\right)\tau^2\right]^2+4\omega^2\tau^2\gamma^2}\delta^2X_{ain}+\\&+\frac{4r_{in}^{a}\rho\Delta^2\tau^2}{\left[\gamma^2+\left(\Delta^2-\omega^2\right)\tau^2\right]^2+4\omega^2\tau^2\gamma^2}\delta^2X_{av}+\\&+\frac{4\rho r_{in}^{a}\left(\gamma^2+\omega^2\tau^2\right)}{\left[\gamma^2+\left(\Delta^2-\omega^2\right)\tau^2\right]^2+4\omega^2\tau^2\gamma^2}\delta^2Y_{av}.\end{aligned} \tag{11}$$

THEORETICAL RESULTS AND DISCUSSION

EIT-like effects of triple-coupled optical cavity with injection of classical field

Electromagnetic induction transparency effect is produced by eliminating the influence of medium in the propagation of electromagnetic wave by quantum interference. At the same time, the EIT-like effects can also be generated through destructive interference in classical systems. Coupled optical cavity can also simulate the electromagnetic induced transparency of atomic systems, that is, coupled cavity induced transparency. In particular, the coupled optical cavity can give rise to an EIT-like transmission spectrum, is critical for on-chip coherent manipulation of light at room temperatures, including the capabilities of deceleration, storage and release of light pulse.

The absorption and dispersion curves of the reflection filed of the coupled optical cavity can be calculated according to the formulas of amplitude and phase changes of the coupled optical cavity (Fig. 2). The Figs on the left column (subscript I) represent the absorption curves of the reflection field of the coupled optical cavity, and the Figs on the right column (subscript P) represent the corresponding dispersion curves. The Figs from top to bottom show the changes in the reflectivity of the intermediate cavity mirrors M2 and M3, respectively, from large to small. Since the reflectivity of the incident mirror M4 and the exit mirror M1 remains constant ($r_4^2 = 0.96$, $r_1^2 = 0.98$), the above Figs also show the theoretical pattern of the increasing coupled strength of the optical cavity.

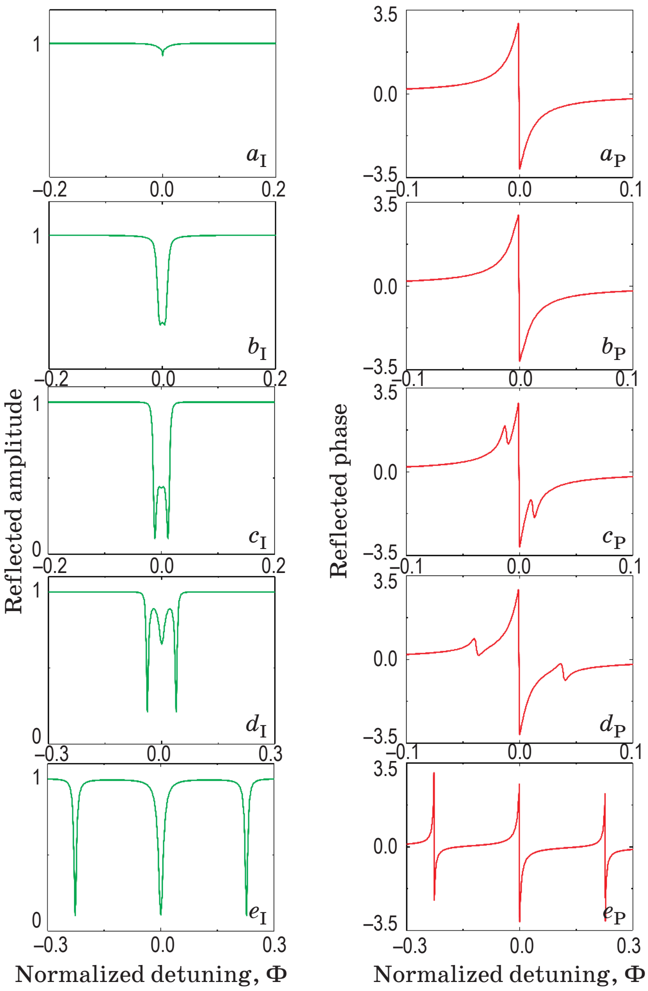

Fig. 2. Absorption and dispersion of reflection field in triple-coupled optical cavity

