Enhanced transmission of light through a gold film due to excitation of standing surface-plasmon Bloch waves

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We have observed enhanced transmission of light through a gold film due to excitation of standing surface-plasmon Bloch waves in a surface Fabry-Perot resonator. Our experimental results strongly contradict the recently suggested model of light transmission via excitation of a composite diffractive evanescent wave.

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Transmission of light through nanostructured metal films remains a topic of considerable interest and unresolved controversy over the last few years. Immediately after the first observations in the late nineties[1,2] the dominant mechanism of light transmission was believed to involve excitation of surface plasmon polaritons (SPP)[3,4] on the periodically nanostructured interfaces of the metal film. Since the SPPs of the nanostructured metal interfaces are strongly coupled to each other and to the free space photons, they seem to be mostly responsible for the effect of extraordinary optical transmission.[5] It should be noted that the mechanism described in Ref. 5 is common for all sorts of periodic metal nanostructures. Periodic arrays of either nanoholes drilled through metal film[1] or surface nanobumps[2] may be used in order to enhance transmission through a metal film. If the particular kind of nanostructure exhibits its own resonances, these resonances contribute to the overall transmission. However, the most important effect seems to be associated with the periodicity of the nanostructure.[5] Very recently a reassessment of the earlier transmission measurements of Ref. 1 and a new theoretical model of the enhanced optical transmission has been offered,[6] which relies on a theoretical construction called a composite diffractive evanescent wave (CDEW). This model has been supported by experimental data (see Ref. 7 and the references therein), which indicate that the transmission of periodically nanostructured nonmetal thin film samples is enhanced, too. These results seem to indicate that SPPs play a minor auxiliary role in the optical transmission of nanostructured metal films, while excitation of CDEWs is primarily responsible for the effect of extraordinary light transmission. The main difference between SPPs and CDEWs is that the SPP is a propagating long-range surface wave of charge density and the associated electromagnetic field,[3,4] while according to Ref. 6 CDEW is a combination of diffracted evanescent modes originating at an abrupt surface discontinuity such as a hole, a bump, etc. The wavelength of a CDEW corresponds to the wavelength of the excitation light in free space.[6] The CDEW is not a propagating surface wave in a sense that its field intensity E^2 is proportional to $1/x^2$, where x is the distance from the source.[6] Since many practical devices are being built or are proposed to be built using the effect of extraordinary light transmission through metal films, understanding of the main mechanism behind this effect is very important. In this paper we report a set of simple experiments, which strongly favor the dominant role of SPPs in the effect of extraordinary light transmission through nanostructured metal films. We show that transmission of light through a gold film is strongly enhanced due to excitation of standing SPP Bloch waves in a surface Fabry-Perot resonator, which is approximately 16 micrometers long. Our experimental results contradict the model of light transmission via excitation of a CDEW. Another important implication of our results is that ability to make two-dimensional Fabry-Perot resonators for surface plasmon polaritons brings us closer to experimental realization of a SPASER,[8] a quantum coherent source of SPPs analogous to a LASER. A plasmonic medium with gain has been already demonstrated recently.[9] Thus, in order to realize the SPASER we need to bring these two advances together in one device.

In our experiments 50-nm-thick gold films were sputtered onto a glass substrate using a magnetron sputtering machine. An overlay of polymethyl methacrylate (PMMA) film was then spin coated and patterned using *E*-beam lithography. The dielectric PMMA film was about 100–200 nm thick. An example of a patterned bigrating is shown in Fig. 1(a). It consists of individual PMMA dots on gold film surface. The grating period is 500 nm in both directions. The gold films under the PMMA layer were still intact after the gratings were developed using MIBK and/or IPA developer. With 532 nm laser light illumination the area of the gold film above which the PMMA grating has been formed exhibited the effect of extraordinary optical transmission similar to the one described in Ref. 1. This is illustrated in Figs. 1(b) and 1(c), in which the area of the gold film under the PMMA grating appears similar in brightness to the areas of the gold film punctured with a periodic array of 200-nm-diameter nanoholes when illuminated at normal direction with the same laser power.

The idea of our experiment was to fabricate a Fabry-Perot type surface resonator for the SPP Bloch waves and to check if there would be a noticeable increase in the effect of extraordinary light transmission associated with the resonance. Our paper reports the observation of such a resonator for the SPP Bloch waves (even though Fabry-Perot resonators for regular SPP waves on nonstructured metal films have been reported previously[10,11]). Note that since CDEWs are nonpropagating waves and do not carry any energy, this effect would be impossible to observe with CDEWs in a surface Fabry-Perot resonator, which is a few tens of micrometers long (it does not make sense to talk about the quality factor of a resonator in the case of evanescent waves, which do not carry any energy).

