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Zhengji Xu and Landobasa Y.M. Tobing

School of Electrical and Electronic Engineering,
Nanyang Technological University,
Nanyang Avenue 639798, Singapore
Email: XUZJ@NTU.EDU.SG
Email: LTOBING@NTU.EDU.SG

Dawei Zhang*

Shanghai Key Laboratory of Modern Optics System,
School of Optics-Electrical and Computer Engineering,
University of Shanghai for Science and Technology,
516 Jungong Road, 200093 Shanghai, China
Email: DWZHANG@USST.EDU.CN

Dao Hua Zhang*

School of Electrical and Electronic Engineering,
Nanyang Technological University,
Nanyang Avenue 639798, Singapore
Email: EDHZHANG@NTU.EDU.SG
*Corresponding authors

Abstract: We propose a cogwheel structure formed by an air ring and equally distributed air cogs along the ring on a gold film for generation of surface plasmon polariton vortex. We show that a well-designed cogwheel can generate an optical vortex-like response and that the characteristics of such SPP vortex are directly related to cogwheel geometries and can be controlled by adjusting the polarisation direction of incident light.

Keywords: cogwheel; surface plasmon polariton; vortex; whispering gallery modes; WGMs; circular polarisation.

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Biographical notes: Zhengji Xu received BEng from Nanyang Technological University, Singapore, in 2010, where he is currently a PhD candidate in School of Electrical and Electronic Engineering. His research interests include plasmonics optics, metamaterials, nanofabrication, VCSEL and nanophotonics integration. He had authored more than 20 papers in the international journals and conferences.

Landobasa Y.M. Tobing received the MS and PhD from Nanyang Technological University, Singapore, in 2004 and 2010, respectively. His research interests and experiences include integrated optics, microring resonator, silicon photonics, electron beam lithography, nanofabrication, nanophotonic, plasmonic, and metamaterials. He has more than 40 peer reviewed publications, and also served as a reviewer of *Optics Express*, *Optics Letters*, *IEEE Photonics Technology Letters*, *Applied Physics A*, *Nanoscale Research Letters*, and *Journal of Vacuum Science and Technology B*.

Dawei Zhang received his PhD in Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences in 2005. He is a Professor in College of Optics and Electronics, University of Shanghai for Science and Technology. His research fields include gratings, guided mode resonance device and thin solid films.

Dao Hua Zhang received the MS from Shandong University, Jinan, China, and the PhD from the University of New South Wales, Kensington, Australia. He joined Nanyang Technological University, Singapore, as a Lecturer in 1991, where he is currently a Full Professor in the School of Electrical and Electronic Engineering and the Director of Photonic Nano-Structures and Application Program. His research interests include semiconductor materials and devices and photonic nanostructures and applications. He has published more than 370 papers in international journals and conferences, five books and proceedings, and three book chapters. He served as an Editor and a Guest Editor for nine international journals, including *IEEE Transaction on Nanotechnology*, *Journal of Crystal Growth* and *Thin Solid Films*. He also chaired and co-chaired several international conferences. He is a Fellow of the Institute of Physics.

1 Introduction

The ability for manipulating light with micro and nanoscale artificial structures become attractive for metamaterial studies [1–11], super-resolution imaging [12–18], optical trapping [19], low loss on chip waveguide [20,21] and transformation plasmonics [22,23]. The propagation of SPPs can be controlled by monitoring polarisation of the incident light [24] and nanostructure geometry [25]. Meanwhile, whispering gallery modes (WGMs) have been used to monitor light in various aspects, such as, realising compact laser [26], detecting light orbital angular momentum [27] and generating optical vortex beams [28]. It is believed that WGM for surface plasmon polaritons should also be able provide more flexibility for light manipulation. In this paper, we report design and study of Cogwheel structures that can generate SPP vortex beam and the direction of the vortex beam can be controlled by varying the circular polarisation of incident light.

2 Structure design and principles

Figure 1 shows the schematic of a cogwheel structure which consists of an air ring and some equally distributed air cogs along the outer circle of the ring formed on a metal film. The air cogs are also in circular aperture. With the addition of the cogs to the ring, angular perturbation is introduced and excitation of SPP WGMs in the structure becomes possible. As the cogs are equally distributed along the ring aperture, the distance between two neighbouring cogs and the radius of the ring are closely related to the coupling condition between the free-space incident light and the in-plane SPP waves, while the circumference of the ring is related to the resonance condition of the WGMs. For a ring with inner radius R and assuming SPP propagation constant β_{SPP}, and an azimuthal mode number p, the resonance condition for the WGMs can be written as

