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RESEARCH ARTICLE

Propagation of polarized photons through a cavity with an anisotropic metamaterial

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We present a theoretical study of the propagation properties of polarized photons passing through the cavity with an anisotropic metamaterial. We find that the resonant peaks of transmission appear for photons polarized in a certain direction corresponding to a negative element of the permittivity tensor. This indicates the potential for applying such cavity structures as filters for photons with certain polarizations. The resonant peak of transmission for photons having a given frequency can be achieved by adjusting the thicknesses of the air and metamaterial. If the frequency of the incident photons and the thickness of the metamaterial are fixed, the cavity structure can be used as a photon switch controlled by the thickness of the air. The effect of the absorption is considered, and the result shows that the transmission peak always appears, even for metamaterials with large absorption. Finally, the polarization manipulation of such structures is explored.

Keywords anisotropic metamaterial, polarized photon, cavity structure

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1 Introduction

Recent developments in the fabrication of metamaterials have broadened the range of available electromagnetic materials. These materials, permitting solutions of Maxwell's equations not available in naturally existing media, are fueling the discovery of new electromagnetic phenomena. Metamaterials composed of periodically positioned scattering elements exhibit a number of peculiar electromagnetic properties, including, for instance, negative refractive indices [1], amplification of evanescent waves [2], subwavelength cavity resonators [3], and zero-averaged refractive-index band gaps [4]. Because the unit resonance structures of metamaterials usually are anisotropic [1], researchers have become interested in their anisotropic properties and have revealed many intriguing phenomena in different kinds of anisotropic metamaterials [5–15]. Research has shown that electromagnetic wave polarizations can be manipulated freely through reflections by anisotropic metamaterials [10, 11]. A single metamaterial plate can serve as a bandpass filter, transparent wall, and polarization converter under illumination from differently polarized waves [12]. Related research mainly focuses on the classical electromagnetic wave properties of anisotropic metamaterials. Quantization is required to deal with nonclassical radiation, such as the entangled photon pairs. Based on the quantization scheme of the radiation fields in metamaterials, the quantum optical correlation through an isotropic metamaterial plate has been studied [13]. A study of the quantization of the electromagnetic field in anisotropic metamaterials has also been performed; and the input-output relations of quantized radiation have been derived for a single anisotropic metamaterial plate [14, 15]. Some unusual properties for the generation and transmission of entangled photon pairs appear in systems containing metamaterials [16]. It is meaningful to study the propagation of polarized photons through multilayer structures, such as the cavity structures of anisotropic metamaterials. In fact, the propagation properties of polarized photons exhibiting resonance with isotropic metamaterials, such as transmission enhancement based on resonant metamaterials, have been well studied [17, 18].

In this work, we study the propagation of polarized photons through the cavity structure of an anisotropic metamaterial and explore the polarization manipulation of such a structure. Our calculations are based on the phenomenological quantization theory. It is valuable to note that the coupled-mode theory has also been adopted widely for analyzing the interaction between an incident light source and a cavity [19]. It may be meaningful to develop the coupled-mode theory to deal with the cavity structure of an anisotropic metamaterial. This is, however, not within the scope of our discussion. The rest of this paper is arranged as follows. Section 2 briefly provides the theory of photon propagation through a multilayer structure composed of different anisotropic metamaterials. The numerical results and discussion appear in Section 3. Finally, Section 4 summarizes the main points of the paper.

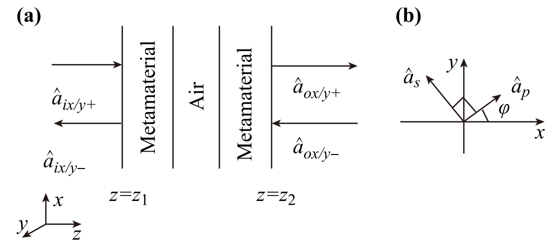

Fig. 1 **(a)** The illustration of the cavity structure and the amplitude operators. **(b)** The orientation of polarization direction.

