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Light transmission in nanostructures

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Abstract

We investigate transmission of light in nanoscale structures. We present spatial and temporal domain measurements of the dephasing of surface plasmon excitations in metal films with periodic nano-hole arrays. By probing coherent spatial SP propagation lengths of a few μm and an ultrafast decay of the SP polarization on a 10 fs timescale, we demonstrate that the SP transmission peaks are homogeneously broadened by the SP radiative lifetime. The pronounced wavelength and hole size dependence of the dephasing rate shows that the microscopic origin of the conversion of SP into light is a Rayleigh-like scattering by the periodic hole array. We have experimentally studied the dephasing of surface plasmon excitations in metallic nano-hole arrays. By relating nanoscopic SP propagation, ultrafast light transmission and optical spectra, we demonstrate that the transmission spectra of these plasmonic bandgap structures are homogeneously broadened. The spectral line shape and dephasing time are dominated by Rayleigh scattering of SP into light and can varied over a wide range by controlling the resonance energy and/or hole radius. This opens the way towards designing SP nano-optic devices and spatially and spectrally tailoring light-matter interactions on nanometer length scales.

Keywords : light transmission, nanostructures, surface plasmon

1. Introduction

The interaction of light and subwavelength scale periodic structures have attracted much attention in recent years. The extraordinary high light transmission through nano-scale holes perforated periodically in a metal film [1] have renewed interests in surface plasmon polaritons (SPP), i.e., bound electromagnetic surface waves that propagate along metal surface [2]. Phenomenologically, the incident light is grating coupled to SPP excitations on the metal interfaces and

SPPs on either side of the metal film are coupled through the nano-holes. These excited SPPs may eventually be reemitted into far-field radiation and this mechanism enhances the on-resonance transmission by 2-3 orders of magnitude over that of isolated nano-apertures, giving rise to a wide range of possible applications, e.g. as near-field sources, in photonic integrated circuites or in lithography.

Much less is known about the dephasing properties of SP excitations in nano-hole arrays, i.e. about the microscopic origin of the line shapes of the transmission spectra. Such information is of vital importance for a microscopic understanding of the underlying physics as well as for optimization of such nanostructures for possible applications.

In this paper, we report a direct measurement of the dephasing of SPP excitations in periodic nano-hole arrays. By probing coherent spatial SPP propagation lengths of a fe μm and an ultrafast decay of the SPP polarization on a 10 fs timescale, we demonstrate that the SP transmission peaks are homogeneously broa-

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dened by the SPP radiative lifetime. The pronounced wavelength and hole size dependence of the dephasing rate shows that the microscopic origin of the conversion of SPP into light is a Rayleigh-like scattering by the periodic hole array [4].

2. Experiment

Nano-hole arrays are fabricated by a dry etching technique after e-beam patterning on a 300 nm thick gold film grown on a $\lambda/5$ flat sapphire substrate. The optical axis of the substrate is perpendicular to the metal surface to avoid birefringence effects. The experiments are performed on a sample with a hole radius r of 125 nm and an array period a_0 of 761 nm. Its far-field emission spectrum [Figure 1(a)] shows transmission peaks assigned to SPP resonances at either the air-metal (AM) or sapphire-metal (SM) interfaces. The peak at 827 nm corresponds to the AM [1, 0] mode, and that at 925 nm is the SM [1, 1] SP resonance with its symmetry along the grating diagonal. We use a near-field scanning optical microscope (NSOM) in transmission geometry. The sample is illuminated with linearly polarized light from a Ti:sapphire laser through the substrate and the electric field intensity at the metal-air interface is coupled into a metal-coated near-field probe with sub-100 nm aperture diameter.

Fig. 1 (b) shows the near-field emission pattern for excitation at 820 nm near the AM [1, 0] resonance, within a scan range of about 5 × 5 μm^2. The emission pattern is dominated by stripe-like patterns that run perpendicular to the polarization direction, indicated by an arrow. This conclusion is confirmed by the agreement between experimentally recorded near-field images and 3D finite difference time domain simulations [3].

To measure the dephasing of SP excitations, we first probe their spatial propagation length, employing the experimental geometry shown in Fig. 2. The AM [1, 0] SP mode is resonantly excited at the metal-air interface of a first nanohole array. This mode is scattered at the edge of the array, where only the first diffraction order propagates onto the flat gold surface with the propagation length is on the order 40 μm. To measure its damping inside a nano-hole array, we probe the decay of the detected field intensity that occurs when this mode encounters a second hole pa--ttern. This experiment is sensitive to both SP population decay (characteristic time T_1) and purely phase

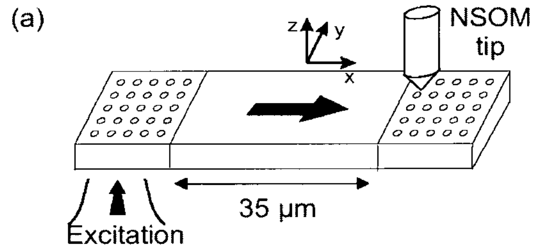

Fig. 2. Schematics of the experiment.

