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Plasmonic toroidal excitation with engineering metamaterials

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ABSTRACT

Natural toroidal molecules, such as biomolecules and proteins, possess toroidal dipole moments that are hard to be detected, which leads to extensive studies of artificial toroidal materials. Recently, toroidal metamaterials have been widely investigated to enhance toroidal dipole moments while the other multipoles are eliminated due to the spacial symmetry. In this talk, we will show several cases on the plasmonic toroidal excitation by engineering the near-field coupling between metamaterials, including their promising applications. In addition, a novel design for a toroidal metamaterial with engineering anapole mode will also be discussed.

Keywords: Toroidal dipole, Metamaterials, Surface plasmon, Non-radiating anapole mode.

1. INTRODUCTION

Toroidal dipole is an independent term in the family of electrodynamic multipole expansion that was first proposed in 1957 to interpret the parity non-conservation in nuclear physics [1]. It is associated with a term $\vec{r} \cdot \vec{j} \neq 0$, where $\vec{r}$ and $\vec{j}$ are position vector and current induced by external stimuli, respectively and hence toroidal dipole is naturally different from the electric and magnetic multipoles ($\vec{r} \times \vec{j} \neq 0$). Normally the toroidal dipolar response is neglected from the other electromagnetic multipoles because of its much weaker far-field scattering field intensity. Recently, plasmonic metamaterials and metasurfaces have been widely proposed for enhancing and manipulating electromagnetic field through artificial structures at the sub-wavelength scale [2-6]. These abilities provide a way to design toroidal dipolar response as the dominate term in the electromagnetic response. For instance, by structural or excitation optimization, the intensity of toroidal dipole can be enhanced while the other electromagnetic multipoles are eliminated [7]. Not long time ago, toroidal metamaterial was first theoretically proposed and experimentally verified at microwave region [8]. The toroidal resonances have also been pushed to optical frequencies with metallic and dielectric metamaterials [9, 10]. In general, to excite a toroidal dipole, it is required to have poloidal surface currents, producing magnetic dipoles within a coil and forming a circulating current [11]. However, this is difficultly to be excited by an optical far-field illumination. Recent developments in toroidal metamaterials employ specific illumination directions and methods, such as radially polarized light or local electron dipolar modes for the generation of toroidal dipoles [12, 13]. In addition to the isolated toroidal response in artificial media, the coupling effect of toroidal and electric dipoles has been explored to yield non-radiating anapole mode, which was first demonstrated in microwave [14]. In terms of the destructive coupling between toroidal and electric dipoles, dynamic anapole mode can lead to optical response with high quality factor for nonlinear signal enhancement (eliminated far-field radiation with strong near-field confinement) [15, 16]. The resonant wave-band of anapole mode is further pushed to visible light by using dielectric disk. However, the produced toroidal dipole moments via aforementioned approaches are embedded in dielectric that limits the practical usages in the interaction with molecules. In the meantime, most of the published results shown the toroidal dipole moments are perpendicular to the surface of the metamaterials, which hinders the observation of toroidal dipolar signal. The success of observing the non-radiating anapole mode in a single dielectric nanoparticle clearly demonstrated the poor flexibility of manipulation

of anapole modes for further applications of toroidal metamaterials. For the feasible applications of the toroidal metamaterials, the key is to generate transverse toroidal dipole moments available at free space which can be coupled with external objects at the sample surface.

Here, we present a novel design and experimental demonstration of a toroidal metamaterial with multilayered structures of dumbbell-shaped aperture on a nano gold film and a nano vertical split-ring resonator (VSRR) as shown in Fig. 1(a). The direction of induced toroidal dipole, depicted by red arrows, show aligned parallel to the surface of the structure. This design overcomes the challenge in detecting the scattering of the induced toroidal dipole and provides a possibility of coupling with other dipolar moments in free space. Figure 1(b) shows an example of toroidal dipole radiation pattern in a toroidal metamaterial unit cell, in which one can find that it is identical to the electric dipole. The identical radiation patterns in electric and toroidal dipoles can lead to an interesting phenomenon when they have identical scattering field intensity but π phase shift. Such destructive interference resulting in the so-called anapole mode with strong near-field intensity since the far-field radiation is eliminated, as shown in Fig. 1(c). It is particularly noticeable that the resonant wavelength of both toroidal dipole and non-radiating anapole mode can be tuned through the change of distance between designed nano-structures. To our best knowledge, this is the first proof-of-concept demonstration of anapole mode through specifically designed plasmonic coupling nanostructure that offers a flexible way for the design and investigation of optical properties with complicated electromagnetic fields.

