From Near-Field to Far-Field: Radiative Coupling of Particle Plasmon Resonances in Three-Dimensional Geometries

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Abstract

We demonstrate superradiant-like effects in a three-dimensional arrangement of particle plasmonic oscillators at Bragg distance. In a Bragg-stacked multilayer structure we observe the formation of a very broad photonic band gap that spans almost one octave in the optical frequency range.

1 Introduction

Coupling between individual particle plasmon resonances (PPRs) has been a field of extensive research over the past few years. Most of the work was dedicated to near-field coupling [1,7] with close spacing between the resonant particles. In this limit, retardation is negligible, but also the interesting properties of radiating PPRs are mostly neglected. In contrast, when particles are positioned at distances on the order of their emission wavelength, coupling can be mediated by the radiation fields of the PPRs [2-5].

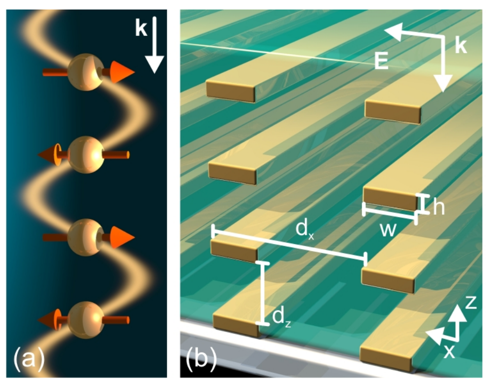

Figure 1: (a) Schematic of radiative coupling of particle plasmons. (b) Geometry of the Bragg stacked four-layer structure. The gold nanowires with width w and height h are arranged in a three-dimensional lattice with lateral period d_x and vertical spacing d_z.

We investigate far-field coupling in three-dimensional stacked plasmonic nanostructures. Stacking the oscillators at Bragg distance is of particular interest as in this case the spatial arrangement of the oscillators is matched to their resonance wavelength. Increasing the number N of layers stacked at Bragg distance leads to the formation of a very broad photonic band gap of about 1 eV.

2 Far-field coupling in Bragg-spaced structures

Fig. 1 (b) shows a schematic of a Bragg lattice with four layers of gold wires embedded into a dielectric spacer material with a refractive index of $n_{\mathrm{Sp}} = 1.46$. For incoming light polarized perpendicular to the wires particle plasmons are excited. Depending on the distance d_z, Fabry Pérot (FP) modes are excited in this structure which can couple to the PPR. A special situation occurs for distances d_z, where the FP modes spectrally match the PPR, i.e., when the Bragg condition for the PPR wavelength $d_z = \lambda_{\mathrm{PPR}}/(2n_{\mathrm{Sp}})$ is fulfilled. Only one broad transmittance feature is observed in the spectrum and the coupled system

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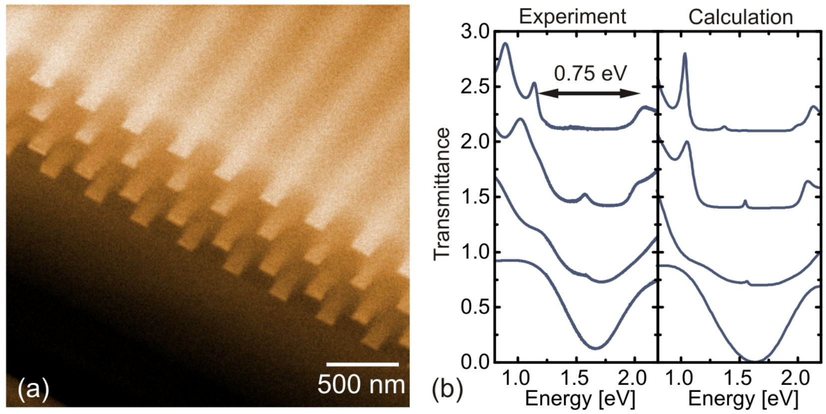

Figure 2: (a) Scanning electron microscope image of a four-layer plasmonic Bragg structure. (b) Experimental transmittance spectra of a plasmonic Bragg structure. S-Matrix calculations are shown in dashed gray.

mimics a single oscillator with increased oscillator strength in a far-field measurement. This is similar to the observation of superradiance in Bragg-stacked multi-quantum-wells [8].