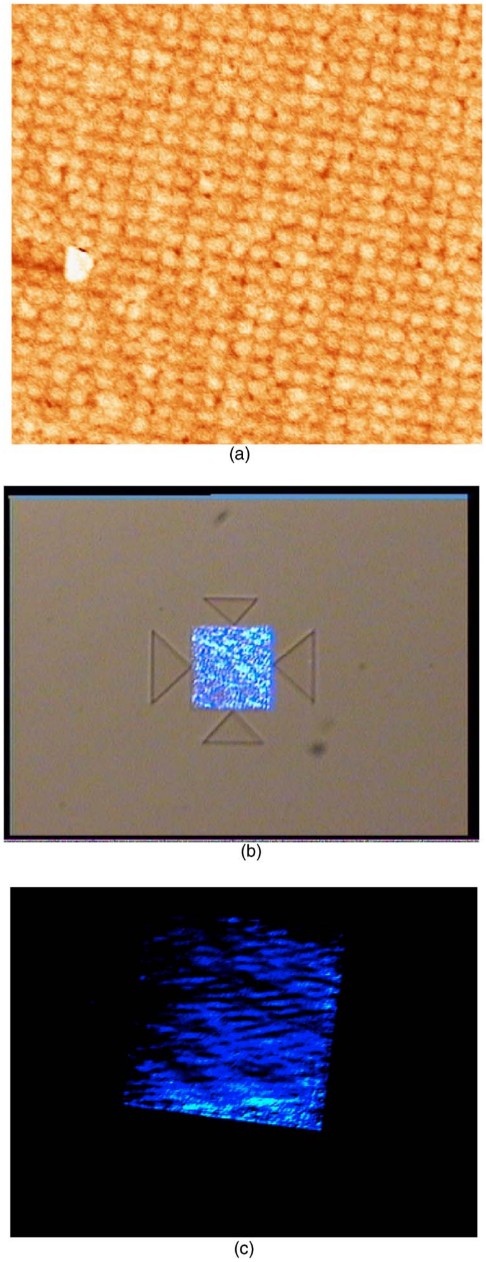

FIG. 1. (Color online) (a) An atomic force microscope (AFM) image of a bigrating fabricated on the surface of 50-nm-thick gold film, which consists of individual PMMA dots. The grating period is 500 nm in both directions. (b) With 532 nm laser light illumination at normal direction the area of the gold film above which the PMMA grating has been formed exhibits the effect of extraordinary optical transmission similar to the one described in Ref. 1. This is illustrated in (c), in which the area of the gold film punctured with a periodic array of 200-nm-diameter nanoholes made using a focused ion beam machine appears to have similar brightness when illuminated with the same laser source and in the same experimental conditions as in (b).

A surface plasmon polariton Bloch wave can be excited on the surface of the rectangular bigrating [Fig. 1(a)] if the projection of the wave vector of the incident photons on the metal plane $\vec{k}_{\parallel}$ satisfies the quasimomentum conservation law[4]

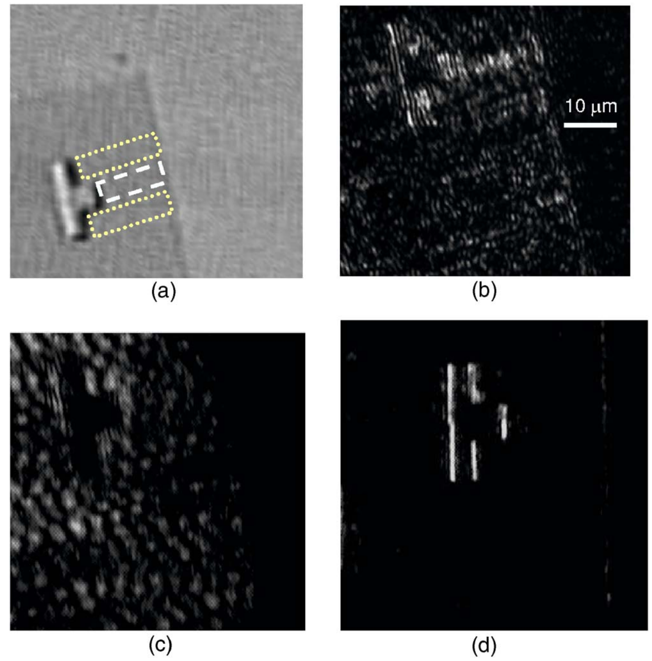

FIG. 2. (Color online) Photos of the Fabry-Perot resonator for the SPP Bloch waves illuminated from the top with white light (a), and illuminated from the bottom with 532 nm light (b). The resonator area between the long leg of the T and the edge of the periodic nanobump array is marked in (a) by a dashed box. (c) The effect of resonant transmission through the Fabry-Perot resonator area disappears when illumination angle is increased by 3 degrees: compare (b) and (c). (d) When the illumination angle is further increased by 3 degrees, the effect of enhanced transmission through the periodic nanobump array disappears altogether.