2 Theory

We consider a cavity structure composed of different anisotropic metamaterials. The cavity structure placed between $[z_1, z_2]$ is composed of anisotropic metamaterial plates and the air, as shown in Fig. 1(a). The permittivity tensor $\overleftrightarrow{\varepsilon}$ and permeability tensor $\overleftrightarrow{\mu}$ of the anisotropic media are given by

$$\overleftrightarrow{\varepsilon} = \begin{pmatrix} \varepsilon_x & 0 & 0 \\ 0 & \varepsilon_y & 0 \\ 0 & 0 & \varepsilon_z \end{pmatrix} \tag{1}$$

and

$$\overleftrightarrow{\mu} = \begin{pmatrix} \mu_x & 0 & 0 \\ 0 & \mu_y & 0 \\ 0 & 0 & \mu_z \end{pmatrix}. \tag{2}$$

Such a metamaterial can be readily constructed with elements of either algebraic sign [5]. For absorbing anisotropic media, ε_j and $\mu_j (j = x, y, z)$ are complex numbers. In order to study the transmission of the polarized photon through such a system, we first need to obtain input-output relations for quantized radiation through this system. The input-output relations of quantized radiation through a single-layer structure with anisotropic metamaterials have been given in Ref. [15]. Generalizing these input-output relations to a multilayer system is straightforward.

Let us first focus on photons linearly polarized in the x- and y-directions and propagating in the z-direction. The amplitude operators $\hat{a}_{ix/y^\pm} \equiv \hat{a}_{x/y^\pm}(z = z_1, \omega)$ represent the incoming photons (+) and outgoing photons (−) polarized in the x/y-direction from the left side of the anisotropic metamaterial. The amplitude operators $\hat{a}_{ox/y^\pm} \equiv \hat{a}_{x/y^\pm}(z = z_2, \omega)$ correspond to the incoming photons (−) and outgoing photons (+) from the right side, as shown in Fig. 1(a). Here the subscripts "+" and "−" represent the photons propagating to the right and the left, respectively. The relations between $\hat{a}_{ox/y^\pm}$ and $\hat{a}_{ix/y^\pm}$ are determined by the definition of the vector potential $\hat{A}(z, \omega)$ and the boundary continuity conditions at the interface of the multilayer structure. Based on the work in Ref. [15], the input-output relations for the amplitude operators through the multilayer structure can be obtained from

$$\begin{pmatrix} \hat{a}_{ix^-} \\ \hat{a}_{ox^+} \\ \hat{a}_{iy^-} \\ \hat{a}_{oy^+} \end{pmatrix} = \boldsymbol{T}(\omega) \begin{pmatrix} \hat{a}_{ix^+} \\ \hat{a}_{ox^-} \\ \hat{a}_{iy^+} \\ \hat{a}_{oy^-} \end{pmatrix} + \boldsymbol{A}(\omega) \begin{pmatrix} \hat{g}_{x^+}(\omega) \\ \hat{g}_{x^-}(\omega) \\ \hat{g}_{y^+}(\omega) \\ \hat{g}_{y^-}(\omega) \end{pmatrix}. \tag{3}$$

The matrix $T(\omega)$ is block-diagonalizable because both the permittivity and permeability tensors are diagonalizable. If the photon is incident normally from the left side, the transmissions for the photons linearly polarized along the x-direction and y-direction are $T_x = |\hat{a}_{ox^+} \hat{a}_{ix^+}|^2 = |T_{21}(\omega)|^2$ and $T_y = |\hat{a}_{oy^+}/\hat{a}_{iy^+}|^2 = |T_{43}(\omega)|^2$, respectively.

In order to study the propagation of the photons polarized in an arbitrary direction, we define the amplitude operator for the s-polarized photon as $\hat{a}_s = -\sin\varphi \hat{a}_x + \cos\varphi \hat{a}_y$ and the amplitude operator for the p-polarized photon as $\hat{a}_p = \cos\varphi \hat{a}_x + \sin\varphi \hat{a}_y$, as shown in Fig. 1(b). Here φ is the angle between the polarization direction of the input photon and the x-direction. The p-polarized input photon may have an s-polarized output component because the transmissions T_x and T_y are different for the anisotropic materials. Then we use the transmission T_{pp} to measure the conserved p-polarized photon and the transmission T_{ps} to measure the converted s-polarized photon while the input photon incident from the left side is p-polarized. They can be obtained from

$$T_{pp} \equiv |\hat{a}_{op^+}/\hat{a}_{ip^+}|^2 = |T_{21}(\omega)\cos^2\varphi + T_{43}(\omega)\sin^2\varphi|^2 \tag{4}$$

and

$$T_{ps} \equiv |\hat{a}_{os^+}/\hat{a}_{ip^+}|^2 = |(T_{43}(\omega) - T_{21}(\omega))\cos\varphi\sin\varphi|^2. \tag{5}$$

Let us then define a polarization conversion ratio (PCR) as

$$\mathrm{PCR} = T_{ps}/(T_{pp} + T_{ps}), \tag{6}$$

which measures the energy portion transformed from the p polarization to the s polarization.

