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Dark and bright mode hybridization: From electric to magnetic Fano resonances

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ABSTRACT

The excitation of plasmonic Fano resonances leads to a dual advantage in nano-photonics, in terms of local field enhancement and far-field spectral selectivity. Nevertheless, a remarkable challenge related to the hybridization between bright and dark plasmonic modes, *i.e.* between the two elements cooperating to the Fano resonance generation, consists in the sub-wavelength activation of dark modes *via* near-field channel. In this regard, strongly coupled plasmonic nano-assemblies are ideal systems providing a highly efficient way towards their excitation. Here, we analyze two trimer nano-architectures supporting respectively electric and magnetic Fano resonances. The different approaches employed for describing the two systems highlighted the role that the near-field coupling and the LSPs de-phasing separately play in the Fano hybridization phenomena.

1. Introduction

Plasmonic hybridization in sub-wavelength systems has recently revealed unconventional electromagnetic (EM) properties, which result from the combination of strongly radiative bright modes (*super-radiant*) and spectrally sharp dark plasmons (*sub-radiant*) [1–3]. The near-field coupling of dipolar and multipolar plasmonic modes can produce characteristic spectral signatures in far-field read-out [4], generally ascribed to interference phenomena [5]. Around the spectral position of a dark mode, the scattering efficiency can experience an abrupt suppression related to the activation of a *plasmonic Fano resonance* [5,6]. The sharpness of these spectral modes finds wide applications in bio-sensing [7–9], metamaterial engineering [10,11] and nanometrology [12], while the high field enhancement factors associated to the Fano resonances are employed in non-linear spectroscopic investigation/detection, *e.g.* SERS [13–17] and SEIRA [11,18]. Moreover, the spatial distributions of the Fano resonant hot-spots inside the plasmonic gaps make the spectral response of these systems very sensitive to the slightest variations in the dielectric environment [7]. Few percent changes in molecule concentrations can induce extremely small differences in the refractive index of a solution (around 10^{-3}) and conventional plasmonic resonances could not perceive this kind of environmental fluctuations. Nevertheless, it is experimentally documented how the surrounding sensitivity of Fano resonances can reach shift values up to 1000 nm/RIU (Refractive Index Unit) [19]. This unique property conferred by the sharpness of sub-radiant modes allows the detection of ultra-small molecule concentrations *via* linear spectroscopy [7,19].

From a more innovative point of view, the capability of properly tailoring the Fano current distributions in coil-type configuration can lead to magnetic-like resonances [20,21]. The possibility of having access to the weak magnetic properties of matter would open fascinating scenarios in the fields of high-resolution imaging and sensing [22] for bio-applications. In spite of the high potentialities presented by the Fano resonance, the excitation of this particular hybridized mode is subject to strict constraints (*e.g.* near-field coupling between bright and dark modes and phase retardation, *i.e.* de-phasing, among current distributions in the single nanostructures). Under Fano excitation, the de-phasing among localized surface plasmons (LSPs) converts the global charge density from a super- to a sub-radiant configuration, opening a near-field transition channel between bright and dark modes [2]. This phenomenon, usually hindered in sub-wavelength systems, can be promoted by *ad-hoc* symmetry breaking processes [4,23] which introduce retardation effects among charge oscillations. When the sub- and super-radiant resonances are properly tuned, the dark and bright modes are efficiently coupled *via* near-field channel and the Fano "signature" clearly appears in the scattering cross-section. Therefore, the LSPs de-phasing (retardation) and the dark/bright modes spectral ovelapping are both essential key-points for the study of Fano resonances.

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In this work we theoretically analyzed how these aspects are separately involved in the excitation of Fano resonances. We considered two trimer nano-assemblies in which we could control respectively the dark resonance position and the LSPs retardation (de-phasing), clarifying the role that these two parameters play in the super- and sub-radiant mode hybridization.

2. Results and discussion

A possible approach to tailor the far-field response of a plasmonic architecture consists in combining elemental sub-systems, each of them presenting a dipolar behavior [23,24]. The rod-like nanoantenna is one of the simplest systems, which can be adopted for the realization of strongly coupled nano-assemblies. The dipolar LSP supported by this nanostructure is characterized by two electric lobes which spread out from the apexes of the rod (Fig. 1(a), panel i). If we consider an aligned nanoantenna dimer (Fig. 1(a), panel ii), we can hybridize two dipolar LSPs oscillating in out-of-phase condition. The resulting mode presents a negligible dipolar moment and for this reason can be denoted as dark (sub-radiant). In terms of local field enhancement it behaves similarly to a bright mode (see Fig. 1(a), panels i and ii), but it is endowed with a lower level of radiative dissipation [24].

