Observation of Fano Resonances in All-Dielectric Heptamers

Katie E. Chong\textsuperscript{1*}, Ben Hopkins\textsuperscript{1}, Isabelle Staude\textsuperscript{1}, Andrey E. Miroshnichenko\textsuperscript{1}, Jason Dominguez\textsuperscript{2}, Manuel Decker\textsuperscript{1}, Dragomir N. Neshev\textsuperscript{1}, Igal Brener\textsuperscript{2} and Yuri S. Kivshar\textsuperscript{1}

\textsuperscript{1}Nonlinear Physics Centre, The Australian National University, Canberra, ACT 2602, Australia
\textsuperscript{2}Center for Integrated Nanotechnologies, Sandia National Laboratory, Albuquerque, New Mexico 87185, United States
*corresponding author, E-mail: katie.chong@anu.edu.au

Abstract

While Fano resonances in nanoparticle clusters have been predominately studied in the plasmonic area, the recent observation of magnetic resonances in low-loss dielectric nanoparticles suggests that Fano resonances are achievable in all-dielectric nanoparticles. Here we study light scattering by all-dielectric heptamers composed of silicon nanoparticles. We observe pronounced Fano resonances driven by magnetic modes as well as their tuning behaviour when the diameters of the heptamers’ central particles are systematically varied. The experimental results show good agreement with numerical calculation based on the coupled electric and magnetic dipole approximation.

1. Introduction

Fano resonances have attracted a great deal of interest in the recent decade due to their sharp asymmetric lineshapes and sensitivity to structural and environmental parameters [1–4]. These features give Fano resonance promising nanophotonics applications, such as sensing [5–7] and optical switching [8, 9]. Numerous plasmonic nanostructures have been studied and fabricated with successful experimental observation of Fano resonances driven by electric modes [2, 10]. However, plasmonic nanostructures, including metallic nanoparticle heptamers, suffer from a significant amount of non-radiative loss from the visible to the mid-infrared spectral region. This motivates research into low loss, high-refractive-index all-dielectric materials. Recent experiments have shown strong magnetic resonant responses from subwavelength all-dielectric particles in the spectral region of interest [11–16]. These observations now open up a new route for creating Fano resonances in nanoparticle clusters.

Fano resonances in all-dielectric nanoparticle clusters have not been demonstrated experimentally so far. Nevertheless, high-refractive-index all-dielectric heptamer nanophotonics structures have been predicted to exhibit Fano resonances due to interference of their optically-induced magnetic eigenmodes [17,18]. Here we verify this prediction by studying experimentally the optical response of silicon heptamer structures consisting of seven nanoparticles: six nanoparticles arranged in a ring-like fashion and one central nanoparticle. We observe pronounced Fano resonances as predicted, as well as a redshift of the resonance as the diameter of the central nanoparticles is systematically increased.

2. Results and Discussions

Experimentally, we realize arrays of heptamers consisting of silicon nanodisks using electron-beam lithography on silicon-on-insulator wafers followed by reactive-ion etching of the top silicon layer. Four different sets of heptamer structures with various central nanodisk diameters are fabricated. Scanning electron micrographs of single heptamer structures are shown in Fig. 1.

We measure linear-optical transmittance spectra of the heptamer arrays with normally incident light using a custom-built white light spectroscopy setup with an optical spectrum analyser. These results are presented in Fig. 1(b)
as extinction cross-sections \( \sigma_{\text{ext}} \), using the relationship to transmittance \( T \) given by the first order approximation to the Beer-Lambert Law,

\[
\sigma_{\text{ext}} \propto (1 - T).
\] (1)

Fano resonance in these structures is associated with a resonant suppression or a dip in the extinction [17] as indicated by the arrows in Fig. 1(b) and Fig. 1(c) in the shaded region. Importantly, a systematic red-shift of the Fano resonance can be observed as the diameter of the central nanoparticles increases.

The existence of the Fano resonance and its lineshape together with its tuning behaviour agree qualitatively well with numerical calculations [see Fig.1(b)] based on the coupled electric and magnetic dipole approximation [19], while the quantitative discrepancy is primarily due to the approximate modelling of the nanodisks as pairs of electric and magnetic dipoles in the numerical calculation. Other minor contributions to the discrepancy include sample imperfections, influence of the substrate and non-zero interaction between various oligomers in the sample arrays.

To understand the interference of modes in the heptamer structure, we need to look at the calculated extinction spectra in terms of the structure eigenmodes. As can be seen in Fig. 2(a), the magnetic contribution to the extinction spectrum is responsible for the overall Fano lineshape while the electric component plays no role in it. Therefore, analysis of only the magnetic eigenmodes is sufficient.

Fig. 2(b) shows a decomposition of the three heptamer magnetic eigenmodes. The raw sum i.+ii.+iii. of the mode amplitudes shows that in the artificial case where mode interaction is absent, the Fano dip is missing. Here, we notice that the Fano lineshape in extinction seen in Fig. 2(a) occurs at the intersection of the resonance curves of the two magnetic eigenmodes denoted by i. and ii. in Fig. 2(b), indicating that the Fano lineshape arises from the interference of these two resonant eigenmodes.

The dipole distribution of the three eigenmodes in Fig. 2(c) can be used to further explain the central nanoparticle size dependent tuning behaviour seen in Fig. 1(a) and Fig. 1(b). The resonant mode denoted by i. is heavily localized at the central particle, making it very sensitive to a variation of \( d_2 \). Whereas, the mode denoted by ii. is less concentrated at the central particle. Mode ii. is therefore not significantly influenced by a variation of \( d_2 \). The combination of these two effects therefore results in the observed easily traceable tuning characteristics of the Fano resonance.

3. Conclusions

We have, for the first time to our knowledge, experimentally observed magnetic Fano resonances in high-refractive-index all-dielectric heptamers composed of silicon nanodisks. Our results agree with the numerical calculation performed using the coupled electric and magnetic dipole approximation, showing a systematic tuning behaviour of the Fano resonance as the central nanoparticle diameter varies. Our coupled-mode analysis confirms that the observed Fano resonances indeed originate from interference between two optically-induced magnetic modes of the collective heptamer structure. Our results show that Fano resonances originated from magnetic modes in all-dielectric heptamers are very sensitive to geometrical variations, and hence have the potential for a variety of nanophotonics applications, such as sensing in conditions not compatible with the use of metals or plasmonic materials.

Acknowledgement

This work was performed, in part, at the Center for Integrated Nanotechnologies, an Office of Science User Facility operated for the U.S. Department of Energy (DOE) Office of Science. Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy’s National Nuclear Security Administration under contract DE-AC04-94AL85000.

References


