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Unidirectional channel-drop filter by one-way gyromagnetic photonic crystal waveguides

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We theoretically and experimentally study the side coupling between guided modes and cavity modes in a one-way waveguide that is composed of a regular photonic crystal and a gyromagnetic photonic crystal. At the cavity resonant wavelength, the backward mode can be completely blocked while the forward mode is only slightly influenced in the transmissivity for a specially designed waveguide. This unique light transport property can be exploited to construct a unidirectional band stop filter and a unidirectional channel-drop filter that can selectively process a light signal propagating only along a particular direction. © *2011 American Institute of Physics*.
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Magneto-optical photonic crystal (MOPC) has attracted much attention of researches in recent years.[1–5] It can support a so-called chiral edge state (CES) that exhibits a unique directionality and strong robustness against disorder and interface configuration, similar to the electron current along the edges in a two-dimensional quantum Hall effect system. Due to the unidirectionality of the CES, a one-way waveguide can be realized via confinement of the surface states,[3,4] and more and more work has been done to explore the one-way property in gyromagnetic PC (GPC), the counterpart of MOPC in the microwave regime.[6–8]

The coupling between guided modes and cavity modes is of fundamental importance in a PC integrated optical system. It can be used to build splitters,[9] resonators,[10] directional couplers, channel drop filters (CDF),[11] and other integrated optical devices. In a regular all-dielectric PC CDF, the add/drop functionality is the same for a light signal propagating along both directions of the waveguide due to the reciprocal behavior of light.[12,13] Recently, a circulator based on the match of MO defect modes and the waveguide modes has been proposed theoretically.[14] However, the coupling of the one-way waveguide and MOPC/GPC cavity is still untouched. In this letter, we report a unidirectional band stop filter and a unidirectional channel-drop filter built by one-way GPC waveguides and cavities.

We adopt a similar experimental configuration to Ref. 5 except that a cavity formed by some point defects in the GPC was placed near the waveguide channel as seen in Fig. 1. The upper part is a square-lattice alumina ($\varepsilon_1=9\varepsilon_0$) PC, where the lattice constant is $a_1=0.94$ cm and the rod radius is $r_1=0.155$ cm. The GPC in the lower part is a square lattice of microwave ferrites yttrium-iron-garnet (YIG) rods embedded in foam with a refractive index close to 1. The lattice constant is $a_2=1.33$ cm and the radius of the YIG rods is $r_2=0.16$ cm. The permittivity of YIG is a constant of $\varepsilon_2=15\varepsilon_0$, while its permeability takes a form of a second-rank tensor under an applied dc magnetic field.[5,15] All theses rods are 1 cm high and sandwiched between two aluminum plates, which form a metallic cavity (below 15 GHz, it only supports TM electromagnetic modes).

According to our previous calculation, the common band gap of the two PCs is located between 14.2 and 15.1 GHz under an external field of $H_0=2020$ Gs.[5] A GPC cavity built via eradicating two rods along the [01] direction is resonant at 14.72 GHz. For a waveguide of width as $1.5a_2$, the one-way band (only forward wave can pass through) spans from 14.86 to 15.1 GHz, and the forward and backward waveguide modes can both match the cavity mode.

Using a multiple scattering method,[16] we calculate the transmission spectra for the $1.5a_2$ waveguide coupled with the cavity, whose size is tuned. We can find from Figs. 2(a) and 2(c) five changes when introducing the cavity. (1) A shallow dip appears around 14.7 GHz in the forward spectrum. (2) A deep dip also emerges around the cavity resonance frequency 14.7 GHz in the backward spectrum. (3) The upper gap edge of the backward mode shifts to a higher frequency. (4) A small peak inside the backward gap appears at 14.92 GHz. (5) The tunability of the resonance frequency can be readily achieved by varying the lateral size of the cavity [Figs. 2(e) and 2(f)], as seen in the spectra. Most of these phenomena have been observed experimentally in Figs. 2(b) and 2(d) except the fourth one.

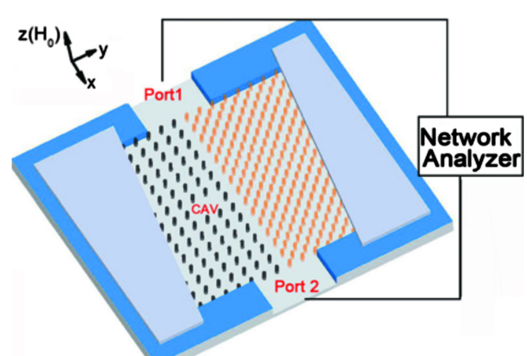

FIG. 1. (Color online) Schematic of the side-cavity-coupled edge state waveguide formed by the interface between a YIG PC (left-bottom) and an alumina PC (right-up), which are surrounded by microwave absorbing materials.

