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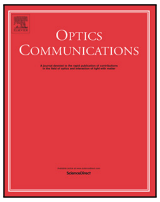

Surface wave resonance and chirality in a tubular cavity with metasurface design

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ABSTRACT

Optical microcavities with whispering-gallery modes (WGMs) have been indispensable in both photonic researches and applications. Besides, metasurfaces, have attracted much attention recently due to their strong abilities to manipulate electromagnetic waves. Here, combining these two optical elements together, we show a tubular cavity can convert input propagating cylindrical waves into directed localized surface waves (SWs), enabling the circulating like WGMs along the wall surface of the designed tubular cavity. Finite element method (FEM) simulations demonstrate that such near-field WGM shows both large chirality and high local field. This work may stimulate interesting potential applications in e.g. directional emission, sensing, and lasing.

1. Introduction

Optical microcavities have attracted much attention due to their potential applications in various fields, such as ultra-small optical filters, high-efficiency light emission diodes, low threshold lasers, nonlinear optics and quantum information processing [1–6]. Whispering gallery mode (WGM) resonators have attracted increasing interests due to their excellent performance and simple fabrication in geometry [7–9]. Via rolled-up technology, tubular WGM resonators show unique potential in both fabrication and application [7,10–14]. In a traditional WGM cavity, the propagating waves (PWs) of clockwise (CW) and counterclockwise (CCW) are coupled together and equal in their properties (e.g. amplitude, polarization and phase) in the presence of backscattering. However, the balance between CW and CCW can be broken due to explicit symmetry breaking, including asymmetrical scattering [15] and special cavity design [16,17], and spontaneous symmetry breaking, including optical nonlinearity [18,19]. Therefore, the chirality is commonly treated as the consequence from the difference between the CW and CCW components [15–17,19–22]. On the other hand, metasurface, formed by flat optical microstructures with carefully tailored radiation amplitude and phase distributions in subwavelength scale, has attracted great interest of photonic researches recently [23–32]. A reflection typed metasurface has been reported to be able to serve as a new bridge to convert a propagating wave to a surface wave (SW) with high efficiency, which is verified by experiments from microwave [33] to optical regimes [34].

Here, we propose a tubular cavity with metasurface design under the illumination of cylindrical electromagnetic (EM) waves excited from a line source inside at microwave regime. Replacing the wall of tubular cavity by metasurface, a chiral SW-based WGM resonance is achieved by our structure rather than conventional WGM resonance. The chirality of WGM is solely determined by the phase gradient provided by the designed metasurface. Moreover, we suggest a multilayer structure to guide the inner SWs flowing outside the tubular cavity, achieving higher conversion efficiency and quality factor (Q factor). These studies may inspire potential applications on the enhanced light-matter interactions.

2. Results and discussion

2.1. Structure and characteristic of tubular cavity

The general structure of our tubular cavity is shown in Fig. 1(a). A layer of metal is put at the outside of a dielectric tubular cavity, while various predesigned metallic blocks are put at inner surface of the tube. This metal–insulator–metal structure presents unique characteristic as metasurface. According to the previous research, the phase gradient is

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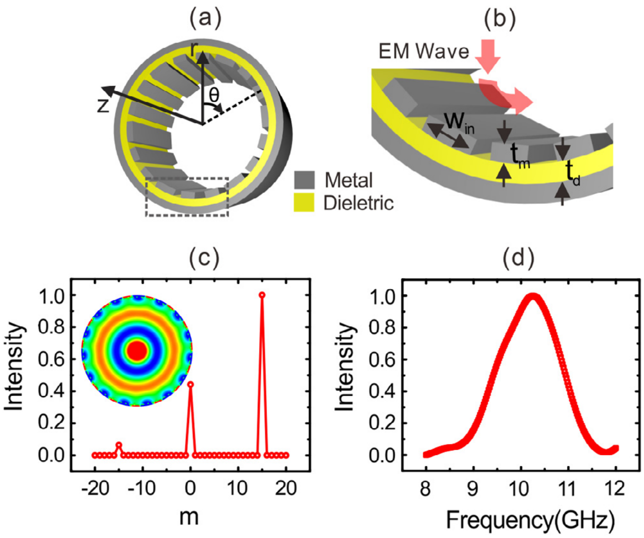

Fig. 1. General structure and characteristic of the tubular cavity with metasurface design. (a) Schematic diagram of tubular cavity. (b) The detailed structure of the supercell. Four metallic blocks are evenly distributed in a supercell. Here the length of the supercell is set as 20 mm. And the widths of metallic blocks w_{in} are set as 1.2 mm, 2.9 mm, 3.2 mm and 4 mm, respectively. And the thicknesses of the layers t_m and t_d are as 0.6 mm and 1.2 mm. (c) The calculated normalized angular momentum distribution at the working frequency $f = 10$ GHz of the tubular cavity. The positive and negative mode numbers correspond to CW and CCW components, respectively. The H_z field distribution is shown in the inset. (d) The average intensities around the inner surface of the tubular cavity at the working frequency $f = 10$ GHz.

designed as ξ in the metasurface [33]. Assuming that the metasurface is illuminated by the incident wave along the radial direction, it can be obtained that the tangential wave vector $k_t = \xi$. The cylindrical wave is produced by a transverse magnetic (TM) line source which was put at the center of the tube with the magnetic field along the axial direction.

