Ultrafast Phenomena XII, **2000**, 410-412

Ultrafast Interferometric Studies of Multiple Scattering of Light in Photonic Structures

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Abstract. We report the first observation of pronounced recurrent signals in the pump-probe interferometry measurements of structured metallic interfaces. The coherent multiple scattering of surface plasmons from the microsphere overlayer causes light localization in the photonic structure.

Photonic structures have attracted extensive attention in the past decade because of their unprecedented potential for manipulating light.[1] Previous research on photonic structures almost exclusively employed CW light, thereby limiting the studies to static and linear properties.[2] Elucidation of the dynamics of wave packet propagation in the photonic structure requires ultrafast spectroscopic techniques.[3] Further, the use of high peak-intensity femtosecond pulses opens possibilities to exploit the nonlinearity of photonic materials.[4]

Scattering of light plays a critical role in many important phenomena including multiple scattering as a precursor for light localization in a random medium.[5] Interference of scattered light in the photonic structure is responsible for the formation of photonic band-gaps. In our earlier studies, coherent multiple scattering of surface plasmon polaritons on rough metal surfaces was observed in pump-probe measurements[6]. In the present study, surface waves associated with the surface plasmon that propagates on a decorated metal film are used as a 2-D model system. Surface plasmons can be launched by light by satisfying the dispersion relation at the interface.[7] Plasmon scattering can be introduced by spatially modulating the interfacial dielectric properties.

In this paper, we report the first observation of pronounced recurrent interferometric signals resulting from multiple scattering of surface plasmons propagating in photonic structures. The ultrafast laser system and the experimental setup have been described elsewhere.[8] The surface plasmon was launched in the Kreschmann geometry.[7] The pump-probe laser pulses with controlled interferometric delay were sent to a prism coupler and focused onto a thin metallic film sample. A CCD camera was used to acquire the plasmon field distribution. The sample, a 46-nm thickness Ag film, thermally evaporated on a glass slip, was spin-coated with a monolayer of latex spheres (diameter = 2.1μm). Optical contact between the glass slip and the prism hypotenuse was made by index matching oil. The interferometric signal resulting from the surface plasmon created by the pump beam scattering into the direction of the probe beam was detected by the lock-in demodulation detection technique. A 100-μm wide slit was placed before the detector to achieve angular (hence momentum) resolution.

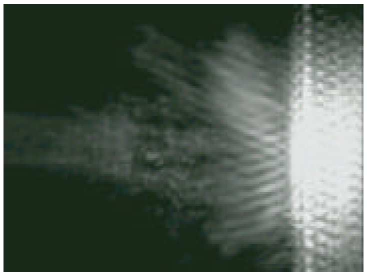

Figure 2. A microscopy image (60 x 44 μm) acquired with a 100x objective showing the directional back scattering of surface plasmons. The propagation direction is from left to

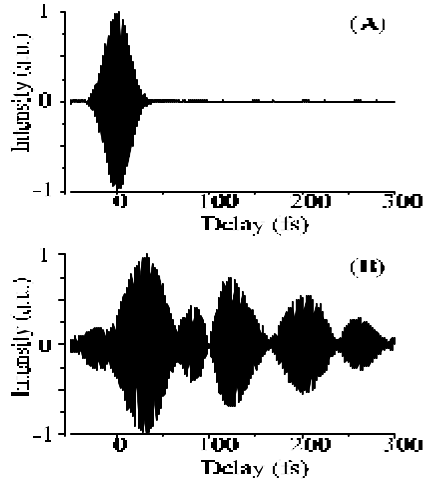

Figure 1. Pump-probe interferometric signals measured at non-ATR-resonance condition (2A) and when the laser beams were directed to the photonic structures (2B)

At the resonance angle attenuated total internal reflection (ATR) was observed indicating that light was converted to surface plasmons. Almost no scattered light is observed from the region of the smooth Ag film. Efficient plasmon scattering occurs when the surface plasmon propagates into the perfect hexagonal lattice region. In particular, Fig. 1 clearly shows the directional backward scatter from the lattice. The forward and backward propagating fields create the standing wave pattern observed.

The dynamics of the plasmon scattered out of the 2-D photonic structure are monitored with interferometric pump-probe measurements. Figure 2A shows the signals measured at a non-ATR-resonance angle representing the instrument response. Fig. 2B is the result acquired as the surface plasmon propagating in the periodically patterned region. Pronounced recurrent interferometric signals lasting as long as 1 ps were observed. The decay of the interferogram indicates a loss of amplitude (and coherence) due to propagation or scattering out of the film. Further, the temporal pattern is strongly altered by the lattice orientation with respect to the optical/plasmon k-vector in the film.

Interpretation of these data is aided by considering the Fourier power spectra. The reference interferogram gives a smooth laser spectrum. The Ag film interferogram (not shown) reflects the resonance absorption that follows from satisfying the single valued dispersion relation of the unstructured Ag film. The Fourier spectrum of Fig. 2B shows two “dips”, reflecting the dual valued solution of the dispersion relation, separated by the “stop band”, a characteristic of a photonic band-gap structure.

The momentum-energy relation of the surface plasmon propagating in the photonic structure is obtained by Fourier transformation of the angle-resolved pump-probe interferograms displayed in Figure 3. The upper part of the dispersion diagram shows the single-valued dispersion relation of the surface plasmon.

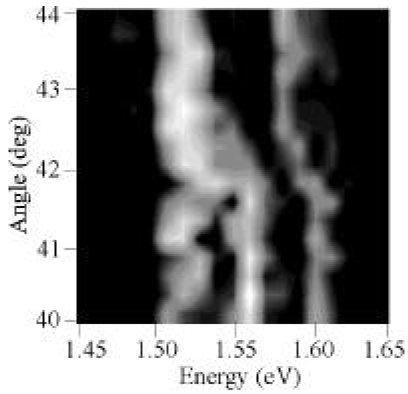

Figure 3. The dispersion diagram of surface plasmons propagating in the photonic structure.

Notably, the dispersion of the surface plasmon is split as shown at Fig. 3 with a peak in the center indicating the existence of a photonic bandgap. The dispersion of the surface plasmon is altered by the spatially modulated dielectric function at the interface. The surface plasmon scattered elastically by the dielectric lattice carries a different momentum while maintaining the same energy resulting in the spitting of the dispersion curve. The lattice momentum can be obtained with spatial Fourier transformation of the real-space dielectric lattice pattern. The location of the bandgap is well predic ted by taking into account the lattice momentum accessible by the surface plasmon.

Studies of the intensity distribution of the plasmon (field) and the spatially dependent dynamics are being conducted with scanning probe microscopy methods.[9] Other diele ctric decorations, including metals and polymers, are being employed to expand the range of perturbations and to facilitate the construction of nonlinear photonic structures. We are also pursuing the fabrication of programmable devices using patterned self-assembled monolayer formation methods with electrochemically reversible attachment chemistry[10,11].

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11 Acknowledgement: W. M. Keck Foundation and NSF-MRSEC.