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Plasmon-induced transparency and Fano resonances in metal-insulator-metal nanorod dimers: A numerical analysis

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ABSTRACT

Three-dimensional plasmonic nanorods are theoretically investigated to achieve plasmon-induced transparency and Fano resonances in visible to near-infrared region. The plasmonic nanostructure consists of periodic array of a top in-plane side-by-side assembling nanorod dimer and a bottom nanorod separated by a dielectric spacer. With transverse excitation, which means that the E-component of the incident field is along the short axis of the nanorods, anti-parallel oscillations in the metal-insulator-metal (MIM) structure lead to magnetic resonances in the dielectric cavity, and magnetic surface plasmons (MSPs) can also be induced by the mode couplings in the in-plane nanorod dimer. Interferences of magnetic resonances and localized surface plasmons (LSPs) of nanorods lead to Fano resonances in MIM nanorod dimer. Furthermore, a significantly broad optical magnetism and transparency window is shown through the hybridization of the vertical and in-plane mode interactions. The extinction spectra can be tuned by the aspect ratio (AR), gap and periodicity of nanorods. This unique characteristic of MIM nanorod dimer can realize many potential applications of plasmon-induced transparency and Fano resonances, such as multi-wavelength biosensing and optical antenna. PMMA block is chosen to simulate non-uniform distributed analyte. It is localized on different zones upon the MIM dimer to theoretically determine the sensing effectiveness. Simulation shows that the in-plane small gap of the top MIM dimer largely increases the sensing sensitivity of the magnetic resonance of MIM structure.

1. Introduction

Metamaterial, which is artificial effective media with both negative magnetic permeability and dielectric permittivity, has attracted lots of attention due to its unique properties and promising applications. Split ring resonator (SRR) is one kind of metamaterials, as it can realize artificial magnetism in a wide window of operating frequencies from radio and microwaves up to THz region. The SRR is equivalent to a LC circuit, and the out-phase current in the two arcs results in a magnetic resonance [1].

However, when it goes into the optical frequencies, the magnetic response of the SRR begins to saturate. The magnetic resonance frequency no longer linearly scales reciprocally with the structural size [2]. Instead, it is found that in optical

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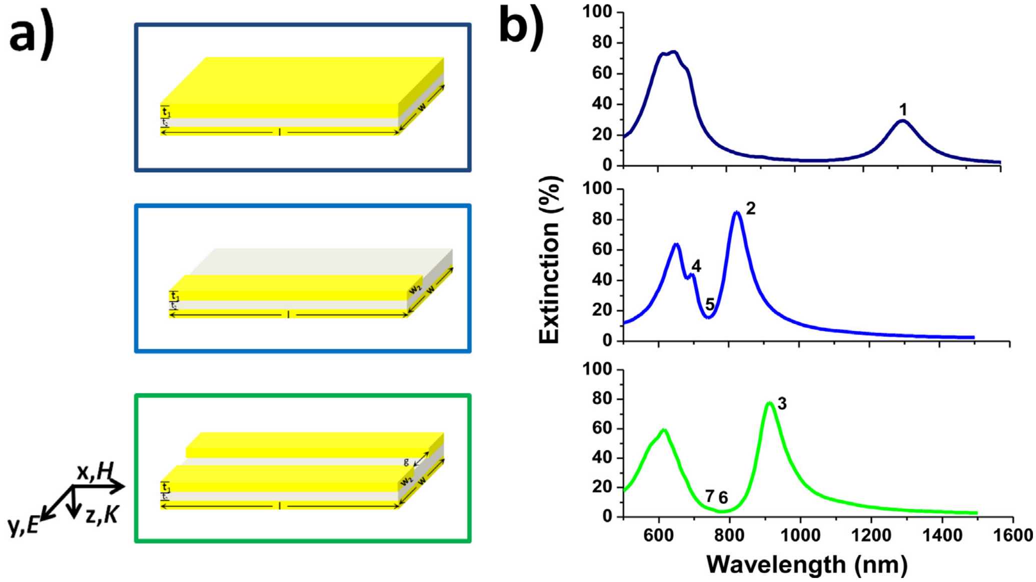