$$\nu_{\text{WGM}} = \beta_{\text{spp}} R = p. \tag{1}$$

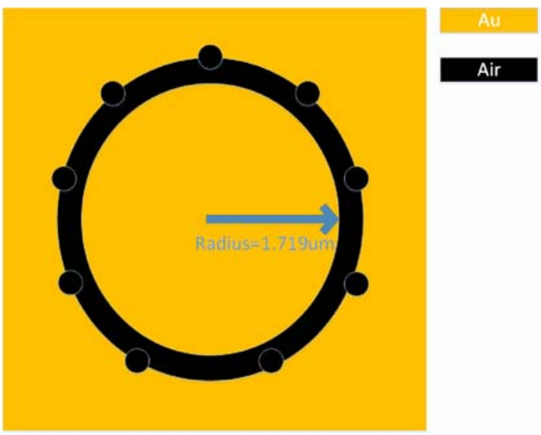
While the angular phase matching condition is

$$\nu_{\text{rad}} = \nu_{\text{WGM}} - gq = 0, \tag{2}$$

where q is the number of cogs, and g is an integer denoting the grating order that satisfies the phase match condition. The SPP propagation constant in a metal slot is denoted by $\beta_{SPP} = 2\pi/\lambda_{SPP}$, where λ_{SPP} is the SPP wavelength. For a circularly polarised beam of $\lambda = 633$ nm normally incident from the bottom of 200-nm thick gold film, the SPP wavelength is found to be λ_{SPP}~600 nm. If the azimuthal mode order p is taken as 18, then the corresponding to a ring radius of $R = p\lambda_{SPP}/(2\pi)$~1.719 µm.

Let us consider three cogwheel structures with $q = 9$, $q = 18$ and $q = 12$, respectively, for the fixed p of 18. For the first two structures, the angular phase matching conditions are satisfied with $g = 2$ (for $q = 9$) and $g = 1$ (for $q = 18$), respectively. In these two cases, SPP whispering gallery waves are excited in clockwise and counter clockwise directions, which is similar to the excitation of counter propagating SPP waves when light is normally incident on a grating. However, if the cogwheel structure is designed in such a way that no integer g can satisfy the phase matching condition, such as in the third structure where $q = 12$ (which corresponds to $g = 3/2$), the propagation characteristics of SPP WGM would depend strongly on the polarisation of incidence. The left/right circularly polarised light can also be denoted as positive or negative spin angular momentum (SAM) or spin state [29,30]: $|\sigma_{\pm}\rangle$, $\sigma_{+} = +1$ for the right circularly polarisation (RCP), and $\sigma_{-} = -1$ for the left circular polarisation (LCP).

Figure 1 Schematic of a typical cogwheel structure consisting of an air ring and a number of circular cogs equally distributed along the outer circle of the ring. The inner radius of the big ring is 1.719 µm, the ring slot is 200 nm wide and the diameters of the cogs are100 nm (see online version for colours)

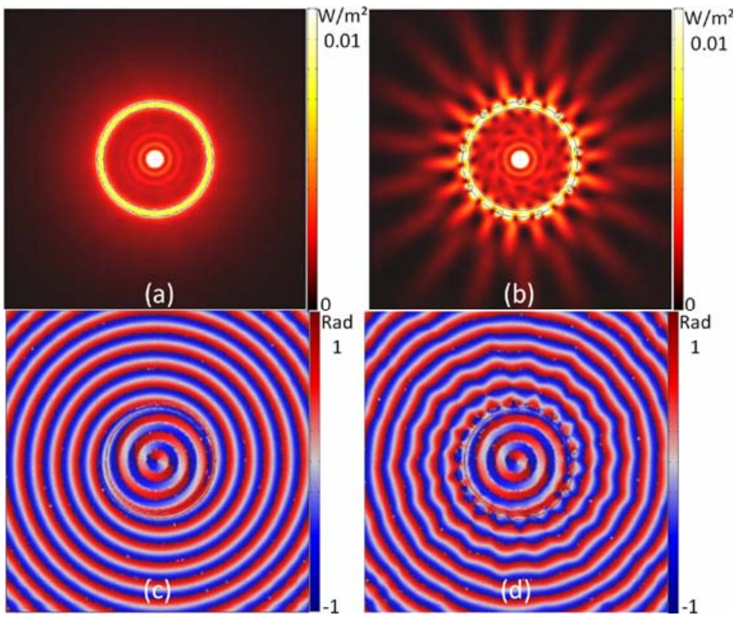


3 Simulations and discussions

Numerical simulations were carried out by finite element method (COMSOL Multiphysics), where permittivities of gold is taken as $\varepsilon_{\text{Au}} = -9.586 + 1.18i$ (at $\lambda = 632.8$ nm) [31], and both the slot width and gold film thickness are set to 200 nm. The scattering boundary condition was used owing to its accuracy and efficiency. The generalised minimal residual method (GMRES) is chosen for matrix inversion owing to its rapid convergence and short calculation time.