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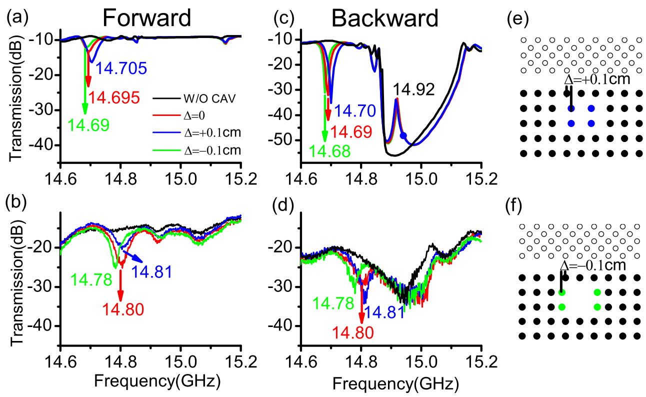

FIG. 2. (Color online) Calculated [(a); (c)] and measured [(b); (d)] spectrum for the side-cavity coupled one-way waveguide. Both forward [(a) and (b)] and backward [(c) and (d)] spectra are shown. The width of the cavity is changed by shifting four lateral rods [denoted with blue color in (e) and green in (f)] with a length of Δ.

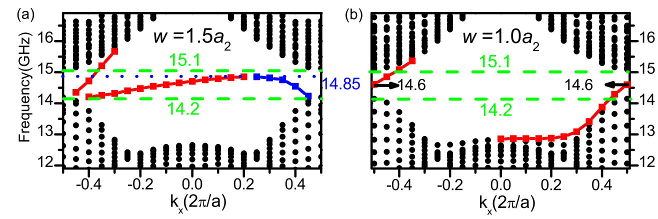

FIG. 4. (Color online) Calculated band structure of the one-way waveguide with a width of 1.5a_2 (a) and 1.0a_2 (b). The black solid circle denote the eigenmodes of the two PCs. The red symbol-lines represent the forward guided modes, and the blue ones are the backward modes.

We focused on the cavity resonance at 14.7 GHz and did more simulations of the field pattern as shown in Fig. 3. At the frequency, both the forward and backward wave can pass through the waveguide but the detailed field distribution of the modes is different [Figs. 3(a) and 3(b)], reflecting their different intrinsic characters. Although both the forward and backward wave can feed into the cavity, the coupling strength is different. The out-going wave from the cavity cannot maintain the same character as the incoming wave. It partially couples to both the forward and backward modes. Because of the coupling loss, the forward transmission is slightly decreased; meanwhile, the out-going backward mode from the cavity totally destructively interferes with the original backward wave and causes a deep transmission dip. Based on this asymmetric coupling mechanism, a *unidirectional band stop filter* is formed at 14.7 GHz [Figs. 3(c) and 3(d)]. As the cavity is very close to the waveguide, the band properties are seriously affected in the coupling process.[10] The one-way band gets wider and the cavity resonance frequency shifts from 14.72 to 14.7 GHz.

We change the size of the cavity by moving the rods with a small length of Δ. The transmission spectra change obviously and the resonance wavelength redshifts when a wider cavity is chosen, both seen in the forward and backward spectra, theoretically and experimentally. Unfortunately, the measured resonance frequency position in Figs. 2(b) and 2(d) does not fit exactly our calculation. This might be caused by the incomplete match of the YIG material properties adopted in the calculation with those in the practical materials used in experiment. However, the cavity mode is clearly observed at 14.80 GHz and confirmed by tuning the size of the cavity, and the one-way band widening is also verified in Fig. 2(d).

The band structure of the PC-GPC waveguide adopting a super-cell method was calculated and is shown in Fig. 4. For comparison, two waveguides with widths of 1.5a_2[Fig. 4(a)] and 1.0a_2 [Fig. 4(b)] are chosen. The 1.0a_2 waveguide only supports a one-way mode wave inside the whole common gap, where the group velocity of the waveguide mode maintains positive. In contrast, the situation is more complicated for the 1.5a_2 waveguide. Above 14.85 GHz, it still only supports one forward mode; whereas below 14.85 GHz the waveguide supports two forward modes and one backward mode, which is consistent with the transmission spectrum in Fig. 2. The left forward mode in Fig. 4(a) and the single mode in Fig. 4(b) obviously have the similar dispersion characteristic, due to their common origins from the CES. The CES has been transferred into the waveguide mode with the existence of the PC cladding, and its dispersion is also influenced by the interface.

When the waveguide is widened to 1.5a_2, more ordinary guided modes appear and the waveguide become two-way propagating in a certain frequency region. In principle, all the guided modes can be coupled with the cavity mode. However, the total destructive interference cannot be reached for all the guided modes with different dispersion relationships at the same time. In such an asymmetric waveguide lack of time-reversal symmetry, the band stop effect based on the total reflection will never happen in two directions simultaneously.

