Invisibility cloaking via Fano resonances

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Abstract

We demonstrate analytically that the characteristic Fano lineshape observed in the Mie scattering by high-index dielectric nanoparticles leads to a dramatic suppression of scattering giving a birth to a novel cloaking mechanism for invisibility at any angle of observation. We verify these concepts numerically and also experimentally, by switching a water cylinder from visible to invisible regimes when its dielectric permittivity is changed by heating.

1. Introduction

Scattering of electromagnetic waves by small particles, the so-called Mie scattering, is a well-known phenomenon that makes a particle visible to an outside observer (Fig. 1a). Here we demonstrate that at special condition the Mie scattering can be negligible leading to a novel mechanism of the invisibility cloaking. Our analysis is based on the recent results that the resonant Mie scattering from high-index dielectric nanoparticles is represented by cascades of Fano resonances [1]. Fano resonance takes place when a narrow-band radiation of virtually any origin is superimposed onto a radiation with a broad spectrum [2], and it is observed across many different branches of physics including nanostructures and photonic crystals [3, 4, 5, 6].

In order to describe interference between a narrow band and a broad-band radiation manifested in an asymmetric profile in the observed frequency spectrum, Ugo Fano derived a simple expression [1],

\[ I(\omega) = \frac{(q + \Omega)^2}{1 + \Omega^2}, \]  \hspace{1cm} (1)

where \( q \) is the Fano asymmetry parameter, \( \Omega = (\omega - \omega_0)/(\Gamma/2) \), while \( \omega_0 \) and \( \Gamma \) correspond to the position and width of the narrow band radiation spectrum, respectively. Recently, we have demonstrated [1] that the scattering by each individual Mie resonance can be described by the Fano formula (1). Our analysis is based on the analytical Mie solution of Maxwell’s equations for light scattering by spatially homogeneous bodies of revolution. We have found that the Lorenz-Mie coefficients \( a_n \) [7] of the Mie solution are genetically expressed as infinite series of Fano functions as they describe interference between two scattering channels with the Mie modes as narrow bands. For the sake of simplicity, the consideration below is limited by the two-dimensional case of the Mie scattering by an infinitely long dielectric cylindrical rod. However, the proposed approach is rather general, and it can be generalized to other systems and higher dimensions.

2. Fano resonance and invisibility cloaking

The scattering efficiency of a dielectric rod

\[ Q_{\text{sc}} = \frac{2}{x} \sum_{n=-\infty}^{\infty} |a_n|^2 \]  \hspace{1cm} (2)

(where \( x = 2\pi r/\lambda \) is the dimensionless size parameter and \( r \) is the radius of the rod) demonstrates an infinite series of peaks of strong scattering and also a series of dips [1]. According to Eq. (1), the Fano profile corresponds to the amplitude vanishing at some frequency \( \omega = \omega_0 - q\Gamma/2 \). At \( q = 0 \) we have a symmetric Lorentzian dip at the resonance frequency \( \omega = \omega_0 \) (Fig. 1b). When the Fano parameter \( q \) deviates from zero, the Fano lineshape becomes asymmetric and zero-intensity frequency becomes shifted away from the resonance \( \omega_0 \). Thus, the characteristic Fano lineshape leads to the suppression of scattering for the electromagnetic waves of a given polarization at fixed frequencies.

Figure 1: (a) Schematic of the scattering geometry. Plane wave is scattered by a dielectric cylinder. (b) Fano lineshapes depending on the sign and value of the Fano parameter \( q \).
3. Numerical and experiment results

Existence of dips in the scattering efficiency spectrum $Q_{sca}$ (see Fig. 2a) provides a spectacular effect on the diffraction patterns. We calculate numerically the distribution of the magnetic field $H_z$ in Fano-cloaking regimes ($x = 0.505$) and strong Mie scattering regime for the rod with dielectric permittivity $\varepsilon = 60$, see Figs. 2(b-e). We observe practically complete suppression of scattering at the frequency corresponding to the dip at $x = 0.505$. This means that an incident light with the TE polarization passes through the rod without scattering, and the rod becomes invisible from any observation angle. We notice that at $x = 0.505$ we have strong Mie resonances inside the rod and the $H_z$ field is inhomogeneous.

To verify these results experimentally, we use a water cylinder characterized by dielectric constant of $\varepsilon = 80$ at $20^\circ\text{C}$ degree and $\varepsilon = 50$ at $90^\circ\text{C}$ at frequency 1-6 GHz in the microwave frequency range. Figure 2(a) shows strong suppression of the experimentally measured microwave scattering from a finite-length water cylinder around the special frequencies demonstrating an excellent agreement with our analytical results. Strong temperature dependence of the water dielectric permittivity $\varepsilon$ leads to the pronounce shift of both scattering maxima and minima. Therefore, the proximity of the maxima and minima of the Fano profiles in the frequency scale allows us switching the water cylinder from the regime of strong Mie scattering ($T = 90^\circ\text{C}$) to the regime of invisibility cloaking ($T = 50^\circ\text{C}$) at the same frequency of 1.9 GHz.

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References


