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Continual mode transformation in a unidirectional compound waveguide

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We propose a new mechanism to achieve mode transformation. In a unidirectional air waveguide we place some metal slabs to form the unidirectional edge loop. Based on the effect of mode interference, the even mode or the odd mode can be completely canceled from their degenerated state through a precise adjustment of slab position, which leads to another mode to be released. By this mechanism, we have achieved continual transformations between even mode and odd mode.

Keywords: mode transformation, unidirectional waveguide, metal slabs.

1. Introduction

State or mode transitions are well-known phenomena in solid state physics and optics [1–4]. There exist rich fascinating physical applications. Some schemes are based on the simultaneous temporal and spatial modulation of the refractive index, which induces the transition between two photonic states of different frequency and wave vector [1–3]. The simultaneous temporal and spatial modulation of the refractive index has to be dependent on the external condition, such as a pump pulse [3]. Much recently, a flip between two states is realized upon encircling the exceptional point [4], but the realization of experimental is very difficult. Optical waveguide modes are the particular solutions of Maxwell's equations in waveguides. Frequency and wave vector are the two basic parameters of a mode. A frequency may correspond to two or more wave vectors calling mode degeneration, that is, one source frequency excites two different modes. Recently, unidirectional edge waveguides (UEWs) and unidirectional air waveguides (UAWs) give rise to fascinating phenomena [5–15], such as the one-way transmission and the ability to cancel the scattering loss. We have found that two kinds of modes called even mode and odd mode can both occur in a UAW [13–15]. Based on the positions of excited source, the even or the odd mode can be independently excited [14]. In this work, we propose and demonstrate a new simplified version of complete mode transformation. Although in our previous work we have made a similar transformation in a cross UAW, but the transformation is not complete [15].

2. Model and method

Here we firstly introduce our idea. The UAW structure is taken from our previous paper [13]. A line defect air waveguide with the width $d = 1.5a$ (a is the lattice constant) divides a two-dimensional magneto-optical photonic crystals (2-D MO PCs) composed of YIG rods into two parts. An external direct current (dc) magnetic field applied in the out-of-plane (z) direction induces strong gyromagnetic anisotropy, with the relative permeability tensor taking the form [6]

$$\mu(\mathbf{r}) = \begin{bmatrix} \mu_1 & j\mu_2 & 0 \\ -j\mu_2 & \mu_1 & 0 \\ 0 & 0 & \mu_3 \end{bmatrix}$$

As is known, the YIG material has material dispersion and loss, and the material parameters are dependent on the working frequency and the applied magnetic field [6]. At 4.28 GHz and with a 1600 gauss applied field, the tensor elements are taken as $\mu_1 = 14$ and $\mu_2 = 12.4$. In this paper we do not consider the dispersion effect. The up and the down parts are under $+z$ and $-z$ magnetic field directions, respectively. The structure and the dispersion curves of UAW modes are shown in Fig. 1 that is referred from [13, 15]. Curves A and B correspond to the odd mode and even mode, respectively. The right insets (see Fig. 1**b**) are the eigenfields of the two modes. Clearly, the even mode has a symmetric configuration, whereas the odd mode has an antisymmetric configuration. A source with a frequency indicated by the dashed line in the figure may simultaneously excite the two modes. However, it is found that for the source at the center of the UAW, the odd mode is completely suppressed [14] and only the even mode has

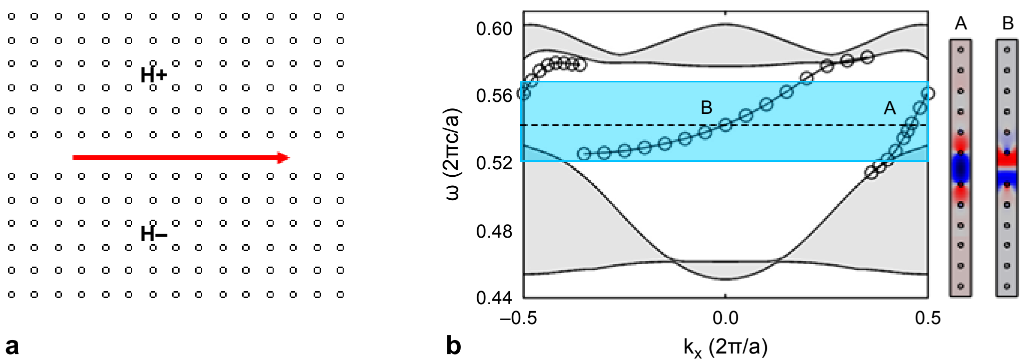

Fig. 1. The UAW structure model (**a**) and the project bands of the coupled modes (**b**). The dashed line denotes $\omega = 0.542$ ($2\pi c/a$) that interacts with the two curves at points A and B, and the corresponding eigenfields of A and B are also shown. The project wave vector k_x is along the waveguide direction.