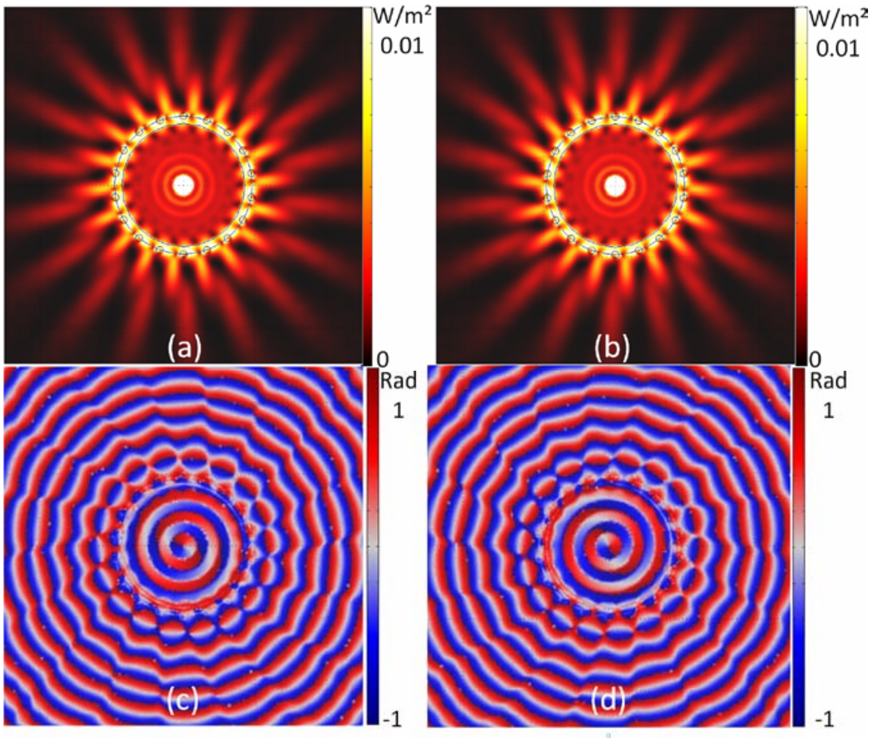
Figure 2 shows the power distributions and phase responses of a ring (a) and (c), and a cogwheel with nine equally distributed cogs (b) and (d), when they are illuminated with right circularly polarised (RCP) light at normal incidence. Here, the phase response (θ) is used to illustrate the wave front of the excited SPPs, which is obtained from the phase response of longitudinal electric field (E_z), i.e., $\theta = \arg(E_z)$. As expected from the circular symmetry of the ring aperture, the radial counter-propagating SPP waves are excited [Figure 2(a) and (c)]. It is interesting to note that the wave front is of spiral shape. This is attributed to the circular polarisation of the incident beam that excites SPP at different direction at different delays, causing the wave front to lag along with the ring circumference. Equally interesting is that the spiraling direction is determined by the orientation of the circular polarisation, as will be shown later in Figure 3. The spiraling is clearly seen at the inner side of the ring aperture while it is less prominent at the outer side where the SPP waves appear more as radial waves. It should be noted that the spiral phase response resembles the phase of optical vortex beam [28]. In terms of power distribution [Figure 2(a)], most of the light is confined in the slot, while some are localised at the centre of the ring owing to standing wave patterns.

Figure 2 Power distributions in the structure surface plane with right circularly polarised incidence for (a) a ring aperture and (b) a cogwheel with 9 equally spaced gears. (c) and (d) are the normalised phase graph for (a) and (b), respectively (see online version for colours)