3 Numerical results and discussion

In this section, we present numerical results for the polarized photon through the cavity structure, as shown in Fig. 1(a). The elements of $\overleftrightarrow{\varepsilon}$ and $\overleftrightarrow{\mu}$ of the tensor of the metamaterial are given by $\varepsilon_x = 2 + \mathrm{i}\ 10^{-6}$, $\varepsilon_y = -3 + \mathrm{i}\ 10^{-6}$, and $\varepsilon_z = \mu_x = \mu_y = \mu_z = 1$. We introduce a small imaginary part to describe the absorption of the metamaterial, with the symbol i representing the imaginary unit. Given the rapid development of nanofabrication techniques, metamaterials having permittivity or permeability tensors with elements of either algebraic sign can be achieved by using a periodic array of H-shaped metallic patterns printed on a circuit-board slab [9]. The parameters of the air are given by $\varepsilon_x = \varepsilon_y = \varepsilon_z = 1$ and $\mu_x = \mu_y = \mu_z = 1$.

The numerical results for the transmission, as a function of frequency, of photons polarized in the x-direction and y-direction through such a cavity structure are shown in Fig. 2. The thickness of each metamaterial plate and the thickness of the air are taken to be $l_{\mathrm{Meta}} = 0.002$ m and $l_{\mathrm{air}} = 0.005$ m, respectively. The results show that several equally distributed sharp peaks appear for the transmission T_y. The transmission T_x is fluctuant with the change of the frequency and does not show any resonant peaks.

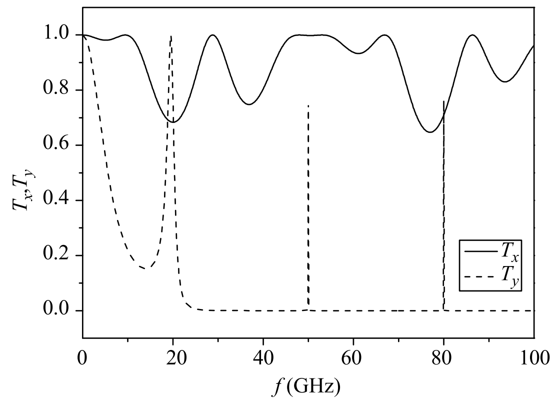

Fig. 2 The transmissions T_x (*solid line*) and T_y (*dashed line*) for a cavity structure each as a function of frequency. The thickness of each metamaterial plate and the thickness of the air are taken as $l_{\mathrm{Meta}} = 0.002$ m and $l_{\mathrm{air}} = 0.005$ m.

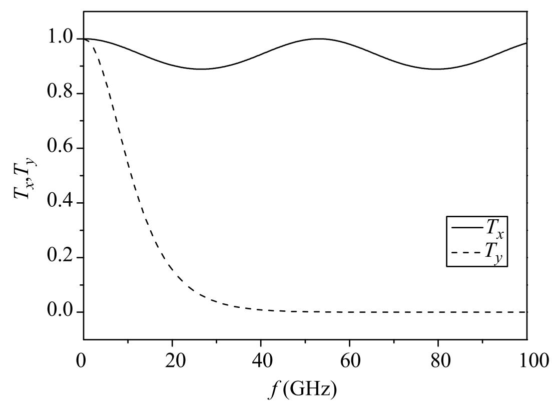

Fig. 3 The transmissions T_x (*solid line*) and T_y (*dashed line*) each as a function of frequency for a single layer of metamaterial with the thickness $l_{\mathrm{Meta}} = 0.002$ m.