Exploiting the hybridization capability of strongly coupled plasmons, we investigate a T-shape trimer (Fig. 1(a), panel iii) consisting of a single rod-like structure of length $L=200$ nm (see Fig. 1(a), panel i) combined with an aligned nanoantenna dimer presenting two arms of length l (see Fig. 1(a), panel ii). The distance between the adjacent apexes of the perpendicular antennas (inter-particle gap) has been set equal to 10 nm. Due to the system configuration (*i.e.* incoming electric field parallel to the symmetry axis of the T-shape trimer – Fig. 1(a), panel iii), – it is possible to make the trimer interact with the external radiation exclusively *via* the single nanostructure. In fact, by polarizing the light parallel to the single antenna main axis (see Fig. 1(a), panel iii), the aligned dimer does not couple directly to the impinging radiation. However, by exploiting the intense near-field coupling in the two gap regions, the single antenna LSP can induce the charge oscillation in the aligned nanoantenna dimer. The symmetry of the system forces the charges in the dimer to oscillate mutually out-of-phase, triggering the excitation of a dark mode. We can easily recognize the similarities between the electric field distribution of the aligned dimer dark mode (Fig. 1(a), panel ii) and

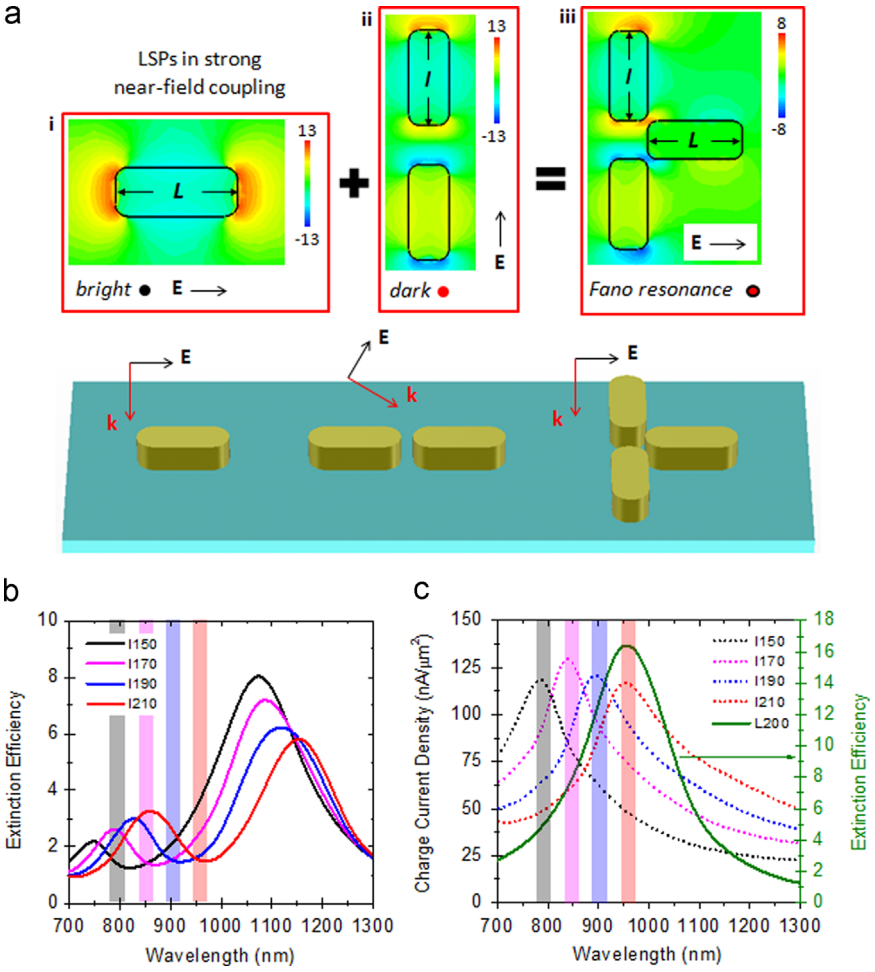

Fig. 1. (a) 2D plots of the electric field enhancement factor simulated on a plane parallel to the substrate, passing through the center of the structures. Panel i: horizontal component of the electric field distribution for the single nanoantenna LSP (bright) excited by light polarized along the main axis of the structure. Panel ii: vertical component of the electric field distribution for the aligned dimer dark mode excited in out-of-normal incidence condition. Panel iii: vertical component of the electric field distribution for the T-shape trimer in Fano resonance condition, excited by light polarized along the main axis of the horizontal nanoantenna. Lower sketches: profile schematics representing the optical incidence configurations in the cases of respectively single antenna, antenna dimer and T-shape antenna. (b) Extinction efficiency spectra of T-shape trimers respectively for $l=150$ nm (black continuous curve), 170 nm (pink continuous curve), 190 nm (blue continuous curve) and 210 nm (red continuous curve) (L is kept fixed to 200 nm). (c) Spectral responses respectively of the out-of-phase dark mode supported by antenna dimer and the LSP bright mode supported by the single antenna. Left axis: charge current density distribution evaluated inside the arms of the aligned dimer for $l=150$ nm (black dot curve), 170 nm (pink dot curve), 190 nm (blue dot curve) and 210 nm (red dot curve). Right axis: extinction efficiency spectrum of the single nanoantenna for $L=200$ nm (green continuous curve). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)