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

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\textbf{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 [23–52]. 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
The length of the supercell is set as 20 mm. And the widths of metallic blocks are set as 1 mm, 2.9 mm, 3.2 mm and 4 mm, respectively, which satisfy the range of transmission phase, as shown in Fig. 2(a). The detailed design process of the metasurface is shown in the inset. The average intensities around the inner surface of the tubular cavity at the working frequency of the metasurface. As a result, the WGM only 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 illuminate 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 $w_{out}$ 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

$$
\Psi (\rho, \varphi) = \sum_{am=-\infty}^{+\infty} b_{am} H_m^{(2)}(\kappa \rho) \exp(i m \varphi),
$$

(3)
where $H_{21}^{(2)}$ is the second kind $m$th order Hankel function. The normalized angular momentum distribution is plotted in Fig. 2(c). Strong chirality is represented due to the great contrast between the intensities in $m = 15$ and $m = -15$ modes. The calculated chirality is approximately 0.983 according to Eq. (2).

Fig. 2(d) shows the average intensity around the outer surface of the tube. This result shows that the SW propagates around the outer surface and forms a WGM cavity, showing the combination of the directional SW and the WGM cavity. The resonance frequency deviates from the working frequency for the coupling. The schematic structure is sketched in Fig. 3(a). Microwave can propagate along the mushroom structure in acting as functional plasmonic lasers.

3. Conclusion

To summarize, a tubular cavity with metasurface design is proposed, working at microwave regime. Under the illuminance of a cylindrical wave, the tubular cavity could couple the SW along its inner surface, achieving a SW-based WGM resonance. The predefined phase gradient of the metasurface leads to uni-chirality of the SW-based WGM. Moreover, we couple the inner SW flowing outside the tubular cavity by using designed metallic structures instead of the PEC layer and realize a SW-based WGM high $Q$ factor and high PW–SW conversion efficiency. Coupling mushroom structure to the tubular cavity, a SW-based WGM cavity is numerically demonstrated by FEM simulations. Therefore, combining both high $Q$ factor and strong chirality comparing to other WGM or flat structure, our results might stimulate potential applications in such as near-field sensing, functional plasmonic circuitry and lasers.

See supplementary material for the design of the tubular cavity and the robustness of chirality.
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Appendix A. Supplementary material

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.optcom.2018.02.011.

References