$$\vec{k}_{\parallel} = \vec{k}_p + \vec{e}_x \frac{2\pi n_1}{a} + \vec{e}_y \frac{2\pi n_2}{a}, \qquad (1)$$

where the magnitude of the plasmon wave vector k_p is approximately equal to the SPP wave vector on the flat metal surface, a is the period of the rectangular bigrating, $\vec{e}_x$ and $\vec{e}_y$ are the unit vectors in the x and y directions, and n_1 and n_2 are integer (positive or negative). Thus, Eq. (1) defines the resonant incidence angles of SPP excitation as $k_{\parallel}=k \sin \alpha$, where k is the wave vector of photons in free space. Such SPP Bloch waves have been observed in Ref. 12. The geometry of our sample is shown in Fig. 2(a). A rectangular array of the PMMA dots shown in Fig. 1(a) occupies the bottom left corner of Fig. 2(a). The outside area is the nonstructured PMMA film on top of the gold film. The T-shaped feature inside the array of PMMA dots was exposed to the E beam and etched away, so that the gold film is naked in this area. The microscopic photo image of this structure illuminated by 532 nm laser light is shown in Fig. 2(b). It is quite apparent from this image that the area of the PMMA dot array between the end of the long leg of the T and the nearest edge of the PMMA dot array (marked by a dashed box) exhibits much higher transmission than the rest of the PMMA dot array. On the other hand, the two areas of the array between the edge of the structure and the two arms of the T exhibit about the same transmission as the rest of the PMMA dot array. These areas (marked by dot boxes) have different length. They do not exhibit a Fabry-Perot type resonance at the illumination angle, which corresponds to the enhanced transmission through the array. The observed effect is very sensitive to the illumination angle. Compared to the image in Fig. 2(b), the illumination angle of the 532 nm laser light in Fig. 2(c) was increased by only 3 degrees. If the illumination angle is further increased by another 3 degrees [Fig. 2(d)], the effect of enhanced light transmission through the nanodot array disappears altogether in accordance with Eq. (1).

In order to prove that the area between the leg of the T and the nearest edge of the PMMA array behaves as a Fabry-Perot resonator for surface plasmon polaritons we have analyzed the dependencies of the optical signal in Fig. 2(b) on the coordinate along the lines shown in Fig. 3(a). The line section in Fig. 3(b) is performed along the optical axis of the Fabry-Perot resonator. The maxima of the optical field indicated by the arrows are separated by $\sim\Lambda_{Bloch}/2$ distances, where the wavelength of the SPP Bloch wave is defined via Eq. (1) as

$$\frac{2\pi}{\Lambda_{Bloch}} = k_p + 2\pi n/a, \tag{2}$$

where $n_x=-1$ and $n_y=0$. As a result,

$$\Lambda_{Bloch} = -\frac{a\lambda_p}{(\lambda_p - a)} \approx 8.3\ \mu\text{m}. \tag{3}$$

λ_p in Eqs. (2) and (3) is defined as the wavelength of surface plasmons, which propagate over unperturbed metal-vacuum interface. Note that the intensity distribution in the Bloch waves do not exhibit a simple $\sin^2$-like dependence on the coordinate. Weaker secondary maxima should be expected, which has been demonstrated, for example, in Ref. 13. The periodicity indicated by the arrows in Fig. 3(b) is confirmed by the Fourier analysis of this line section, which is shown in the inset in Fig. 3(b). The Fourier spectrum indicates a very pronounced feature marked by the arrow, which corresponds to the $\Lambda_{Bloch}/2$ periodicity. The spectral intensity of this feature exceeds the intensity of the background by at least a factor of 5, which proves the $\Lambda_{Bloch}/2$ periodicity beyond doubt. The background over which this feature is superimposed is basically a white noise (produced by light scattering at all angles) whose spectral width (indicated by the dashed line) corresponds to the spatial resolution of the far-field optical microscope used in the experiment.