Fig. 2 (b) displays experimental spectra acquired by an FTIR measurement as well as S-Matrix calculations [6] of a fabricated structure with $w = 180$ nm, $h = 20$ nm and $N = 1 - 4$. A scanning electron microscope image of this sample is shown in Fig. 2 (a). The sample is fabricated by a multilayer electron beam lithography technique [7]. The individual layers are defined with respect to a common coordinate system. Subsequently the sample is planarized using a spin-on dielectric.

3 Dependence of band gap formation on plasmonic oscillator strength and number of layers

Ivchenko et al. [8] predicted that the radiative width of the superradiant mode in a structure of Bragg-stacked quantum wells is proportional to the number of layers. This can be intuitively understood by the matching of the oscillator phase to their vertical distance, which leads to an increased, "collective" dipole moment of the coupled system.

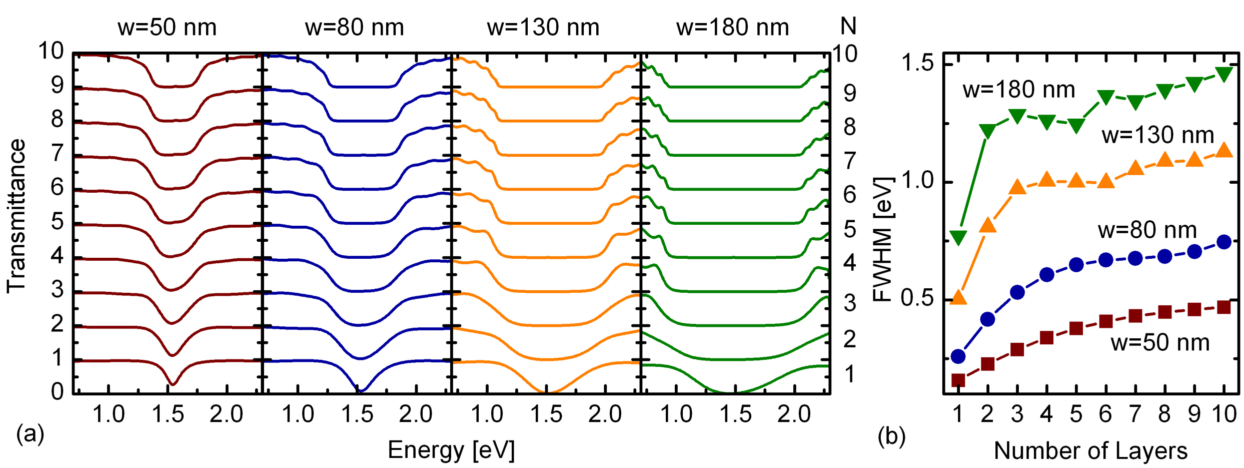

Figure 3: (a) Calculated transmittance spectra for different wire geometries, each stacked at Bragg distance for increasing layer number N. (b) Full width at half maximum extracted from the calculations in (a).

A similar effect can be observed in Bragg spaced plasmonic structures. Fig. 3 shows the FWHM extracted from calculated spectra of Bragg stacked nanowires for one to ten layers. The FWHM of the coupled system increases strongly for increasing number of layers. The dependence of the stop gap width on the plasmonic oscillator strength is investigated by considering different wire geometries: w and h are changed, keeping a constant aspect ratio to fix the spectral position of the PPR and only changing its oscillator strength.

For the small wires with low oscillator strength, the spectral width increases slowly but linearly up to approximately 7 layers and starts to saturate for more layers. In contrast, the large wires, which exhibit a large oscillator strength, show a strong increase for the first two layers and almost no further change for higher N. This issue can be understood by taking into account that interaction with neighboring oscillators is only possible within a certain range given by the dephasing time of the PPRs and hence their radiative width: as the large wires couple more efficiently to the radiation field, their decay is on the order of only a few cycles of the light field. Interaction with oscillators beyond this range is not possible. This interpretation is supported by deducing an interaction length from the radiative lifetime of a single oscillator, which can be extracted from the linewidth at $N = 1$.

4 Conclusion

In conclusion, we have shown that 3-dimensional stacking of plasmonic oscillators at Bragg distance leads to a superradiant-like behavior. Upon increasing layer number, a nearly octave-wide photonic band gap in the optical domain emerges. The width and spectral position of the band gap is strongly tunable by modifying the spectral position and width of the single oscillator resonance. Plasmonic far-field coupling could be utilized for tailoring unusual optical properties of plasmonic nanostructures or in the coupling of quantum emitters to plasmonic structures without the common problems of near-field quenching.

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