We make $r_2^2 = 0.99999$ and $r_3^2 = 0.9999999$, and first study the absorption and dispersion curves calculated by formulas, as shown in Figs a_I and a_P. When the reflectivity of these two intermediate mirrors is large, the signal light entering the cavity C_2 is very weak, so there is basically no EIT-like effect occurs in the cavity at this time, and the reflected light field is just the reflection field of the optical cavity C_3. In addition, the reflectivity of the incident cavity mirror is much smaller than that of the exit cavity mirror ($r_4 << r_3$), the optical cavity C_3 is over-coupled. So, the absorption curve of reflection field shows only a small absorption at the resonance place and no splitting occurs, as shown in Fig a_I. The corresponding dispersion curve is shown in Fig a_P.

Now, we set $r_2^2 = 0.99993$ and $r_3^2 = 0.99999$, and study the absorption and dispersion curves calculated by formulas, as shown in Figs b_I and b_P. When the reflectivity of the two intermediate cavity mirrors decreases, the coupled strength of the cavity increases, and the absorption curve splits slightly at the resonance, which indicates that a weak EIT-like effect takes place in the cavity. When the reflectivity of the intermediate cavity mirrors is reduced again, the corresponding splitting will increase due to the increase of coupled strength. If $r_2^2 = 0.9995$, $r_3^2 = 0.9998$, as can be seen from Figs. c_I and c_P, a tiny split appears again at its resonance, and the absorption spectrum of the optical coupled cavity has three transmission windows, moreover, the dispersion curve is changed from zero-crossing point at resonance to three times zero-crossing point at resonance and near detuning.

When $r_2^2 = 0.995$ and $r_3^2 = 0.999$, it can be seen from Figs d_I and d_P that the transmission window in the middle also becomes larger, indicating that the EIT-like effect becomes more obvious. When we reduce the reflectivity of the intermediate mirrors to $r_2^2 = 0.9$ and $r_3^2 = 0.9$, the absorption spectra split into three independent absorption curves due to the strong coupled, the corresponding phase curves split into three independent dispersion curves, as shown in Figs e_I and e_P.

Based on the above analysis of the classical field, we can draw a conclusion that the coupled optical cavity with the coupled strength as shown in Fig D is an ideal system for optical deceleration and optical storage. At this time, the whole medium appears a region of sharp changes in the dispersion curve with low absorption at the resonance, which is the ideal region for optical deceleration and optical storage.

Quantum noise fluctuation of triple-coupled optical cavity with injection of a squeezed vacuum field

The noise fluctuation curve can be obtained from the noise fluctuation formula of the reflection field, as shown in Fig 3. The Figs on the left column (subscript S) represent the noise fluctuation curve of the quadrature amplitude component of the reflection field, while the Figs on the right column (subscript AS) represent the noise fluctuation curve of the quadrature phase component of the reflection field.

Since the reflectivity of the intermediate mirrors R_2 and R_3 are so large that there is no coupled between the optical cavities, so only the noise of the single optical cavity exists. Fig a_S shows the noise fluctuation of the quadrature amplitude component of the reflection field at this time. It can be seen that the compression degree of the light here is slightly lower than that of the incident squeezed vacuum light field due to the weak absorption effect at the resonance. And at the detuning point, the interference caused by phase inversion makes the compressed light here amplified into the anti-compressed light, so the noise here is much higher than the (shot noise limit) SNL. At the place far away detuning, the compression of the light field is equal to the compression of the incident field because the light field is completely reflected, so the quadrature amplitude noise curve of the whole reflection field is presented as a Lorentz curve with splitting (as shown in Fig a_S). Similarly, due to the absorption and dispersion characteristics of the optical cavity, the quadrature phase noise fluctuation curve of its reflection field appears as an inverted Lorentz curve with splitting (as shown in Fig a_AS).