The wall of tubular cavity is divided into 15 supercells. The detailed structure of a supercell is shown in Fig. 1(b). A supercell consists of a layer of dielectric between a metallic layer and a layer with four metallic blocks. The relative permittivity of the dielectric is set as $\varepsilon = 10$. The metal is considered as perfect electric conductor (PEC) at microwave regime and the relative permittivity is set as infinite. Since both thickness of the dielectric and width of metallic blocks have similar influences in the reflection phase, we set the thickness of the dielectric is fixed as $t_d = 1.2$ mm, and the thickness of inner and outer metal is $t_m = 0.6$ mm. The width of the metallic blocks w_in in one supercell are set as 1 mm, 2.9 mm, 3.2 mm and 4 mm, respectively, which satisfy $\Delta\Phi = \pi/2$. The detail design process of the metasurface is shown in the supplementary material (Part S1 and S2).

Since the outer metallic layer acts as PEC in the microwave regime, the EM field is confined inside the tube. Through FEM simulation, the H_z field distributions are obtained and plotted in the inset of Fig. 1(c). Comsol Multiphysics software is applied for the two dimensional simulation process. The boundary is set as perfect matched layer (PML) and mesh size is fine enough comparing to the size of metallic blocks (the maximal 8 mm and the minimum 0.01 mm). As revealed in the field distribution, the PW is converted to the directional SW along the surface. In addition, the SW is periodical, which exactly agrees with the number of periods of the metasurface, showing the feature of WGM. It is noted that the WGM here is a driven state since the SWs are not the eigenmodes of the metasurface and are produced by PWs inside every individual supercell. Different from the traditional WGM resonator, the EM wave in our tubular metasurface travels along the inner surface forming the driven-WGM rather than experiences totally reflection in the dielectric layer. Due to the predesigned phase gradient direction, the SW propagates in a specialized direction. As a result, the intensity of CW waves and CCW waves will be different, leading to the uni-chirality of the cavity.

By solving the Helmholtz equation, the wave functions inside the cavity can be expanded in cylindrical harmonics

$$\Psi(\rho,\varphi) = \sum_{m=-\infty}^{+\infty} a_m J_m(nk\rho)\exp(im\varphi), \tag{1}$$

where m is the quantum number of angular momentum. Parameter k is the wave vector. ρ and φ are coordinates in the polar coordinate system. J_m is the mth order Bessel function, and a_m is corresponding coefficient. The calculated normalized angular momentum distribution at the working frequency of the metasurface is plotted in Fig. 1(c). Positive and negative values of the angular momentum mode number m correspond to the CW and CCW propagating components, respectively. It is to be noted that the positive and negative values of the same azimuthal mode index represent same mode index of CW and CCW components along the inner surface, respectively. The intensity difference between the CW and CCW components indicates chirality in the cavity. Defining the chirality of the tubular cavity as

$$\alpha = 1 - \frac{\min\left\{\sum_{m=-\infty}^{m=-1}|a_m|^2, \sum_{m=1}^{m=\infty}|a_m|^2\right\}}{\max\left\{\sum_{m=-\infty}^{m=-1}|a_m|^2, \sum_{m=1}^{m=\infty}|a_m|^2\right\}}, \tag{2}$$

the chirality is approximately 0.935. Therefore, the intensity of CW component is much larger than CCW component, demonstrating that our structure can produce a chiral EM wave with high efficiency.

According to the field distribution, we could achieve the PW–SW conversion efficiency as approximately 80% since the radial modes formed by scattering loss.

As shown in Fig. 1(d), we obtain the average intensities around the inner surface of the tubular cavity. When the SW propagates along the surface and satisfies $2\pi R = m\lambda_{SW}$, it is similar to the PW in the normal WGM cavity and resonates at a certain frequency. Besides, the frequency should not only satisfy the tubular resonator but also be consistent with the working frequency of the metasurface. As a result, the WGM only exists when the mode number exactly equals to the number of periods. Since the phase gradient only exists at the specialized frequency, then the intensity increases greatly at the working frequency.

2.2. Structure and characteristic of tubular cavity based on transmission model

Considering that the SW based WGM is only a driven state under the illuminance of input EM wave, the SWs experience significant scattering between the supercells and leading to high loss and low conversion efficiency. Therefore, we replace the outside PEC by periodic metallic blocks to convert the SWs to be the eigenmode of the metasurface. It is also worthwhile to note that the distribution of transmission phase should be large enough to maintain the phase gradient when we lead the SW to the outside. Therefore, a multilayer structure is applied to expand the range of transmission phase, as shown in Fig. 2(a). The detail design process is shown in the supplementary material (Part S3). As a result, we set w_{in} in one unit as 0.2, 3.6, 3.2 and 4.5 mm respectively, while w_{mid} blocks are set in one unit as 1, 2, 4, 4.8 and 4.8 mm respectively, and w_{out} is set as 4 mm in every supercell for the chosen frequency 10 GHz. The thicknesses of metallic layers t_m are set as 0.6 mm, while the dielectric layers t_d are 1.2 mm. Applying such structure, the H_z field distribution is achieved through FEM simulation and plotted in Fig. 2(b). The field distribution also reveals WGM produced by the SW on the outer surface, which is similar to the reflection model. Besides, the EM wave travels around the outer surface of the tube as SW in certain direction, and the radiation loss is compressed. The PW–SW conversion is 98% due to the suppression of the radial mode formed by the scattering wave.

Similarly the wave functions inside the cavity can be expanded in cylindrical harmonics as

$$\Psi(\rho,\varphi) = \sum_{m=-\infty}^{+\infty} b_m H_m^{(2)}(nk\rho)\exp(im\varphi), \tag{3}$$