For a purely one-way waveguide (1.0a_2) coupled with a cavity, it is seen from Fig. 5(a) that the field inside the cavity is strongly enhanced, but the out-going wave has to go forward due to the absence of the backward channel. However, if another waveguide is connected to the cavity as shown in Fig. 5(b), a drop channel is built up for the one-way wave. In the upper waveguide, the electromagnetic wave does not go further than the cavity site and almost totally travels to the

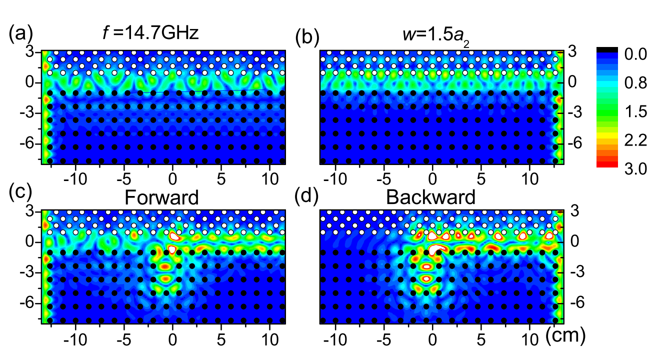

FIG. 3. (Color online) The electric field intensity distribution for the waveguide-cavity system at the resonance frequency of 14.7 GHz.

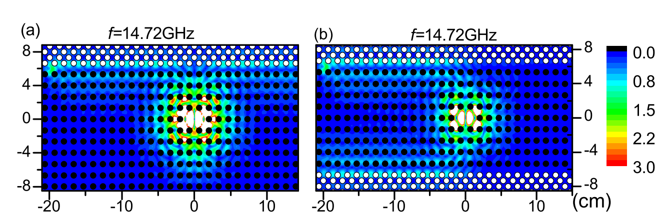

FIG. 5. (Color online) (a) The coupling between a cavity and a pure one-way waveguide (1.0a_2). (b) A channel-drop filter made from two unidirectional waveguides (1.0a_2) and a cavity.

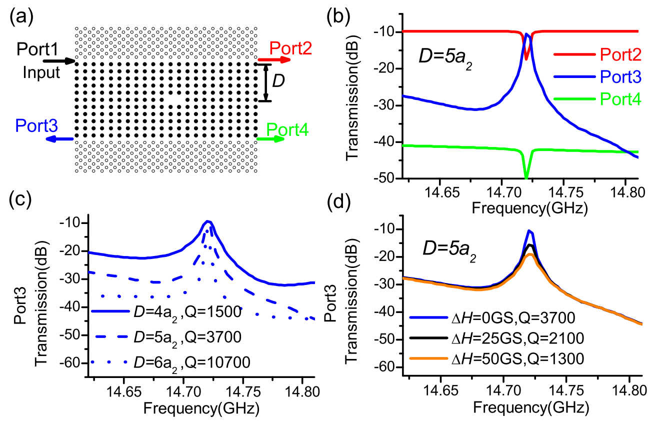

FIG. 6. (Color online) The calculated transmission spectra near the resonate frequency for the four port filter. (a) The schematic picture of the four-port CDF. (b) The relative transmittance of the three output ports; (c) Relationship of the Q factor with the thickness (i.e., D) of the cavity wall. (d) Influence of the material loss on the filter.

lower waveguide. This clearly shows that the pure one-way mode can be loaded by a cavity, and a *unidirectional CDF* is formed.

We further characterize the quality (Q) factor by calculating the transmission spectrum of a four-port filter [Fig. 6(a)] with the same configuration as Fig. 5(b). The results in Fig. 6(b) show that, away from the cavity resonance frequency, almost all the energy of the waveguide mode from port 1 flow to port 2. While at the resonance point of 14.72 GHz, most of the energy goes to port 3, and there is hardly any wave passing through port 4, for the wave toward port 4 of the lower waveguide is forbidden. A simple optimization for a larger Q factor was done by increasing the distance between the cavity and the waveguides. From Fig. 6(c), we can see the thicker of the cavity wall, the higher the Q factor of the filter, with a tolerable reduction in the drop efficiency.

The loss property of the ferrite was also taken into account in Fig. 6(d), which is of critical importance for application. Fortunately, our results indicate that for most commercial YIG product with a loss level of ΔH (resonance linewidth)[7,8,15] less than 50 Gs, the Q factor degrades not too much in our system. As seen in Fig. 7, the theoretical and experimental spectra have the similar line shape although the resonance point does not exactly fit. The Q factor is 700 in experiment and 1300 in calculation, which is sufficiently large for practical use.[17]

In summary, we have systematically investigated the side-cavity coupling property with nonreciprocal GPC

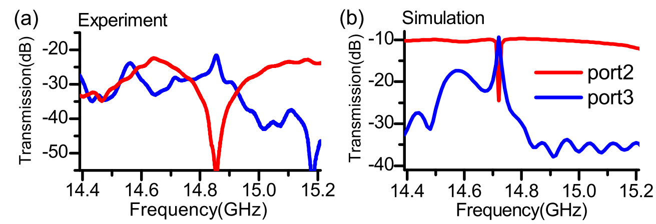

FIG. 7. (Color online) (a) Experimental and (b) calculated transmission spectra of the four port unidirectional CDF.

waveguides. A one-way channel-drop filter is proposed and realized based on the unidirectionality and robustness of the CES. The robust unidirectional wave can be downloaded by another one-way waveguide with the help of a coupling cavity. This opens up a window for further understanding of the unique one-way transport properties of GPCs and exploring their great power of controlling electromagnetic waves.

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