In order to find the physical origin of such a resonant peak, we plotted in Fig. 3 the transmission of polarized photons through a single layer of metamaterial. The thickness of the metamaterial plate is taken as $l_{\mathrm{Meta}} = 0.002$ m; the other parameters are the same as those in Fig. 2. Then Fig. 3 illustrates the transmissions for different polarized photons showing different variation trends when the frequency changes. The transmission T_x is fluctuant with the change of frequency; the transmission T_y decreases rapidly with increases in frequency. We use the refractive indices of classical waves to explain this phenomenon. For normal incidence, the refractive indices for the x-polarized wave and the y-polarized wave are $n_x = \sqrt{\varepsilon_x \mu_y}$ and $n_y = \sqrt{\varepsilon_y \mu_x}$, respectively. In the x-direction, the element of the permittivity tensor for the anisotropic metamaterial ($\varepsilon_x = 2 + \mathrm{i}\ 10^{-6}$) has a positive real part. The refractive index for the x-polarized wave is $n_x = \sqrt{\varepsilon_x \mu_y} = 1.4 + \mathrm{i}\ 3.5 \times 10^{-7}$. The absorption is insignificant for the x-polarized wave. The transmission T_x then shows oscillating behavior. But in the y-direction, the element of the permittivity tensor for the anisotropic metamaterial ($\varepsilon_y = -3 + \mathrm{i}\ 10^{-6}$) has a negative real part. The refractive index for the y-polarized wave is $n_y = \sqrt{\varepsilon_y \mu_x} = 2.9 \times 10^{-7} + \mathrm{i}\ 1.7$. The real part of n_y is near zero, while the imaginary part of n_y is large. Then the metamaterial gives rise to large absorption of y-polarized waves. In this situation, most of the incident wave will be reflected or absorbed and less will transmit through the metamaterial. As a result, the transmission of y-polarized photons decreases rapidly with the increase in frequency. But for the cavity structure, the transmission of y-polarized photons is always near zero, except for some resonant peaks appearing at certain frequencies. The physical origin for such a phenomena is the interference effect at the interface between the metamaterial and the air. The result indicates that a cavity structure with an anisotropic metamaterial can be used as a quantum filter for a certain polarized photons.

The resonant peaks of the transmission cannot be achieved with traditional materials. In this section, we present numerical results for polarized photons passing through a cavity structure composed by a layer of air sandwiched between two anisotropic traditional materials plates. The elements of $\overleftrightarrow{\varepsilon}$ and $\overleftrightarrow{\mu}$ of the traditional material are given by $\varepsilon_x = 2 + \mathrm{i}\ 10^{-6}$, $\varepsilon_y = 3 + \mathrm{i}\ 10^{-6}$, and $\varepsilon_z = \mu_x = \mu_y = \mu_z = 1$. The numerical results for the transmission of the photons polarized in the x-direction and y-direction through such a cavity structure, as a function of frequency, are shown in Fig. 4. The thickness of each traditional material plate is taken to be $l_{\mathrm{trad}} = 0.002$ m; the thickness of the air is taken to be $l_{\mathrm{air}} = 0.005$ m. There are no resonant peaks for the transmission of either x-polarized or y-polarized photons. We also calculated the transmissions of the cavity structure for metamaterials using $\varepsilon_x = -2 + \mathrm{i}\ 10^{-6}$, $\varepsilon_y = -3 + \mathrm{i}\ 10^{-6}$, and $\varepsilon_z = \mu_x = \mu_y = \mu_z = 1$, as shown in Fig. 5. The result shows that the resonant peaks appear for the transmissions of both the x-polarized and y-polarized photons. The resonant peaks, however, are located at different frequencies for different polarized photons because of the anisotropy of the metamaterial. This means that the negative real part of the permittivity tensor element results in resonant transmission.

Let us fix the frequency of the input photon at $f = 30$ GHz. The calculated result of transmission T_y through the cavity structure with the metamaterial, as a function of the thickness of the air, is shown in Fig. 6. The elements $\overleftrightarrow{\varepsilon}$ and $\overleftrightarrow{\mu}$ of the metamaterial are given by $\varepsilon_x = 2+\mathrm{i}\ 10^{-6}$, $\varepsilon_y = -3+\mathrm{i}\ 10^{-6}$, and $\varepsilon_z = \mu_x = \mu_y = \mu_z = 1$. The solid and dashed lines are the transmission T_y for the thickness of the metamaterial for $l_{\mathrm{Meta}} = 0.001$ m and $l_{\mathrm{Meta}} = 0.002$ m, respectively. The numerical results show that the resonant peaks always appear at certain thicknesses of the air and metamaterial. As a result, we can adjust the thicknesses of the metamaterial and the air to achieve the resonant transmission of polarized photons in a certain frequency. The peaks become sharp and move to higher frequencies as the thickness of the metamaterial increases. If the frequency of the incident photons and the thickness of the metamaterial are kept constant, the cavity structure can be used as a photon switch controlled by the thickness of the air.

