Strong coupling of localized and surface plasmons to microcavity modes

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Abstract

We strongly couple surface plasmon modes on a thin metal layer via localized plasmons of nanowires to photonic microcavity modes. In particular, we place an array of nanowires close to a mirror and position a second mirror at Bragg distance. The coupling becomes evident from an anti-crossing of the resonances in the dispersion diagram. We experimentally determine the dispersion by applying external pressure to the microcavity and find excellent agreement with simulations.

1. Introduction

The enormous potential of metallic nanostructures relies on the excitation of localized and propagating surface plasmons. The exploration of these collective electron oscillations in nanoparticles or nanostructured layers enables the design of novel materials with tailored optical properties, optical nanodevices such as nanoscale waveguides, gratings, or filters, as well as plasmonic sensors and antennas. The strength of plasmon-plasmon and light-plasmon coupling as well as the influence of these interactions on the plasmon resonances decisively determine the properties and functionality of these applications. Enhancing the light-plasmon coupling strength is a crucial factor for improving these ideas. In this paper, we investigate how the coupling strength of localized and surface plasmons can be manipulated by a modified environment created by a photonic microcavity [1], and we examine the influence of this coupling on the plasmon dispersion. In an array of elongated nanowires, localized plasmons are excited. Placing this array close to a thin metal layer allows the additional excitation of propagating surface plasmons on the metal layer surface. These two different plasmon modes can be coupled strongly to light when a second metal layer is placed at an appropriate distance forming a microcavity. The distance has to be accurately controlled, since strong coupling can only be observed where the dispersion functions of the photonic microcavity modes and the plasmon modes intersect.

2. Strong Coupling of Plasmonic and Photonic Modes

In an isolated elongated metal nanowire, localized plasmons can be excited when the incident light is polarized perpendicular to the wire. Placing a thin metal layer near an array of nanowires has two effects [Fig. 1(a)]. First, in analogy to electrostatics, the effects of a mirror close to a charged particle is equal to the effect of an image charge placed on the opposite side of the mirror with opposite charge. Hence, the system of a nanowire placed closely above a mirror resembles very much the system of a pair of stacked nanowires where the antisymmetric plasmon mode (magnetic mode) is excited [2]. The localized plasmon resonance wavelength λ_{LP} is shifted towards higher wavelengths when the distance of the nanowire to the mirror decreases. Using a dielectric spacer of $30\ \mathrm{nm}$ with a refractive index of

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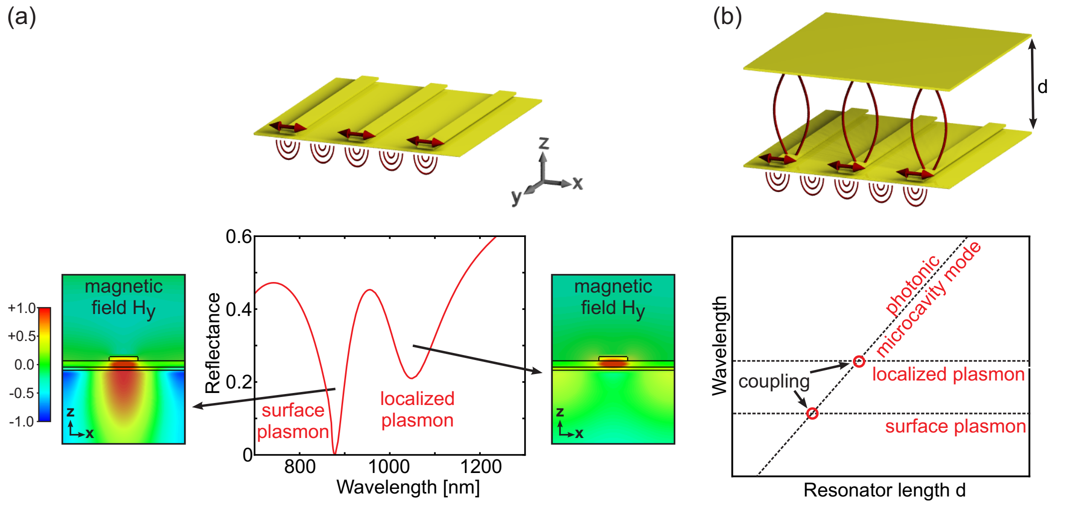

Fig. 1: (a) Localized and surface plasmons can be excited in an array of metal nanowires close to a thin metal layer. The magnetic field plots of the two resonances reveal the nature of the two plasmon modes. (b) By adding a second metal layer, the microcavity modes can interact with the plasmon modes for those mirror distances d where the microcavity modes intersect with plasmon modes in the dispersion diagram. The red lines in the structure illustrations indicate the standing electric field. Illumination is from below with polarization along the x-direction.

$n = 1.38$ between wire and mirror and a mirror thickness of 15 nm, the resonance is shifted to $\lambda_{\mathrm{LP}} = 1050$ nm for nanowires with a thickness of 20 nm and a width of 140 nm. In the same manner as for a nanowire pair, a magnetic dipole is induced for a nanowire close to a mirror. The second effect is the grating-induced excitation of propagating surface plasmons on the metal-substrate interface [3]. For our parameters, a nanowire period of $p_{\mathrm{x}} = 600$ nm allows surface plasmons with a resonance wavelength of $\lambda_{\mathrm{SP}} = 880$ nm. By plotting the magnetic fields [Fig. 1(a)], the two resonances can be identified. In order to obtain strong coupling of light to the plasmon modes, a microcavity is formed by positioning a second mirror at a distance d to the nanowires [Fig. 1(b)]. When the distance d is varied, a strong interaction with the plasmon modes is expected everytime the cavity resonance is equal to one of the two plasmon resonances. The mode coupling causes an anti-crossing of the resonances and can be observed in the reflectance plot of Fig. 2(a, c).