Figure 1. (a) Schematic for toroidal metamaterial consists of gold slab of dumbbell-shaped apertures and VSRRs underneath separated by a dielectric spacer. The red arrows and the streamline show the direction of induced toroidal dipole and the magnetic field distribution on the yz -plane, respectively. (b) Illustration of an toroidal dipole (red arrow and inset) induced by cascading magnetic dipoles within a unit cell. The current of each magnetic dipole is depicted by cyan circulating arrows. (c) Non-radiating anapole mode induced when the toroidal dipole is anti-parallel overlaid with an electric dipole (inset). The charges of electric dipole are shown by red spheres in an instant scheme. The color mesh from red to blue shown in (b) and (c) represents decreased radiation intensity. The radiation intensity in (c) is much weaker than that of (b) because of the deconstructive interference of electric and toroidal dipoles.

2. OPTICAL PROPERTIES OF PLASMONIC DUMBBELL-SHAPED APERTURE

The optical property of a single dumbbell-shaped aperture is shown in Fig. 2. The incident electric field (along x -axis) interacts with the dumbbell-shaped aperture will induce a pair of anti-clockwise current oscillation and create a pair of anti-parallel magnetic dipole, as shown in Fig. 2(a). Both the toroidal dipole and high order magnetic multipoles (especially the magnetic quadrupole) can be realized with such anti-parallel magnetic dipoles. In fact, the toroidal dipolar response and magnetic quadrupole can be selected by taking the interaction with another pair of anti-parallel magnetic dipole into consideration, as shown in Fig. 2(b). Figure 2(c) shows the numerical spectra of the dumbbell-shaped aperture under x -polarized illumination. Both the reflectance and transmittance spectra can be calculated through scattering parameters (S-parameters) which are commonly used for the examination of far-field response of plasmonic metamaterials. The scattering power [Fig. 2(d)] is calculated via induced current on the metamaterials to realize the contribution of each electromagnetic multipole to the far-field radiation. As expected, both the toroidal dipole and magnetic quadrupole dominate the spectra at certain wavelength region, resulting in the resonant characteristic in the far-field spectra shown in Fig. 2(c). By summing the contribution from all multipoles enables us to retrieve the optical spectra. This can be derived and compared with the results obtained directly from the numerical solution of S-parameters shown in Fig. 2(c). Results show a perfect match between two approaches, and the contribution from all electromagnetic multipoles are involved.

Figure 2. (a) Left: Schematic for the dumbbell-shaped aperture. The feature sizes of metallic structures: $P_x = 400$ nm, $P_y = 850$ nm, $R = 130$ nm, $D_x = 50$ nm, $D_y = 60$ nm. Right: relation between incident fields and a 30-nm-thick dumbbell-shaped aperture. (b) Dipolar configuration for magnetic quadrupole and toroidal dipole. (c) Simulated spectra via S-parameters (solid lines) and electromagnetic multipole expansion (dots). (d) Calculated scattering power for each electromagnetic multipole.

3. OPTICAL PROPERTY OF THE TOROIDAL METAMATERIALS

In order to enhance the toroidal dipole signal and suppress the other multipoles, a vertical split-ring resonator (VSRR) is introduced to break the configuration symmetry of magnetic quadrupole. The VSRR has been proposed to generate a