In order to enhance the coupled strength between the optical cavities, we reduce the reflectivity of the intermediate cavity mirrors so that the corresponding noise fluctuation curves can be seen as shown in Fig c_S and c_AS when $r_2^2 = 0.9995$ and $r_3^2 = 0.9998$. Since the EIT-like effect already occurred in this time, splitting occurs at the resonance and there are two phase-crossing zero points near the detuning, casing a drastic change in absorption and dispersion. The resulting quantum destructive interference results in an obvious change in the noise curve of the quantum field at the near detuning. The noise fluctuation curve of the amplitude component appears a triple-splitting Lorentz curve, while the noise fluctuation curve of the

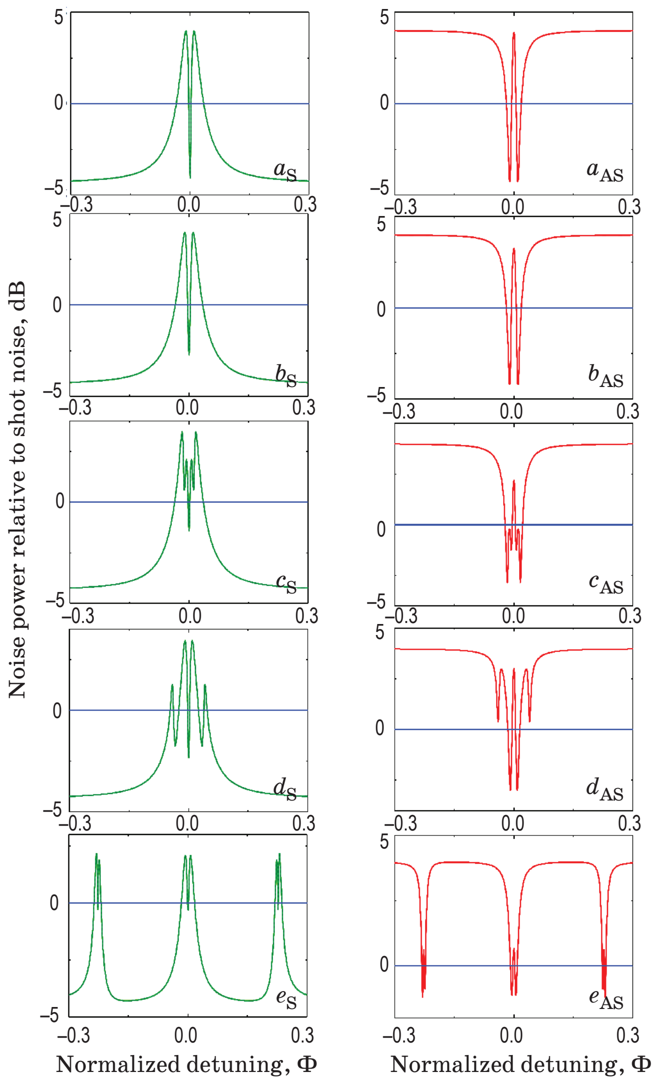

Fig. 3. Noise fluctuation curve of the reflection field of a triple-coupled optical cavity with injection of a squeezed vacuum field

quadrature phase component appears a triple-peak inverted Lorentz curve. With the decrease of the reflectivity of the intermediate cavity mirrors, the coupled strength between the optical cavities increases continuously, and this phenomenon becomes more and more obvious.

When we set $r_2^2 = 0.9$ and $r_3^2 = 0.9$, it can be seen that the noise curve of the quadrature amplitude component eventually becomes three independent Lorentz curves with splitting (as shown in Fig e_{S}) and the noise curve of the quadrature phase component eventually becomes three inverted Lorentz curves with splitting (as shown in Fig e_{AS}). The results show that multiple (three times) quantum coding can be implemented in a device with the increase of the coupled strength between the optical cavities, which provides method for the practical application of quantum information technology.

CONCLUSION

We have theoretically investigated the EIT-like effects and the corresponding quantum noise fluctuation generated in the triple-coupled optical cavity when the squeezed vacuum field is injected. By changing the reflectivity of the intermediate cavity mirrors of the coupled cavity, the amplitude and phase of the reflection light and the corresponding quantum noise fluctuation were obtained. The output spectra of the optical cavity were compared between different cases. It has been demonstrated that the strength of the EIT-like can be changed by changing the reflectivity of the intermediate mirrors in the triple-coupled optical cavity, and the corresponding quantum noise also presents new characteristics. The EIT-like effects and the fluctuation of the quantum noise of the reflection field in the triple-coupled cavity with different coupled strength are studied, the conclusions obtained may have many important applications in quantum information processing such as quantum manipulation, quantum coding and compressed light deceleration, storage and release. This work may also be used as a reference in the related research of quantum manipulation and quantum coding.