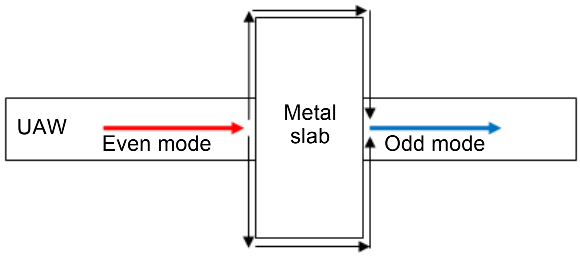

Fig. 2. The schematic of designed model.

been excited. Thus if we designed a structure that can suppress the even mode, the odd mode can be released. If so, a mode transformation has been achieved. Thus how to suppress the even mode is the key point. To achieve this goal, we just make use of the UEW loop. We place a rectangle metal slab in the UAW structure. The UAW cross the metal slab and split it into two parts that extend into the PC lattices. The metal slab can be looked as a perfect electric conductor. The designed model schematic is shown in Fig. 2. According to [7], the UEW loop will be formed around the interface between the rectangle metal and the PC lattice. The UEW loop is split into two parts by the UAW. Because the directions of the magnetic field in the up PC and the down PC are opposite, the group velocity directions of the modes in the up UEW loop and the down UEW loop are also opposite. Thus the UAW and the UEW loop form a compound waveguide. When electromagnetic (EM) waves from a line source at the center of the UAW reach the front side of the metal slab, the even mode EM waves are split into two branch one-way waves in the up UEW loop and the down UEW loop in opposite circulation directions, respectively. The two branch waves will meet and interfere again at the back side of the metal slab within the UAW. If we set the metal slab to be asymmetric with respect of the center of the waveguide, the two branch waves will pass different distance and will have different phase difference between the separation and meeting. If we can make the two branch waves have just the π phase difference at the meeting point, the deconstructive interference will completely cancel the even mode and the suppressed odd mode will be released in the back UAW. Thus the UEW loop and the opposite circulation of EM waves are the key conditions to make the two branch waves cancel each other. To achieve the strict π phase difference, we can precisely adjust the position of the slab and the operating frequencies. On the other hand, if the odd mode EM waves go through the metal slab and meet a deconstructive interference, they will be also transformed into the even mode EM waves.

To demonstrate the above scheme, we perform frequency-domain simulations based on a finite element method software package. As stated above, in order to achieve π phase difference, the position of the slab has to be proper set. The phase difference is also dependent on the wave frequency. The source frequency is set as $\omega = 0.542\ (2\pi c/a)$ that is at the center of the band gap. To compare, we firstly make the slab symmetric with respect of the central line of the UAW. A metal slab with a size of $11.5a \times 8a$ is symmetrically placed in the UAW structure. The up and down sides of the metal slab are flush with the lattice rods. The two branch waves around the slab will have the same phase difference and lead to a constructive interference. As a result, the mode has no changes when EM wave cross the slab. The simulation result is shown in Fig. 3**a** in which the line source is placed at the left port of the UAW and at the central line of the UAW. The red and blue denote the maximum and minimum values of E_z field. It is clear that the even mode has an alternant anti-node and node meaning a quick phase change. But the wave shapes at both sides of the UAW are almost the same. Then we set the slab asymmetric with respect to the central line of the UAW by extending down-