Fig. 1. a) 3D sketches of MIM nanorod, A-MIM nanorod, and MIM nanorod dimer from top down. b) Extinction spectra of the shown nanostructures.

frequencies, the metallic asymmetric split ring resonator (A-SRR) exhibits a sharp transparency band with high quality (Q) factor and asymmetric shape, known as Fano resonance [3,4]. Fano resonance is induced by the destructive interference between the superradiant bright mode and subradiant dark mode [5,6]. In the A-SRR, out-phase current in the two uneven arcs of split ring contributes to the dark magnetic resonance mode, and in-phase current oscillation acts as the superradiant resonance dipole mode. In addition, it seems like that symmetry-breaking is not necessary for generating Fano resonance. By embedding a nanorod in a simple symmetric SRR, Fano resonance can also show up, and double Fano resonances can be realized by adjusting the gaps between the nanorod and the two arcs [7].

Furthermore, plasmonic nanostructures are widely used for obtaining artificial magnetism in visible to near-infrared (NIR) region. In-plane metallic nanostructures show Fano resonances, such as asymmetric concentric nanoring/disk cavity and nanoparticle clusters, etc [8–10]. Among these, varies of nanorod oligomers, e.g., nanorod dimer and dolmen-shape structure have been investigated due to the anisotropy and easy preparation of nanorods. In these plasmonic nanostructures, subradiant mode is mostly dark high-order localized surface plasmon (LSP) or magnetic surface plasmon (MSP) induced by the near field coupling of LSPs. Generally, Fano resonance in nanorods is sensitive to incident light polarization, which always appears with excitation electric field orientation parallel to the long axis of nanorod. In addition, multiple Fano resonances have been reported in planar cluster of nanodisks and split nanorings, with the resonance wavelengths and strengths determined by the nanostructures' number and arrangement in the clusters [11,12].

Besides in-plane nanoparticle clusters, metal-insulator-metal (MIM) structures are also well studied, such as nanosandwich, fishnet, and photonic cavity [13,14]. The electric fields are strong and anti-parallel in the top and bottom metallic layers, so that a magnetic resonance appears in the middle insulator layer [15,16].

In our paper, three-dimensional plasmonic nanorods are investigated to achieve artificial magnetism and Fano resonances in visible to NIR region. Plasmonic nanostructure is developed, which consists of periodic array of a top in-plane nanorod dimer with side-by-side assembling and a bottom nanorod separated by a dielectric spacer. A significantly broad plasmon-induced transparency window is shown through the hybridization of the vertical and in-plane mode interactions. The extinction spectra can be tuned by the aspect ratio (AR), gap and periodicity of nanorods. This unique capability of MIM nanorod dimer can realize many potential applications of plasmon-induced transparency and Fano resonances, such as multi-wavelength biosensing and optical antenna [17–19]. We further simulate the effectiveness of the MIM nanorod dimer array for sensing with small localized poly-methyl-methacrylate (PMMA) blocks on different zones of the MIM dimer.

2. Structures and simulation method

In the present work, the finite element (FEM) method is applied to simulate the optical properties of the MIM nanorod dimer. MIM nanorod dimers are periodically placed on silica SiO_2 substrate and surrounded by air, with period of $p_x = 500$ nm along x-direction, and $p_y = 300$ nm along y-direction. The material of the metal layer is chosen to be gold Au, and the dielectric constants of Au are given by Johnson and Christy [20]. The insulator layer of MIM nanorod is SiO_2, and the permittivity of SiO_2 are given by Palik [21]. A plane light wave is incident along the z-direction with polarized electric field parallel to the short axis of the nanorod (y-axes, Ey).