REFERENCES

1. Taylor J.M. A quantum future awaits // Science. 2018 V. 361. № 6400. P. 313.
2. Bayliss S.L, Laorenza D.W, Mintun P.J, Kovos B.D, Freedman D.E, Awschalom D.D. Optically addressable molecular spins for quantum information processing // Science. 2020 V. 370. № 6522. P. 1309–1312.
3. Julio T. Barreiro, Dieter Meschede, Eugene Polzik, E. Arimondo, Fabrizio Illuminati, Luigi Lugiato. Atoms, photons and entanglement for quantum information technologies // Procedia Computer Science. 2011 V. 7. P. 52–55.
4. David P. Divincenzo. Quantum Computation // Science. 1995. V. 270. № 5234. P. 255–261.
5. Stefanie Barz, Elham Kashefi, Anne Broadbent, Joseph F. Fitzsimons, Anton Zeilinger, Philip Walther. Demonstration of blind quantum computing // Science. 2012. V. 335. № 6066. P. 303–308.
6. Olmschenk S., Matsukevich D.N., Maunz P., Hayes D., Duan L.M., Monroe C. Quantum teleportation between distant matter qubits // Science. 2009 V. 323. № 5913. P. 486–489.
7. Arrazola J.M., Scarani V. Covert quantum communication // Phys. Rev. Lett. 2016. V. 117. 250503.
8. Fowler A.G., Wang D.S., Hill Ch.D., Ladd T.D., Van Meter R., Hollenberg L.C.L. Surface code quantum communication // Phys. Rev. Lett. 2010. V. 104. 180503.
9. S.J. van Enk. Quantum communication, reference frames, and gauge theory // Phys. Rev. A. 2006. V. 73. 042306.
10. Horodecki R., Horodecki P., Horodecki M., Horodecki K. Quantum entanglement // Rev. Mod. Phys. 2009. V. 81. 865.
11. Song J, Zhang Z.J., Xia Y, Sun X.D., Jiang Y.Y. Fast coherent manipulation of quantum states in open systems // Opt. Express. 2016 V. 24. № 19. P. 21674–21683.
12. Wang L.Y., Hu J.G., Du J.J., Di K. Broadband coherent perfect absorption by cavity coupled to three-level atoms in linear and nonlinear regimes // New J. Phys. 2021. V. 23. 123040.
13. Du S.P., Bai Z.F, Qi X.F. Coherence manipulation under incoherent operations // Phys. Rev. A. 2019. V. 100. 032313.
14. Rohde P.P., Ralph T.C., Nielsen M.A. Optimal photons for quantum-information processing // Phys. Rev. A. 2005. V. 72. 052332.

15. Rips S., Hartmann M.J. Quantum information processing with nanomechanical qubits // Phys. Rev. Lett. 2013. V. 110. 120503.
16. Boykin P.O., Vwani Roychowdhury. Optimal encryption of quantum bits // Phys. Rev. A. 2003. V. 67. 042317.
17. Stannigel K., Komar P., Habraken S.J.M., Bennett S.D., Lukin M.D., Zoller P., Rabl P. Optomechanical quantum information processing with photons and phonons // Phys. Rev. Lett. 2012. V. 109. 013603.
18. Saleh Rahimi-Keshari, Artur Scherer, Ady Mann, Rezakhani A.T, Lvovsky A.I., Sanders B.C. Quantum process tomography with coherent states // New J. Phys. 2011. V. 13. 013006.
19. Xing Z.C., Hong Y.F., Zhang B. The influence of dichroic beam splitter on the airborne multiband co-aperture optical system // Optoelectronics Letters. 2018. V. 14. № 4. P. 250–256.
20. Cosmo Lupo, Vittorio Giovannetti, Stefano Pirandola, Stefano Mancini and Seth Lloyd. Capacities of linear quantum optical systems // Phys. Rev. A. 2012. V. 85. 062314.
21. Mostafa Ghorbanzadeh, Sara Darbari. Efficient plasmonic 2D arrangement and manipulation system, suitable for controlling particle–particle interactions // Opt. Lett. 2019. V. 37. № 9. P. 2058–2064.
22. Bakholdin A.V., Butylkina (Rodionova) K.D., Vasil'ev V.N., Romanova G.É. Development and analysis of reflective and catadioptric optical systems for Earth remote sensing // Journal of Optical Technology. 2017. V. 84. № 11. P. 761–766.