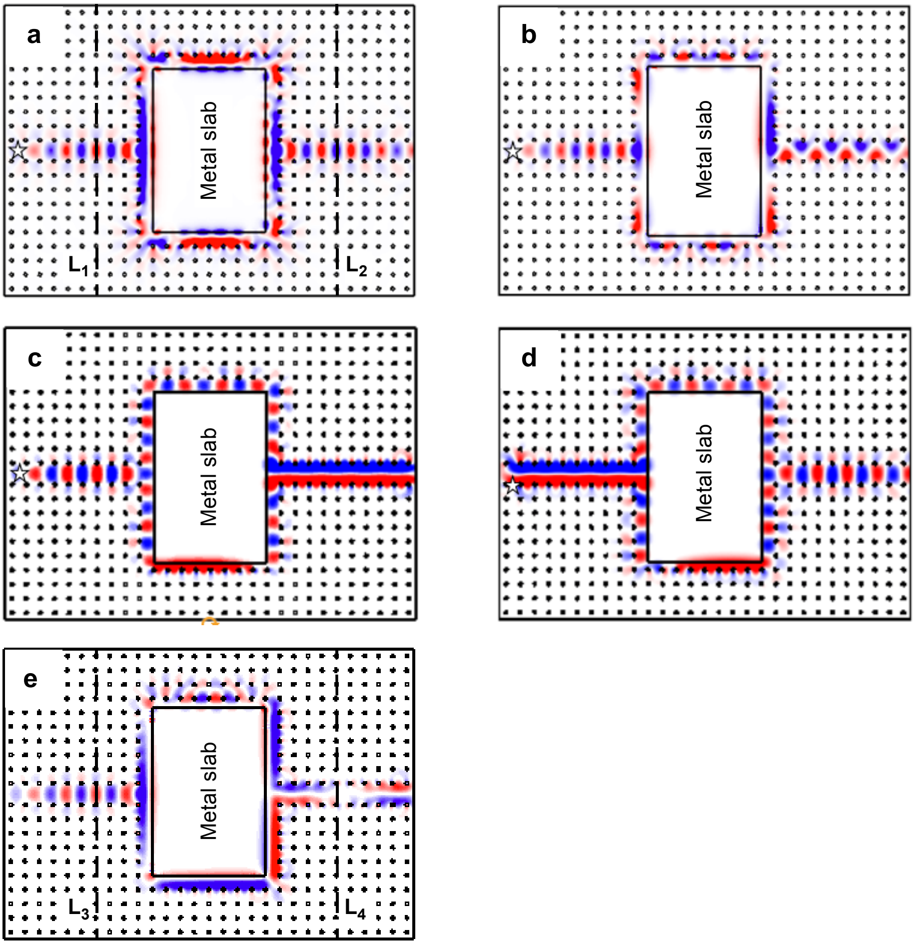

Fig. 3. The mode transformation with different conditions. The slab is symmetric with respect to the central line of the UAW and the source is at the center of the UAW (**a**). The down side of the metal slab is extended with a distance of $0.2a$ and the source is at the center of the UAW (**b**). The down side of the metal slab is extended with a distance of $0.25a$ and the source is at the center of the UAW (**c**). The down side of the metal slab is extended with a distance of $0.25a$ and the source is at the edge of the UAW (**d**). The up side of the metal slab is extended with a distance of $0.352a$ and the source is at the center of the UAW (**e**). The five-pointed star denotes the position of a source.

ward the down side of the slab keeping the slab up side invariant. We find that a hybrid mode occurs at the back side of the UAW, meaning a partial transformation. The simulation result for a down distance of $0.2a$ is shown in Fig. 3**b**. In this configuration, the phase difference of the two branch waves from the separating to meeting is neither 0 nor π. Thus we further extend the slab down side for a distance of $0.5a$ keeping the slab up side invariant. As shown in Fig. 3**c**, the even mode has been completely transformed into the odd mode after the EM wave pass through the slab. We can conclude that the phase difference is just π. The most interesting is that the odd mode at current frequency has no phase change. This is because that for the operating frequency $\omega = 0.542$ $(2\pi c/a)$ the odd mode just occurs near $k_x = 0$ which means a large wavelength. Keeping the slab position in Fig. 3**c** invariant, we move the source to the edge of the UAW. Thus the source excites the odd mode from the left port. When the odd mode wave passes through the slab, the two branch waves have still the π phase difference. Thus the odd mode has been completely transformed into the even mode as Fig. 3**d** shows. In order to further observe the features of modes and the mode transformation, we plot the E_z fields along two vertical lines in Figs. 3**a** and 3**e**. The central line of the waveguide is at $y = 10.25a$. The results are shown in Fig. 4. In Fig. 4**a** the E_z fields along L_1 and L_2