Let us now investigate the effect of the absorption of the metamaterial on the transmission. We plot the transmission T_y for several cases with different values of the imaginary part of ε_y, as shown in Fig. 7. The frequency of the incident photons is fixed at $f = 30$ GHz, and the thickness of the anisotropic metamaterial is taken to be $l_{\mathrm{Meta}} = 0.001$ m. The transmission is plotted as a function of the thickness of the air. With the increase in absorption, the value of the transmission peak decreases. By increasing the imaginary part of ε_y from 10^{-6} to 0.1, the maximum value of the transmission decreases from 0.99 to 0.82. If the imaginary part of ε_y is greater than

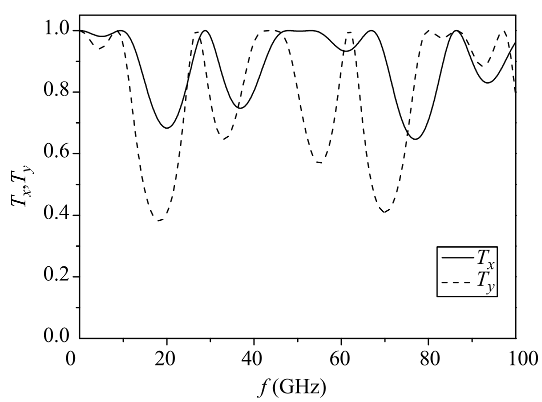

Fig. 4 The transmissions T_x (*solid line*) and T_y (*dashed line*) each as a function of frequency for cavity structure with traditional material ($l_{\mathrm{trad}} = 0.002$ m, $l_{\mathrm{air}} = 0.005$ m). The elements of $\overleftrightarrow{\varepsilon}$ and $\overleftrightarrow{\mu}$ of the traditional material are given by $\varepsilon_x = 2 + \mathrm{i}\ 10^{-6}$, $\varepsilon_y = 3 + \mathrm{i}\ 10^{-6}$ and $\varepsilon_z = \mu_x = \mu_y = \mu_z = 1$.

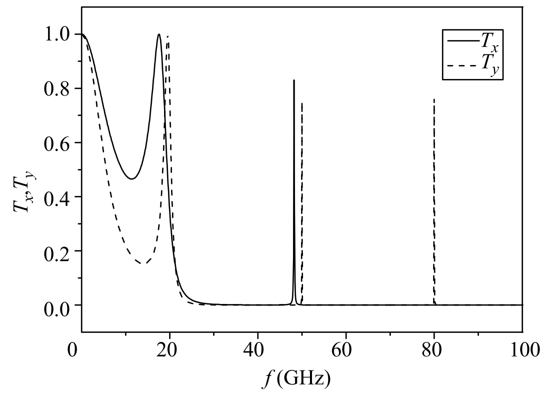

Fig. 5 The transmissions T_x (*solid line*) and T_y (*dashed line*) for a cavity structure each as a function of frequency. The elements of $\overleftrightarrow{\varepsilon}$ and $\overleftrightarrow{\mu}$ of the metamaterial are given by $\varepsilon_x = -2+\mathrm{i}\ 10^{-6}$, $\varepsilon_y = -3+\mathrm{i}\ 10^{-6}$ and $\varepsilon_z = \mu_x = \mu_y = \mu_z = 1$. The other parameters of the system are the same as those in the Fig. 2.

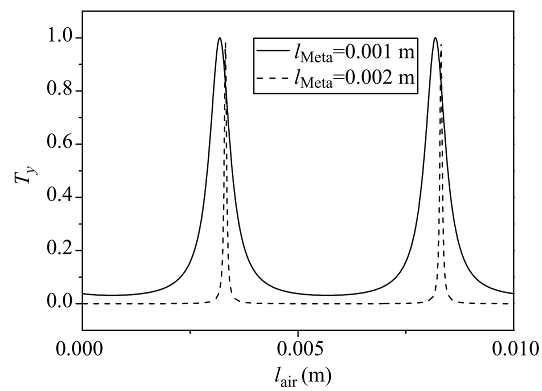

Fig. 6 The transmission T_y as a function of the thickness of the air with the frequency taken as $f = 30$ GHz.