The second line section in Fig. 3(c) is performed along a diagonal direction. It indicates that the intensity of light transmitted inside the plasmonic Fabry-Perot resonator is enhanced by approximately a factor of 4 compared to the transmission of the rest of the PMMA dot array. It appears that this result strongly contradicts the CDEW model described in Refs. 6 and 7. The intensity of a CDEW wave would drop by a factor of $(2\ \mu\text{m}/32\ \mu\text{m})^2 \approx 0.004$ upon the double pass through the Fabry-Perot interferometer. This estimate is based on the $\approx 2\ \mu$m CDEW propagation length cited in Ref. 6, and the length of the plasmonic Fabry-Perot resonator shown in Figs. 2 and 3. Thus, no resonant enhancement of the effect of the extraordinary light transmission is possible

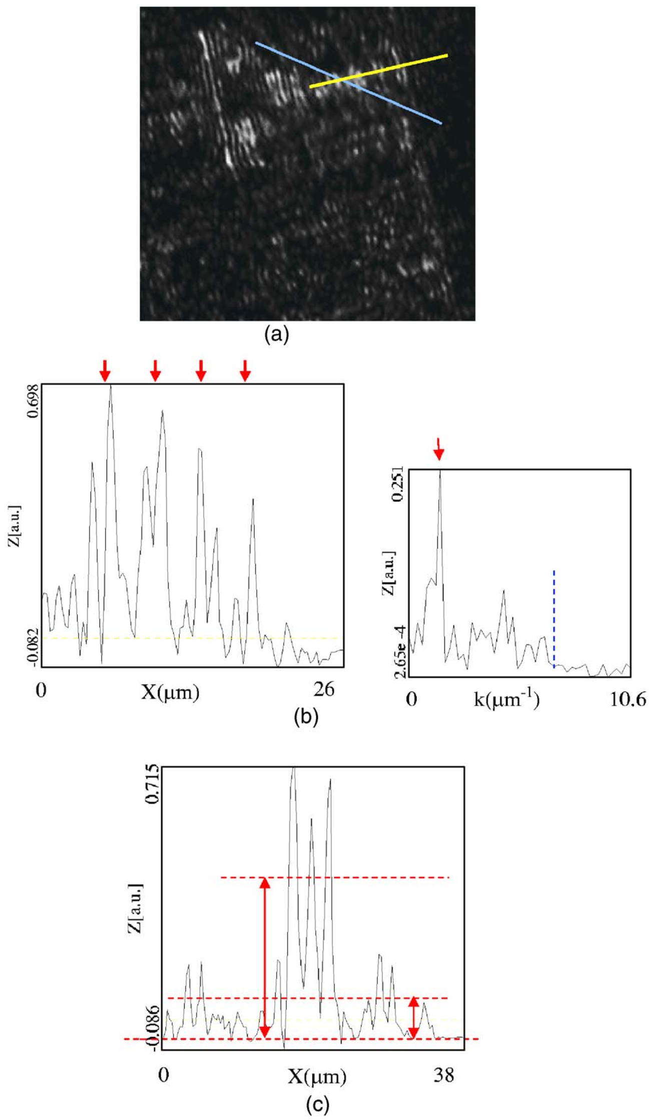

FIG. 3. (Color online) The lines in (a) indicate the paths along which the optical intensity is measured in the graphs of intensity versus coordinate in (b) and (c). The line sections are made along the optical axis of the resonator (b), and in the diagonal direction (c). The distance between the maxima of the optical intensity marked by the arrows in (b) corresponds to $\Lambda_{Bloch}/2$. This periodicity (marked by the same arrow) is also clear from the Fourier spectrum of the line section shown in the inset. The line section in (c) indicates that the transmission of the PMMA dot array inside the Fabry-Perot resonator is approximately four times higher than in the rest of the PMMA dot array.

due to excitation of CDEW in the resonator, unless some exotic mechanism of the evanescent wave amplification occurs in this experiment. While such mechanisms are being considered in the current literature on negative refractive index materials,[14] we believe that our experimental data point towards the explanation involving excitation of standing Bloch waves in a Fabry-Perot resonator. The length of the resonator is smaller than the typical values of the SPP propagation length measured in the experiments and calculated theoretically.[2,4] This length corresponds to approximately two SPP Bloch wavelengths estimated using Eqs. (2) and (3). We strongly believe that the plasmon-assisted mechanism of light transmission is proven beyond reasonable doubt in this case.

In conclusion, we have observed enhanced transmission of light through a gold film due to excitation of standing surface plasmon Bloch waves in a surface Fabry-Perot resonator. Our experimental results contradict the recently suggested model of light transmission through nanostructured metal films via excitation of a composite diffractive evanescent wave (even though we do not argue with the CDEW model in the case of nonmetallic films, which do not support SPP modes). Another important implication of our results is that ability to make two-dimensional Fabry-Perot resonators for surface plasmon polaritons brings us closer to experimental realization of a SPASER.[8]

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