Journal of Physics: Conference Series

PAPER • **OPEN ACCESS**

Toroidal dipolar excitations in all-dielectric nanostructures

IOP Conf. Series: Journal of Physics: Conf. Series **1461** (2020) 012191 doi:10.1088/1742-6596/1461/1/012191

Toroidal dipolar excitations in all-dielectric nanostructures

Lei Xu[1], Reza Masoudian Saadabad[1], Marcus Cai[2], and Andrey E. Miroshnichenko[1*]

[1]School of Engineering and Information Technology, University of New South Wales, Canberra ACT 2600, Australia

[2]Nonlinear Physics Centre, Research School of Physics and Engineering, The Australian National University, Canberra ACT 2601, Australia

E-mail: `andrey.miroshnichenko@unsw.edu.au`

Abstract.
We have numerically investigated toroidal dipolar excitation at optical frequencies in Si nanostructures. Our results show that, through either special structured pump illumination, or by adding an additional layer associated with geometric tuning, we are able to excite strong toroidal dipolar responses with suppressed electric dipolar excitations. These findings may further pave the way to exploit future applications of toroidal resonances including optical nonlinear enhancement, induced transparency for narrow-band filter, etc.

1. Introduction

The toroidal multipoles are considered as complementary set of electromagnetic sources in addition to the familiar electric and magnetic multipoles. They can be visualized as the currents flowing on the surface of a torus, where array of magnetic dipoles originating from poloidal currents are arranged in head-to-tail configuration along the torus[1]. In recent years, toroidal multipoles have attracted a significant attentions due to their ability to induce many unique electromagnetic phenomena such as unconventional optical activity[2], resonant transparency[3], anapole state[4] which is led by the destructively interference between a radiating toroidal dipole mode and electric dipole mode. Furthermore, as compared to electric and magnetic dipoles, toroidal dipole mode offers weaker electromagnetic scattering which could lower the radiative loss and enhance light-matter interactions.

Here, take Si nanodisks as an example, we numerically investigate excitations of toroidal dipolar responses in dielectric nanostrucutres through two approaches: i) using structured pump illumination composed of a radially-polarized beam in conjunction with a plane wave, and ii) adding an additional thin layer to enhance the toroidal responses and meanwhile suppress the electric dipole responses through the near-field interactions.

2. Results and discussions

The first configuration of the proposed toroidal dipolar excitation is shown in Figure 1(a), where a focused radially-polarized (RP) beam with numerical aperture 0.86 illuminates a Si nanodisk of radius 100nm, thickness 108 nm placed at the focal point. Efficient excitation of toroidal dipole