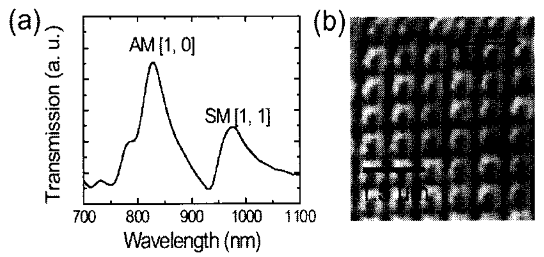

Fig. 1. (a) Transmission spectrum a gold nano-hole array with a=761 nm and r=125 nm. (b) Near -field transmission image at an excitation wavelength 820 nm.

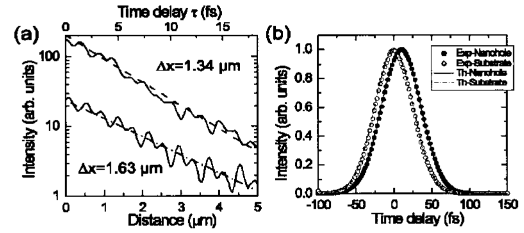

Fig. 3. (a) Decay of intensity measure in Fig. 2. (b)Top (experiment):Cross-correlations of fs pulse transmission through a nano-hole array(filled circles) and through the substrate only (open circles). Solid line (theory).

disturbing scattering processes (characteristic time $\$T_2^*$. Population decay leads to a spatial decay of the field intensity, whereas pure dephasing processes would lead to a change in the shape of the near-field pattern, specifically its image contrast.

3. Results and Discussion

Experimentally, we measure the a non-collinear second-order intensity cross-correlation of a 40 fs pulse transmitted through the sample with a replica of the incident pulse. The laser is centered at 790 nm, close to the AM [1,0] resonance. Fig. 3(b) (top curve) compares cross-correlations recorded for transmission through the nano-hole array (solid line) and through the substrate only (dotted line). A clear time delay of 10 fs is observed, when the pulse is transmitted through the nano-hole structure. In the bottom part of Fig. 3(b), the experimental results are compared to a simulation. Here, a Gaussian profile is taken for the 40 fs input pulse. Good agreement with experiment is obtained if a SP damping time T_{2d} = 10 fs is assumed. This damping time T_{2d} = 10 fs of the total SP polarization matches precisely the value of T_{2p} = 9.7 fs found for an excitation wavelength of 760 nm in the propagation experiments. This indicates strongly that it is indeed the finite damping of the driven SP resonance that is responsible for the delay in light transmission .

We now discuss the microscopic origin of the SP damping. The propagation experiments suggest that damping is mostly limited by a *radiative* SP decay into light through scattering at the nano-holes. Such scattering should well be described by classical Mie theory in the Rayleigh limit. To show that the SP dephasing is indeed dominated by Rayleigh scattering, we probe the wavelength-dependent linewidth of a *single* resonance by measuring angle-dependent transmission spectra near the SM [1,0] resonance. In the inset of Fig. 4(b), the normalized intensity is plotted as a function of λ and incident angle θ shift of the resonance position with θ is well described by the model outlined and an energy gap is clearly observed around θ =0. Fig. 4(b) clearly shows the power-law scaling of Γ and we now find a slope unambiguously demonstrating that the scattering mechanism is indeed Rayleigh-like.

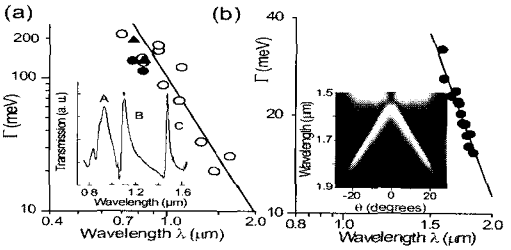

Fig. 4. Log-log plot of linewidth versus peak wavelengths.

4. Conclusions

We have experimentally studied the dephasing of surface plasmon excitations in metallic nano-hole arrays. The spectral line shape and dephasing time are dominated by Rayleigh scattering of SP into light and can varied over a wide range by controlling the resonance energy and/or hole radius. This opens the way towards designing SP nano-optic devices.

Acknowledgments

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