1, the maximum value of the transmission will be less than 0.23. When the imaginary part of ε_y increases to 100, the transmission is close to zero for all thicknesses of air. If, however, we enlarge the curve, as shown in the inset of Fig. 7, we still can find the resonant peak. This means that the resonant peak always exists, even for metamaterials with large absorption.

Finally, we study the propagation in the z-direction of photons, polarized in arbitrary directions, through the above-described cavity structure. The concrete parameters of the system are the same as those in the Fig. 2. Consider the input photon to be p-polarized with $\varphi = 45°$. The calculated results of the transmissions T_{ps} and T_{pp}, where each is a function of frequency, are shown in Figs. 8(a) and (b). The PCR is given in Fig. 8(c). The average value is about 0.2 for both T_{ps} and T_{pp}. The average value of the PCR is about 0.5, and we can see that this result comes directly from the definition of the PCR in Eq. (6). Near the resonant peaks of the transmission T_y, the transmissions T_{ps} and T_{pp} and the PCR also have resonant peaks. Thus, if we want to obtain a steady value of the PCR, we should design the structure away from the resonant peaks.

We plot the PCR with several different values of the angle φ in Fig. 9. If the angle φ increases from 0° to almost 90°, the PCR will increase from 0 to almost 1. We compare this result with the transmissions T_x and T_y in Fig. 2. The transmission T_x is close to 1 in the displayed frequency range. In contrast, the transmission T_y is close to 0. Increasing φ means increasing the components of y polarization and reducing the components of x polarization for the input photons. Thus, T_{pp} decreases and T_{ps} becomes larger with the increase of φ, as we can conclude from Eqs. (4) and (5). Thus, the PCR increases with a large φ. However, at the same time, the total transmission is low for a large φ. We have verified that the optimal choice is $\varphi = 45°$.

Now we study the effect of the thickness of the air on the PCR. Let us fix the frequency of the input photons

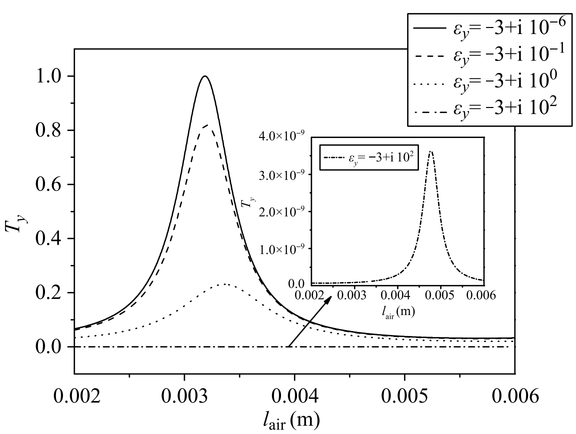

Fig. 7 The transmission T_y as a function of the thickness of the air for several cases with different values of the imaginary part of ε_y. The frequency of the incident radiation and the thickness of the metamaterial are fixed as f = 30 GHz and $l_{\text{Meta}} = 0.001$ m.

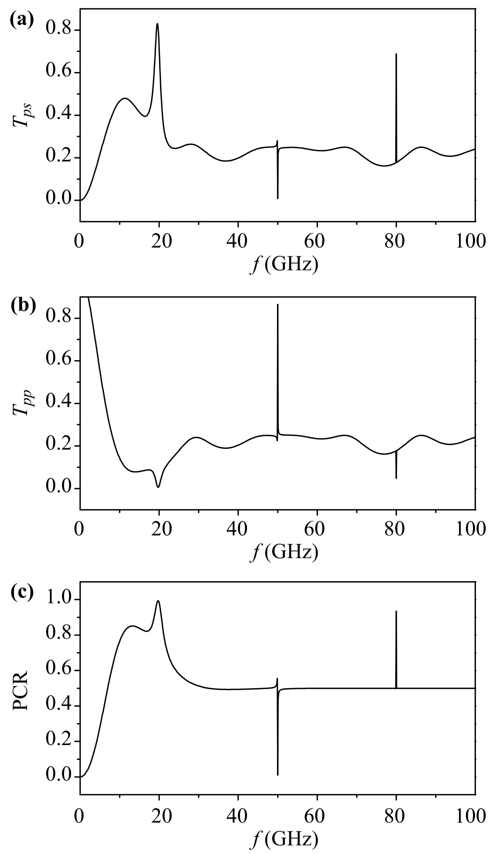

Fig. 8 The transmissions T_{ps} **(a)**, T_{pp} **(b)** and the PCR **(c)** each as a function of the frequency. The input photon is p-polarized with $\varphi = 45°$. The other parameters of the system are the same as those in the Fig. 2.