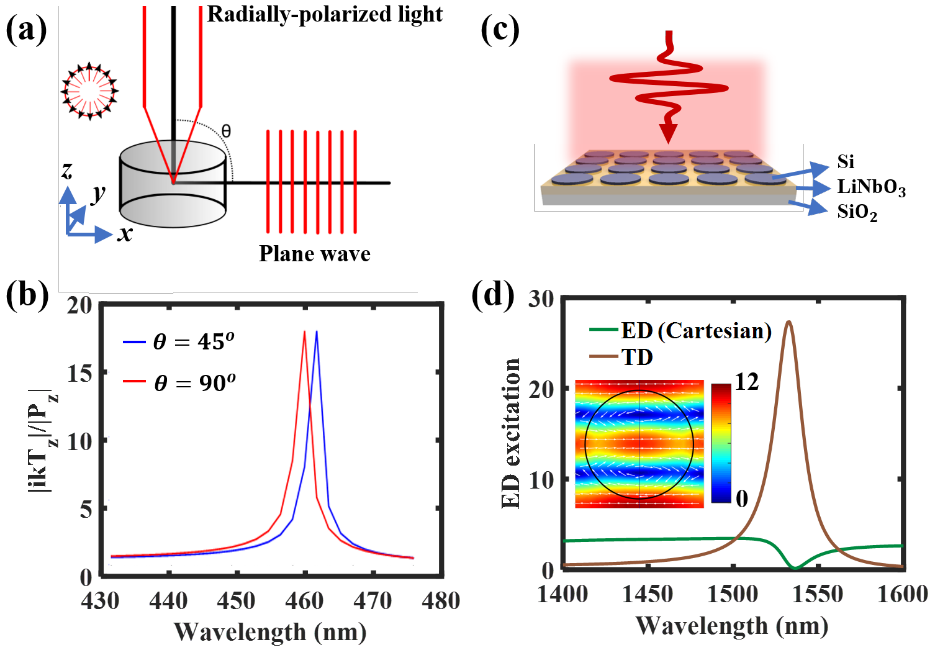

Figure 1. (a) Dielectric Si nanodisk is illuminated by two time-delayed beams: a focused RP beam followed by a linearly-polarized beam. (b) Calculated ratio between the contribution of toroidal dipole and electric dipole moments excited through the Si nanodisk. (c) Schematic illustration of Si-$LiNbO_3$-SiO_2 metasurface under linear-polarized plane wave normal incidence. (d) Calculated Cartesian electric dipole and toroidal dipole mode excitations. (ED) in the designed nanostructures. The radius and thickness of Si disk is 360nm, 60nm, respectively, and the periodicity of metasurface is 840 nm. The inset shows the electric near-field distributions on the interface between the Si nanodisk and $LiNbO_3$ layer.

mode can be expected due to the large spatial overlap between the electric fields of the RP beam and the toroidal dipole mode supported by the Si nanodisk. Our simulation shows that it is able to further increase the toroidal responses and meanwhile suppress the electric dipole response by adding another plane wave illumination. Figure 1(b) gives the calculated ratio of the electric and toroidal dipole moments of the nanodisk as a function of light wavelength for two incident angles (plane wave) 45^o and 90^o, respectively. One sees that through such configuration, it is able to excite strong toroidal dipolar response with negligible ED response.

Alternatively, we can also achieve strong toroidal dipolar responses with suppressed ED by designing special nanostructures which support strong toroidal responses and suppress other multipolar responses. As an example, here we add an additional 200-nm-thickness $LiNbO_3$ layer beneath Si nanodisk metasurface, as shown in Figure 1(c). In such configuration, through the near-field interactions between the electric fields in the Si nanodisk and $LiNbO_3$ layer, strong toroidal contribution is expected from such well-designed metasurface (Figure 1(d)). It manifests a strong electric near-field enhancement, which provides a novel method to significantly enhance the nonlinear process through low-index materials as $LiNbO_3$.

3. Conclusions

In summary, we have numerically investigated the excitation of toroidal dipole responses through dielectric nanostructures. We found that the strength of toroidal dipole moment can be enhanced with suppressing electric dipole responses when using a RP beam in conjunction with a plane

IOP Conf. Series: Journal of Physics: Conf. Series **1461** (2020) 012191 doi:10.1088/1742-6596/1461/1/012191

wave illumination on a Si nanodisk. Furthermore, *pure* toroidal dipole excitation can be achieved by designing Si-$LiNbO_3$-SiO_2 metasurface which supports strong toroidal responses and suppress other multipolar responses. Our findings may further boost future research of toroidal resonances such as nonlinear generation, sensing, etc.

References

[1] N. Papasimakis, V. A. Fedotov, V. Savinov, T. A. Raybould, N. I. Zheludev 2016 *Nat. Mat.*, 15: 263–271, 2016

[2] T. A. Raybould, V. A. Fedotov, N. Papasimakis, etc 2016 *Phys. Rev. B: Condens. Matter Mater. Phys.*, 94, 035119.

[3] W. Liu, J. Zhang, and A. E. Miroshnichenko, 2015 *Laser Photonics Rev.*, 9(5), 564-570.

[4] A. E. Miroshnichenko, A. B. Evlyukhin, Y. Yu, etc 2015 *Nat. commun.*, 6, 8069.