Various multipole combinations for conical Si particles

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Abstract. In this work, we investigated the possibility of creating various multipole combinations in conical silicon nanoparticles. It was found that in conical silicon particles it seems possible to create key effects for nanophotonics, such as various kinds of Kerker effects (Generalized Kerker, Transverse Kerker), Hybrid anapole state, Bound states in the continuum. This greatly simplifies the manufacturing process of photonic devices due to the easier production of nanocones in practice. Also, conical particles allow an additional degree of freedom, which opens up new horizons for obtaining previously unknown effects.

1. Introduction
In recent years, an increasing number of scientific studies have been devoted to areas in which subwavelength dielectric nanoparticles are used. The fact is that such particles can be used to create various kinds of devices, the characteristics of which either significantly exceed the characteristics of existing ones, or even open up the possibility of creating a new class of devices. Their undeniable advantage lies in their high efficiency and relatively easy production. There are a lot of examples of the use of devices based on dielectric nanoparticles: nanolasers [1], nanoantennas [2], metamaterials [3] and metasurfaces [4], ultrathin lenses [5], detectors [6] and other equally interesting applications [7,8].

A huge impetus to the development of high-index dielectric nanophotonics was made by opening the possibility of separate control of multipole excitations in scatterers and, as a consequence, combining multipole moments to obtain various effects [9–12].

Thanks to this possibility, it became possible to obtain the Kerker effect, which was originally introduced for a hypothetical magnetic sphere and did not attract the attention of researchers [13]. Now, the Kerker effect has been significantly expanded thanks to the capabilities of dielectric nanophotonics, where it became possible to obtain a magnetic moment in small particles. An excellent example for this is the generalized Kerker effect, which allows one to obtain resonant excitation and interference of various electromagnetic multipoles [14–18] or transverse Kerker, characterized by transverse isotropic scattering by subwavelength nanoparticles with simultaneous suppression of both forward and backward scattered fields [19].

Another important discovery related to multipole combinations is the possibility of obtaining a hybrid anapole state (HAS) of nanoobjects. It is possible to create a metasurface from such nanoobjects, which will have many useful properties, for example, a zero phase shift of a light wave when passing through a metasurface, almost complete light transmittance, the ability to apply such a metasurface on various types of substrates [20]. This opens up incredible opportunities for creating various kinds of devices for flat optics.
Devices using bound states in the continuum (BIC) also play an important role in the development of dielectric nanophotonics. The flexibility that quasi-BICs has brought to the design and implementation of high Q resonances in nanophotonic systems has made them very useful to the nonlinear photonics community. BICs have so far been used to amplify a variety of nonlinear effects, including optical Kerr effect, laser action, second and third harmonic generation, and four-wave mixing. Thanks to BIC, lasers, harmonic generating devices, optical fibers, beamforming devices, etc. can be created [21].

All of the above cases were presented for particles with elementary geometry, for example, on spheres or cylinders, but, for example, frustoconical scatterers are currently poorly studied, although this geometry has many advantages.

Due to the additional degree of freedom in the form of the upper radius, unpredictable new effects may appear that have not been investigated before.

Another important advantage of the geometry of the cones is that the practical production of elements for photonic devices has not yet been perfected. For example, in the process of fabricating such scatterers, it is practically impossible to obtain a perfectly flat nanocylinder with the given parameters. It is much easier in practice to create a truncated cone.

Thus, this work is devoted to the study of the optical properties of the scatterer in the form of a truncated cone, the search for cases that are inaccessible to standard geometries, and testing the obtained results.

2. Results and discussion

Figure 1 shows a schematic drawing of the model for which mathematical modeling was carried out. As a scatterer, a silicon nanocylinder was taken from which, by changing the upper and lower radii, height and wavelength, various combinations of multipoles were obtained (a). Distributions for the far-field were plotted (c,e) for conical silicon particles, which were confirmed by theoretical combinations of multipoles for a point (b,d).

![Figure 1](image_url)

Figure 1. Artistic representation of the considered silicon particle composed of nanocylinders (infinite nanostructure illuminated with the linearly polarized plane wave) (a), theoretically far-field distributions of different combinations of multipoles for point (b,d) and simulated far-field distributions of different combinations of multipoles for conical silicon particles.
It can be seen that by varying the parameters of conical silicon particles, we managed to obtain various combinations of multipoles, for example, the usual Kerker (c) and generalized Kerker effect (e). In the report we will show other possible combinations and unusual effects enabled by the truncated cone shape via separate tailoring of different multipoles.

3. Conclusion

Thus, this work is devoted to the extensive tutorial study of the optical properties of truncated conical nanoscaters. In this work, various optical effects are obtained by tuning the parameters of the fabrication-friendly resonators - conical silicon scatterers. This opens up new possibilities for the production of photonic devices based on such shape of nanoscaters. Also, conical particles allow an additional degree of freedom, which opens up new horizons for obtaining previously unknown effects.

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