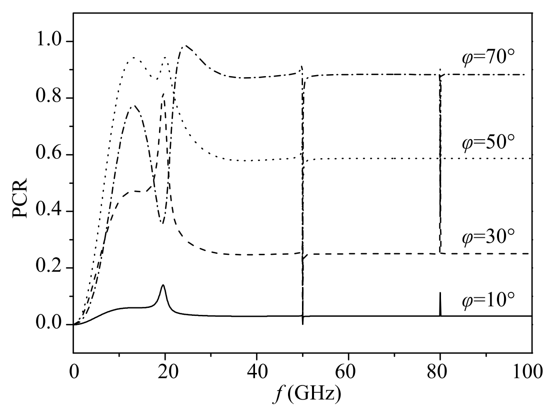

Fig. 9 The PCR of the cavity system for $\varphi = 10°, 30°, 50°, 70°$. The concrete parameters of the system are the same as those in the Fig. 2.

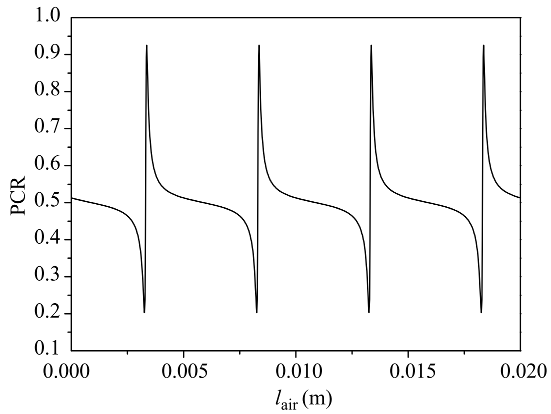

Fig. 10 The PCR as a function of the thickness of air for $\varphi = 45°$. The frequency is fixed as $f = 30$ GHz. The concrete parameters of the system are the same as those in the Fig. 2.

and the thickness of the metamaterial at $f = 30$ GHz and $l_{\text{Meta}} = 0.002$ m. Then the result of the PCR as a function of the thickness of the air is given in Fig. 10. Near the resonant peak, the PCR undergoes an abrupt change. The PCR is smooth, however, over a broad range away from the resonant peaks. This means that the thickness of the air has a small effect on the PCR when the PCR is far away from the resonant peaks. This result indicates that the application of such a structure to realize polarization manipulation can be achieved conveniently. Anisotropic metamaterials may be used to control polarization-entangled photon pairs. Finally, we note that the metamaterial with anisotropic permeability exhibits the same characteristics as metamaterials with anisotropic permittivity.

4 Conclusion

Based on the input-output relations of the quantized radiation field in a multilayer system with anisotropic metamaterials, we calculated the transmission of polarized photons through a cavity structure with anisotropic metamaterials. The results show that the resonant peaks of transmission for certain polarized photons occur in correspondence with a negative value of the permittivity. This indicates the feasibility of applications using cavity structures with anisotropic metamaterials as filters for certain polarized photons. Furthermore, the transmission of polarized photons having a given frequency can achieve resonant peaks by adjusting the thicknesses of the air and the metamaterial. As the thickness of the metamaterial increases, the peaks become sharp, and the frequencies of the resonant peaks increase. If the frequency of the incident photons and the thickness of the metamaterial are kept constant, the cavity structure can be used as a photon switch controlled by the thickness of the air. The effect of the absorption was considered. The results show that the transmission peak would always appear for metamaterials with large absorption. Finally, we studied the propagation of photons polarized in arbitrary directions through such a structure. The results show that the PCR is about 0.5 if the input radiation is p-polarized with $\varphi = 45°$. The above properties hint that the metamaterial may be used to manipulate polarized entangled photon pairs.

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