3. Experiments

The structures were fabricated using electron beam lithography and thermal evaporation. The second mirror is evaporated on a second glass substrate which is then turned around and pressed onto the nanowire array. The pressure is applied via a small annular stamp around the nanowire array. Using this technique, the microcavity length can be tuned from several micrometers to only a few hundred nanometers by simply changing the mechanical pressure. The reflectance plot that was experimentally obtained in this way corresponds very well to the simulated one [Fig. 2(a,c)]. In order to determine the actual distance of the mirrors, the polarization is turned by $90°$. This way, the incident light is polarized along the elongated nanowires. Hence, no plasmons can be excited and only the unperturbed cavity resonances are detected [Fig. 2(b,d)]. In Fig. 2(e,f), the simulated and experimentally determined reflection spectra are plotted for two different cavity lengths $d_{\mathrm{SP}} = 310$ nm and $d_{\mathrm{LP}} = 395$ nm. At these distances, the resonance wavelength of the cavity corresponds to the surface plasmon and the localized plasmon resonance and the splitting energies can be directly observed. For comparison, the unperturbed plasmon resonances are plotted in the graphs as well. The simulated magnitudes of the splittings are 131 nm for the surface

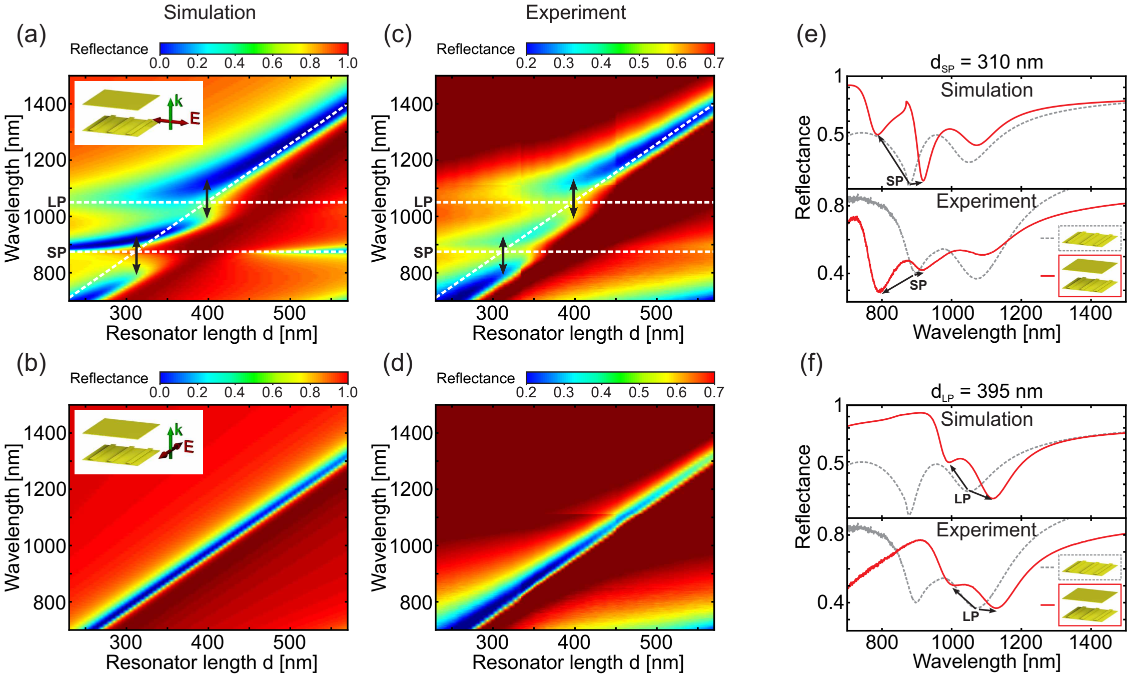

Fig. 2: (a,b) Simulated and (c,d) measured reflectance for different microcavity lenghts d for incident light polarized (a,c) perpendicular to the nanowires and polarized (b,d) along the elongated nanowires. The white dashed lines denote the localized plasmon (LP) and surface plasmon (SP) resonances as well as the unperturbed cavity resonance. (e, f) Simulated and measured reflectance spectra at those cavity lengths where the resonance wavelength of the microcavity corresponds to the SP and LP resonances. The solid red curves correspond to the cavity structure, the dashed grey curves correspond to the unperturbed plasmon resonances of the structure without the second mirror.

plasmon and $126\ \mathrm{nm}$ for the localized plasmon which correspond to splitting energies of $224\ \mathrm{meV}$ and $141\ \mathrm{meV}$. Experimentally, slightly smaller splittings were measured: $122\ \mathrm{nm}$ for the localized plasmon and $119\ \mathrm{nm}$ for the surface plasmon resonance. These values are quite large and correspond to splitting/resonance energy ratios of 1:10 indicating strong coupling.

4. Conclusion

We demonstrated both experimentally and theoretically how the coupling of light to localized and surface plasmons can be significantly enhanced by a microcavity. Applying our concept on functional plasmonic nanostructures such as sensors or antennas where coupling plays an important role will substantially enhance their properties. This work was financially supported by Deutsche Forschungsgemeinschaft (FOR557 and SPP1391) and Bundesministerium für Bildung und Forschung (13N10146).

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