Optical properties of symmetric oligomers: polarization-independent Fano resonances and polarization-dependent hot spots

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Abstract

For a number of years the relationship between the discrete rotational symmetry of a nanoparticle oligomer and the guarantee of polarization-independent transmission has been solidifying, even if this relationship has been explained rigorously only recently. However the extension of this concept to include polarization-independent Fano resonances in oligomers is less well-recognized. Here we will rigorously address the subject of polarization-independent Fano resonances by introducing the mechanisms of symmetry responsible for polarization independence in oligomers and demonstrate how they are able to encompass Fano resonances. This analysis is then further able to provide insight into the use of polarization to offer non-trivial control over the near field distribution and hot spots of symmetric oligomers, despite the associated invariance of the far field transmission and all radiative and dissipative losses.

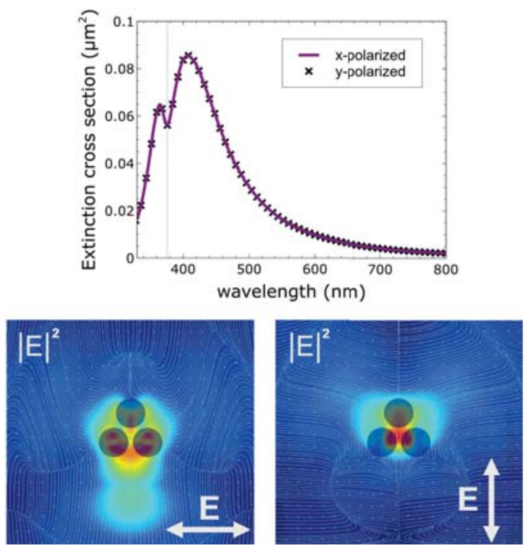

Figure 1: Simulation of a silver nanosphere trimer under plane wave exciation showing polarization-independent extinction cross sections (top) despite substantial variation of the near field with polarization (bottom). Near field profiles were calculated at the Fano resonance wavelength (marked).

1. Introduction

Here we will disucss the effect of the incident field's polarization on oligomer systems. The linear combination of eigenmodes that describe an incident field with a particular polarization is - by default - unique, because the system's eigenmodes form a linearly-independent basis. Subsequently the eigenmodes that are excited by an incident field must change with polarization to guarantee this uniqueness. It could therefore be expected that a Fano resonance, which arises from the interference between these eigenmodes, would be dependent on polarization. In fact it could further be expected that the general response of a symmetric oligomer will vary with polarization. However this is in direct contrast to a recent proof that polarization-independent responses can be enforced with discrete rotational symmetry about the axis of field propagation [1] - a result that has also been observed many times in experiments.

Here we will reconcile these two views in terms of the mode degeneracy that is due to the geometrical symmetry of the oligomer. We will show that Fano resonances in all symmetric oligomers will be independent of the incident field's polarization. However we will also highlight a further consequence of mode degeneracy; substantially polarization-dependent hot spots and near field profiles despite invariant far field measures such as extinction and total dissipative losses (see Figure 1). Why this unintuitive behavior should be expected can then addressed by considering the interference patterns produced by superpositions of degenerate eigenmodes. An experimental demonstration of how polarization can be used to control hot spot location in an oligomer while maintaining excitation efficiency is then also provided. The work presented here subsequently provides a robust method for designing isotropic behaviour into nanoparticle oligomers whilst further allowing the uti-

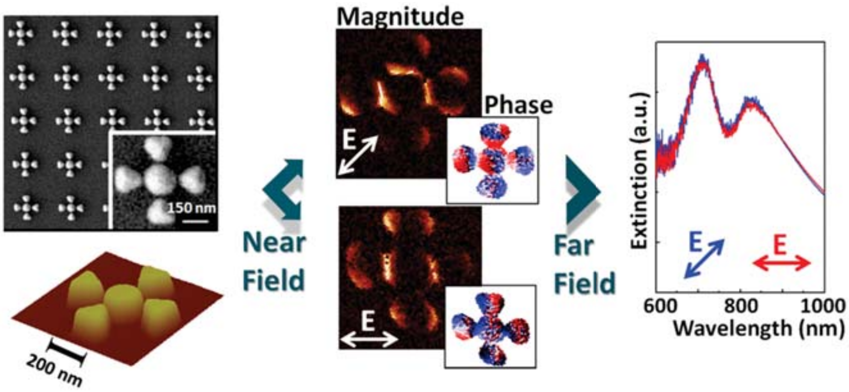

Figure 2: Figure taken from ref. [2], showing (left to right); the fabricated gold pentamer oligomers, the near field electric field magnitude and phase distributions and the extinction spectra for two polarizations. It can be seen that the extinction spectra do not depend on polarization despite the variation of the near field.

lization of polarization to tailor the near field distribution of these structures. In doing so, we are also able to offer better understanding of the underlying mechanisms which lead to the polarization-independence of oligomer Fano resonances.

2. Discussion

The symmetry of nanoparticle oligomers is an effective tool for determining the type and number of eigenmodes that can be excited by a plane wave, particularly when the plane wave is incident normal to the oligomer. The standard definition for symmetric nanoparticle oligomers will, in most cases, be referring to oligomer geometries that transform according to the D_{nh} symmetry group, where $n \geq 3$. In terms of the D_{nh} group, the polarization of a normally-incident plane wave will transform according to the E_1' (E_{1u}) irreducible representation for odd (even) n. We will refer to this representation as simply E from here onwards. Because the incident field polarization transforms according to only one irreducible representation, only eigenmodes that are associated with this particular irreducible representation (E) can be excited by a normally-incident plane wave. Conveniently, the number of such "excitable" eigenmodes in a given oligomer system has a precise analytical solution [3] and, importantly, this number is always greater than or equal to two, which thereby permits modal interference and Fano resonances. However, in regard to polarization, the important feature of these excitable eigenmodes is that they are each associated with a two-dimensional irreducible representation and subsequently each must have a two-dimensional eigenspace. That is to say these eigenmodes must each be doubly-degenerate. Subsequently such eigenmodes will have a degree of freedom analogous to a polarization. In this sense it is possible to define orthogonal x- and y-type degenerate eigenmodes for each *non-degenerate* eigenmode that can be excited by a plane wave. In other words, each non-degenerate eigenmode is associated with a two-dimensional eigenspace that can be spanned by two orthogonal and degenerate eigenmodes, which we can define such that they are excited by x- and y-polarized plane waves respectively. A consequence of this is that the magnitude of excitation of each non-degenerate eigenmode is conserved when changing the incident field polarization and, instead, only the eigenmode's effective polarization is varied. As such, far field features such as Fano resonances do not depend on incident field polarization, however the interference pattern of the constituent x- and y-type degenerate eigenmodes makes the near field distributions highly dependent on incident field polarization. This behavior then has further been observed experimentally [2] in a gold pentamer oligomer geometry, the results of which can be seen in Figure 2 .

3. Conclusions

The effect of polarization on the scattering of nanoparticle oligomers has been considered through a systematic investigation of the symmetries present in such oligomers. It has been shown that the total radiative and dissipative losses (extinction, scattering and absorption cross sections) can protected by discrete rotational symmetry and are thereby independent of polarization. The extension of this understanding to polarization-independent Fano resonances has also been provided. Finally it has further been shown that the variations of the near field can be controlled by polarization - despite the invariance otherwise present in the oligomer's optical response.

References

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