Nontrivial invisibility induced by optical hybrid anapole

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Abstract. The novel hybrid anapole states supported by dielectric nanoparticles are associated with the condition when all the dominant Cartesian multipoles interfere destructively with their corresponding toroidal counterparts. They are characterized by a negligible light scattering for any observation direction. In the current work, we have proven the existence of high order hybrid anapole states in the visible range, resulting in a drastic reduction of the scattered radiation from a cylindrical nanoparticle with dimensions comparable to the wavelength. We demonstrate it by expanding the numerically calculated scattering cross section of the nanoparticle in terms of the Cartesian multipole decomposition. The simulations illustrate the simultaneous resonant suppression of the four leading multipole contributions to radiation (e.g. electric and magnetic dipoles and quadrupoles). Our results confirm the possibility to observe the effect experimentally, paving the way for future applications in dielectric nanophotonics.

1. Introduction

The growing field of all-dielectric nanophotonics is based on the exciting properties of high index dielectric nanoparticles exhibiting both electric and magnetic resonances with very low absorption [1][2][3]. Their applications range from lossless waveguides [4,5] and nanoantennas [6], to cloaking devices, nonradiating configurations [7][8][9],[10], and different metasurfaces[11][12][13][14].

Cloaking techniques and devices have been extensively studied in order to make an object invisible. Currently, several cloaking approaches have been explored, the most popular among them being scattering cancellation techniques and Transformation Optics (TO), along with a few other interesting proposals [15][16].

Their difficult experimental realization prove TO cloaks to be unreliable solutions in many practical situations. On the other hand, scattering cancellation cloaking methods work well for small subwavelength scattering sources, but designs become increasingly complex with the size of the object [15].

Nevertheless, it has been shown that an isolated dielectric scatterer can also display fundamental nontrivial invisibility states at specific resonant wavelengths, without the need of additional cloaking layers. The line-shape of the resulting scattering cross section can then be described in terms of the Fano resonance. In particular, resonant Mie scattering of an infinitely long dielectric rod can be presented through cascades of Fano resonances [17][18].

A greater physical insight into the nature of these scattering-free resonances can be obtained by interpreting them in terms of overlapping radiationless current configurations, the so-called anapole states [19][20]. In the mathematical framework of Cartesian multipole expansions, electric (magnetic)
anapole states of n\textsuperscript{th} order are a consequence of destructive interferences between the scattered fields of the n\textsuperscript{th} order electric (magnetic) irreducible multipole moment and their corresponding electric (magnetic) toroidal counterparts. Additionally, it should be mentioned that a different theoretical study \cite{21} has investigated anapole states in terms of fundamental Fano-Feshbach resonances of an open cavity resonator.

A previous work \cite{22}, already showed theoretically the possibility to excite simultaneously the first order magnetic and electric anapole states in the case of a spherical geometry. However, the higher order moments strongly radiate to the far field, thus destroying the invisibility effect.

In the present work, using COMSOL Multiphysics \textregistered, we have numerically proven the existence of high order hybrid anapole states in the visible range for cylindrical geometries. We have expanded the scattering cross section of an isolated nanoparticle using the irreducible Cartesian multipole decomposition \cite{23}. In order to obtain suitable conditions for an experimental realization of the effect, a numerical model has also been developed for the case of the nanoparticle deposited on a glass substrate.

2. Results and discussion

In the context of this work, anapole states are a consequence of the destructive interference between the scattered far fields of electric (magnetic) irreducible Cartesian multipoles and their toroidal counterparts, sharing the same far field pattern \cite{9}. The condition for their mutual cancellation can be written as \cite{9}:

$$P_{i_1...i_n} \frac{ik}{v_d} T_{i_1...i_n} = 0$$  \hspace{1cm} (1)

Where $P_{i_1...i_n}$ is an element of the n\textsuperscript{th} order irreducible Cartesian electric or magnetic multipole moment, $k$ is the wavenumber of the incident field, $v_d$ is light speed in the medium surrounding the scatterer and $T_{i_1...i_n}$ is an element of the toroidal moment associated with the n\textsuperscript{th} order electric or magnetic multipole term. Analytical expressions for high order toroidal moments up to the electric octupole were recently derived in \cite{9}.

![Figure 1](image_url)

**Figure 1.** (a) Multipole decomposition (dashed lines) of the total scattering cross section of the nanocylinder (solid lines), explained in the text. (b) Electric field map of the x-component (perpendicular to the cylinder axis). The panel shows the scattering suppression at the hybrid four-anapole mode ($\lambda = 630$nm). Inset of panel (a) depicts schematically the simulated scatterer geometry and the exciting wave setup; $h=300$nm and $R=100$nm.

A hybrid anapole state can be obtained when condition (2) is fulfilled for all leading multipole moments of the scatterer in a narrow spectral range, resulting in a strong decrease in far field radiation. In order to demonstrate the low scattering properties of hybrid anapoles, we consider the experimentally
realizable case of an isolated, subwavelength cylindrical nanoparticle illuminated by a normally incident plane wave (inset of Figure 1(a)), made of polycrystalline Si [15].

By fine tuning the aspect ratio of the cylinder and analyzing the evolution of the excited multipoles, it is possible to achieve a hybrid anapole in the visible spectral range. Figure 1 (a) shows the partial contributions of each multipole to the scattering cross section for the cylinder in vacuum, close to the hybrid anapole state. The sum of the individual contributions is in full agreement with the total cross section calculated with COMSOL Multiphysics© (solid grey line in Figure 1 (a)).

A remarkable Fano-like dip in the scattering cross section, centered at \( \lambda = 630 \text{nm} \), can be observed at the hybrid anapole wavelength. Four multipoles, e.g. the electric dipole and quadrupole, magnetic dipole and quadrupole, are excited in the cylinder upon the incident wave. As it can be seen from their respective contributions, all four of them interfere destructively, greatly minimizing radiation to the far field.

The latter fact is confirmed in Figure 1 (b), where we report the calculated electric field distribution at the point of minimum total scattering. An almost complete suppression of scattering takes place; the incident light traverses the cylinder without an appreciable perturbation of its wavefront, making the nanoparticle virtually invisible from any angle of observation.

3. Conclusion
In a summary, our results demonstrate a weak scattering in the optical range induced by a hybrid anapole state, consisting of four overlapping anapoles originating from different terms in the Cartesian multipole expansion of the fields. The Fano-like shape of the hybrid anapole has its local maxima close to its local minima, which may allow fast optical switching from invisibility to visibility states [25].

Furthermore, suppression of all dominant scattering channels results in field confinement inside the nanoparticle. Engineering of these energy hotspots might provide them useful for nonlinear optics applications in the future.

More importantly, the conventional geometry utilized will allow the future experimental implementation of our design. The present work is a relevant example of the potential that irreducible Cartesian expansions offer to tailor at will and understand the scattering properties of individual dielectric nanoparticles.

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