strong magnetic dipolar response under normal illumination when the incident electric field is parallel to its opening gap [17-19]. This mainly arose from the induced circular current oscillation on the surface of VSRR, as shown in the inset of Fig. 3(a). The toroidal metamaterial therefore is turned into a multilayer structure comprises dielectric spacer sandwiched in between a VSRR and a metallic dumbbell-shaped aperture. By optimizing the coupling effect between the dumbbell-shaped aperture and VSRR, a toroidal dipole is induced and oscillating along x -axis with a close-loop magnetic field. This characteristic can be found in Figs. 3(a) and 3(b) which show a reflection/transmission dip/peak at certain wavelength. The resonant feature exhibits a red-shift as the gap size increased. Here, the gap size indicates the distance between the bottom surface of dumbbell-shaped aperture and the top surface of VSRR. The far-field response calculated via electromagnetic multipole expansion also shows a similar behavior, showing again the good agreement between two approaches. The field distribution is subsequently performed to verify aforementioned discussions, as shown in Figs. 3(c) and 3(d). As expected, a close-loop magnetic dipolar response is generated at resonant wavelengths, revealing the excitation of toroidal dipole. The streamline of magnetic field further confirmed this optical property and consequently concentrate the electromagnetic energy at the waist of the aperture.

Figure 3. (a) Reflection and (b) transmission spectra for toroidal metamaterials as a function of gap size. White and light-green dots indicate the reflection dip and transmission peak carried out from electromagnetic multipole expansion. Inset: Schematic for the toroidal metamaterial. The red arrows among the structures indicate the induced magnetic dipole and surface currents, respectively. Simulated (c) magnetic fields and (d) energy density distribution at toroidal dipole resonant wavelength (gap size = 50 nm). Purple lines: streamlines of magnetic field. Inset: Schematic for the observation plane, which is marked as a transparent plane, of Figs. 3(c) and 3(d).

The scattering power of electromagnetic multipoles at around 1350 nm demonstrates its resonant feature corresponds to the toroidal dipolar response, as shown in Fig. 4(a). Importantly, the intensity of other multipoles, especially the magnetic quadrupole is significantly reduced at resonant wavelength because of the presence of VSRR. In addition, the elimination of far-field radiation due to the cancellation between electric and toroidal dipolar radiation is also observed in our system. According to Fig. 4(a), the two leading contributions of radiation power around 1400 nm are electric and toroidal dipoles, which are out-of-phase and therefore attribute a sharp resonant dip in Fig. 4(b) while the total scattering from electric and toroidal dipoles exhibits a maximum level at toroidal dipolar resonance. These two dipolar modes can

only interfere destructively when the phase of radiation field has π phase shift with identical scattering amplitude, resulting in a single resonant dip in total scattering power spectrum although there are two crossovers between electric and toroidal dipolar modes in Fig. 4(a). It, called anapole mode, therefore leads to a strong near-field enhancement with neglected far-field radiation. The near-field intensity and scattering cross section support that both the toroidal and anapole modes can be observed in our system. Because the similar radiation pattern with electric dipole, the near-field intensity shows a maximum level at toroidal dipole wavelength. On the other hand, the scattering cross section performs a minimum level at the anapole mode (shown in Fig. 4(c)), revealing the completely destructive interference. We presume the shift of the maximum of near-field intensity is due to the structural asymmetry, which can be avoided by optimizing the structural configuration. The anapole mode can also be tuned by changing the coupling effect, that is, the gap size between structures, as shown in Fig. 4(d).

Figure 4. (a) Scattering power of electromagnetic multipoles when gap size is 50 nm. (b) Total scattering power (black curve) and phase difference (red dots) from electric and toroidal dipole. (c) Far-field scattering cross section (orange curve) and electric field intensity at the center of dumbbell-shaped aperture (olive curve). (d) The anapole resonant wavelength with different gap distance between VSRR and dumbbell-shaped aperture.

4. CONCLUSIONS

In summary, both the toroidal moment and anapole mode can be generated by our novel multilayer plasmonic metamaterials via the near-field coupling between a VSRR and a dumbbell-shaped aperture. This is the first artificially designed, fabricated, and measured coupled metamaterial with transverse toroidal moment and anapole mode in optical region. The unique structural configuration supports the transverse toroidal dipole for interacting and coupling at the surface. The similarity of radiation patterns of toroidal and electric dipoles provides the availability of destructive

interaction for far-field radiation. Such strong local near-field enhancement from transverse toroidal dipole offers a promising way for the development of meta-devices with locally nonlinear response and generation of complex electromagnetic fields.

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