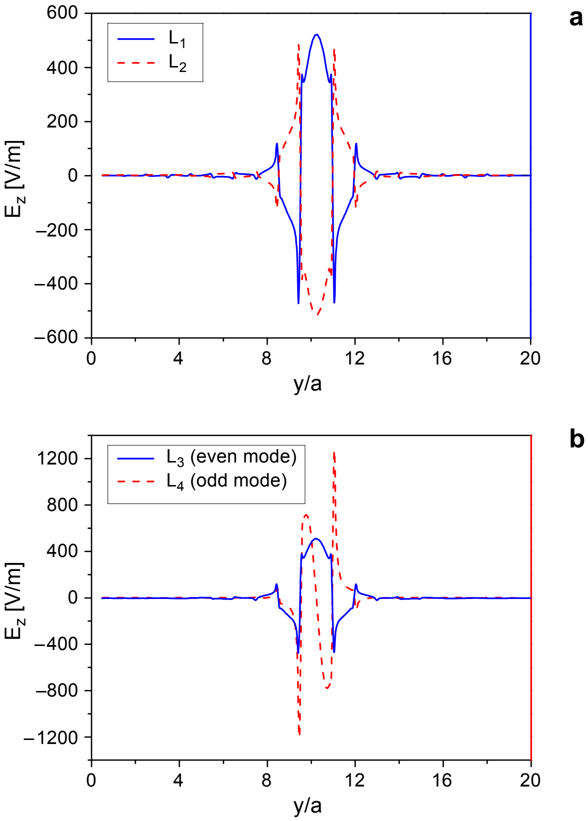

Fig. 4. The E_z fields along lines L_1 and L_2 in Fig. 3**a** (**a**). The E_z fields along lines L_3 and L_4 in Fig. 3**e** (**b**).

show the clear even mode property. They are symmetric with respect to $y = 10.25a$ and out of phase relation. In Fig. 4**b** the E_z fields along L_3 and L_4 show the clear even mode and odd mode properties, respectively. The E_z field along L_4 is antisymmetric with respect to $y = 10.25a$. For the even mode, the field is focused on the center of the waveguide, whereas for the odd mode the field is focused on the two edges of the waveguide. Therefore, the metal slab has been functioned as a mode transformation switching after it is placed at a proper position. The mode transformations are not limited to the current frequency. As the frequency changes, the corresponding position of the slab for the transformation has to be changed accordingly. For example, for the operating frequency $\omega = 0.542$ $(2\pi c/a)$, from the symmetric metal slab with a size of $11.5a \times 8a$, we extend upward the up side of the slab for a length of $0.352a$ keeping the slab down side invariant. When the source is placed at the center of the left UAW, a perfect transformation from the even mode to the odd mode still occurs. The result is shown in Fig. 3**e**. We notice that the wavelength of the odd mode in the right UAW is decreased because the mode point has left $k_x = 0$.

Besides the simple structure and perfect transformation efficiency, another advantage in this work is that the mode can be continuously transformed. We set two identical metal slabs in the structure and their positions are the same as that in Fig. 3**c**. Two sources with the same frequencies $\omega = 0.540$ $(2\pi c/a)$ are placed at the left port. They are at the center and the edge of the UAW, respectively. The simulation results are shown in Fig. 5. For the source at the center of the UAW, continuous transformations from the even mode to the odd mode, further from the odd mode to the even mode

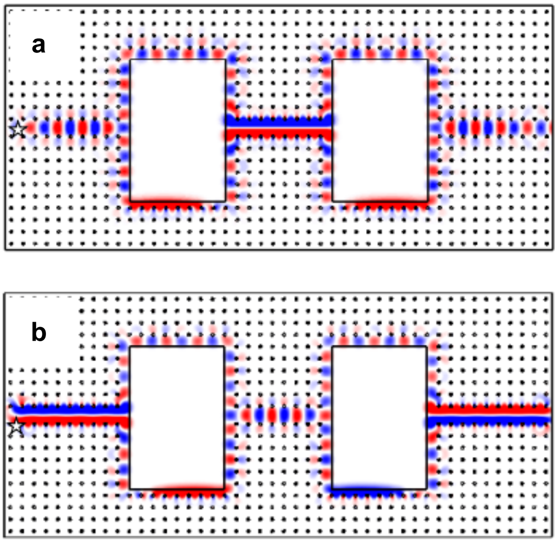

Fig. 5. Continuous mode transformations. Even mode to odd mode to even mode (**a**). Odd mode to even mode to odd mode (**b**). The five-pointed star denotes the position of a source.

have occurred in Fig. 5**a**, whereas for the source at the edge of the UAW, continual transformations from the odd mode to the even mode, further from the even mode to the odd mode have occurred in Fig. 5**b**.

3. Summary

In summary, we propose a new scheme to achieve mode transformation basing on the deconstructive interference effect of modes and the feature of UEW. The realization of mode transformation is just dependent on the structure of the system and does not need any external conditions. The results provide a new mechanism to achieve mode transformation in a multimode system.

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