    Бахолдин А.В., Бутылкина К.Д., Васильев В.Н., Романова Г.Э. Разработка и исследование зеркальных и зеркально-линзовых оптических систем для дистанционного зондирования Земли // Оптический журнал. 2017. Т. 84. № 11. С. 55–61.
23. Ou Z.Y., Pereira S.F., Kimble H.J., Peng K.C. Realization of the Einstein–Podolsky–Rosen paradox for continuous variables // Phys. Rev. Lett. 2019. V. 68. 3663.
24. Lawrence M.J., Byer R.L., Fejer M.M., Bowen W., Lam P.K., Bachor H.-A. Squeezed singly resonant second-harmonic generation in periodically poled lithium niobat // J. Opt. Soc. Am. B. 2002. V. 19. № 7. P. 1592–1598.

AUTHORS

Ke Di — Phd, Associate professor, Chongqing University of Post and Telecommunications, 400065, Chongqing, China, Chongqing Key Laboratory of Autonomous Navigation and Microsystem, Chongqing University of Post and Telecommunications, Chongqing 400065, China, http://orcid.org/0000-0001-6339-923X, dike@cqupt.edu.cn

Jie Ren — Master, Postgraduate Student, Chongqing University of Post and Telecommunications, 400065, Chongqing, China, Chongqing Key Laboratory of Autonomous Navigation and Microsystem, Chongqing University of Post and Telecommunications, Chongqing 400065, China, http://orcid.org/0000-0002-1351-4743, 836537144@qq.com

Wei Cui — Phd, Associate professor, Chongqing University of Post and Telecommunications, 400065, Chongqing, China, Chongqing Key Laboratory of Autonomous Navigation and Microsystem, Chongqing University of Post and Telecommunications, Chongqing 400065, China, http://orcid.org/0000-0002-5675-6910, cuiwei@cqupt.edu.cn

Renpu Li — Phd, Associate professor, Chongqing University of Post and Telecommunications, 400065, Chongqing, China, Chongqing Key Laboratory of Autonomous Navigation and Microsystem, Chongqing University of Post and Telecommunications, Chongqing 400065, China, http://orcid.org/0000-0002-0426-296X, lirp@cqupt.edu.cn

YongLe Lu — Phd, Associate professor, Chongqing University of Post and Telecommunications, 400065, Chongqing, China, Chongqing Key Laboratory of Autonomous Navigation and Microsystem, Chongqing University of Post and Telecommunications, Chongqing 400065, China, http://orcid.org/0000-0002-5958-2629, luyl@cqupt.edu.cn

JunQi Guo — PhD, Postgraduate Student, Chongqing University of Post and Telecommunications, 400065, Chongqing, China, Chongqing Key Laboratory of Autonomous Navigation and Microsystem, Chongqing University of Post and Telecommunications, Chongqing 400065, China, http://orcid.org/0000-0001-9570-530X, guojq@cqupt.edu.cn

Yu Liu — PhD, Professor, Chongqing University of Post and Telecommunications, 400065, Chongqing, China, Chongqing Key Laboratory of Autonomous Navigation and Microsystem, Chongqing University of Post and Telecommunications, Chongqing 400065, China, http://orcid.org/0000-0001-6929-1481, liuyu@cqupt.edu.cn

JiaJia Du — Phd, Associate professor, Chongqing University of Post and Telecommunications, 400065, Chongqing, China, Chongqing Key Laboratory of Autonomous Navigation and Microsystem, Chongqing University of Post and Telecommunications, Chongqing 400065, China, http://orcid.org/0000-0002-0051-6846, dujj@cqupt.edu.cn

The article was submitted to the editorial office 26.05.2021, approved after review 04.04.2022, accepted for publication 24.10.2022