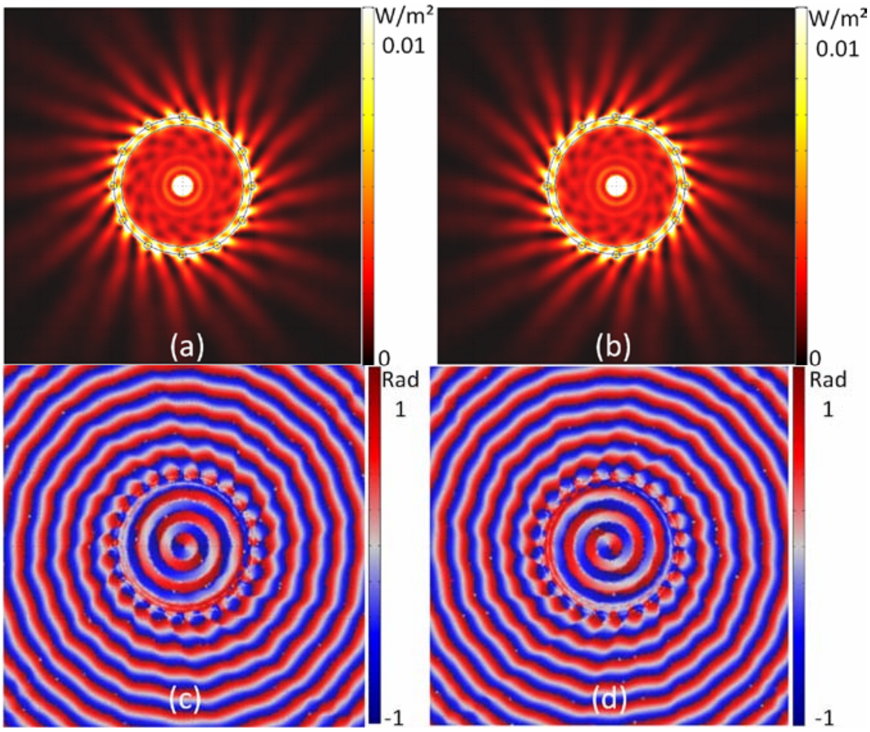
The characteristics of such optical vortex-like response can be changed by introducing angular perturbations. In the cogwheel with $q = 9$, when angular grating is introduced into the ring aperture. There will be the excitation of azimuthal SPP waves with resonance condition dependent on the cog pitch. The interference between radial waves (from ring aperture) and azimuthal waves (from the cogs) gives rise to azimuthal lobes, as shown in Figure 2(b). There are 18 azimuthal lobes from both power distribution and phase response, confirming that the SPP WGM is of the mode number of $p = 18$, as expected from our design ($R = 1.719$ μm). The resonance condition for $q = 9$ is satisfied at $g = 2$ (see equation (2)), which denotes the grating order of 2. The efficiency can be further increased by decreasing the grating order, for example by having 18 cogs ($q = 18$) such that the resonance condition at the first grating order ($g = 1$). Figure 3 shows the power distribution and the phase response of cogwheel structure ($q = 18 = p$) excited under two circularly polarised light. The azimuthal lobes are clearly stronger than those in Figure 2(b). In addition, the phase responses (of both circular polarisations) show that the SPP WGM extends more outward compared with the case of $q = 9$, where the spiraling direction directly depends on whether the light is RCP or LCP.

Figure 3 Characteristics of cogwheel with $q = 18$ under right circularly polarised ($\sigma = +1$) and left circularly polarised ($\sigma = -1$). Power distribution for $\sigma = +1$ (a), and $\sigma = -1$ (b). Phase distribution for $\sigma = +1$ (c), and $\sigma = -1$ (d) (see online version for colours)



We now look at the case when the grating order is not an integer. Figure 4 shows the power distribution and phase responses of the cogwheel structure with $q = 12$, where the resonance condition is satisfied when $g = 3/2$. The number of SPP lobes is increased to 24, double the number of cogs. When the g is an integer, the excited SPP waves from cogs constructively interfere with each other along the circumference of the ring aperture, making SPP WGMs. This is in agreement with the fact that the number of SPP lobes is the same as the mode number ($p = 18$). Since the SPP propagation direction depends on the direction of the longitudinal electric fields, each cog excites SPP waves with direction dependent on incident polarisation. Thus, for integer g, the constructive interference is dominant along the ring aperture, while for non-integer g, the constructive interference is satisfied outside the ring aperture. Figure 4(a) and (b) show a rather skewed SPP lobes distribution in contrast to radically symmetric SPP lobes in integer g (Figures 2 and 3). It is also expected to see that the skew of the SPP lobes is dependent on the circular polarisations of the incident light. The normalised phase plots for RCP and LCP light are shown in Figure 4(c) and (d), respectively. The direction of SPP vortex is clearly seen both along the ring slot and at the centre of the cogwheel structure. For both RCP and LCP incidence, the direction of the SPP vortex is the same as that of the incident circular polarisation at the centre of the cogwheel, while it is the opposite in the ring slot.

Figure 4 Power distributions in the structure surface plane with $q = 12$, (a) $\sigma_+ = +1$ or right circularly polarised (RCP) incidence, (b) $\sigma_- = -1$ or left circularly polarised (LCP) incidence, (c) and (d) are normalised phase graph for (a) and (b), respectively (see online version for colours)



4 Conclusion

We proposed and theoretically studied cogwheel structures for SPP vortex generation. The characteristics of the excited SPP waves can be changed by controlling the interference between the radial and azimuthal SPP waves, which are, respectively, contributed by the ring slot and the angular grating of the cogs. Furthermore, the spiral phase response resembles the properties of an optical vortex, which are controllable by the incident circular polarisation. We believe that the cogwheels presented here can provide additional flexibility in light manipulation and be of potential application in photonics devices such as high speed optical switch, plasmonic circuit integration and optical tweezers.

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