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Ridge-enhanced optical transmission through a continuous metal film

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Optical transmission through a continuous (without holes) metal film with a periodic structure of metal or dielectric ridges on one or both interfaces was numerically studied. The dependencies of the transmission on the ridge width and height as well as the ridge arrangements on the opposite interfaces were investigated in weak- and strong-coupling regimes. The transmission enhancement was shown to depend on the relative position of the ridge gratings on the opposite interfaces of a film, confirming the role of resonant tunneling processes involving states of the surface polariton Bloch modes.

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Optical transmission of metal films with periodic arrays of holes or slits has recently been intensively studied.[1–11] The different, sometimes contradictory mechanisms of the transmission enhancement have been proposed and are being debated invoking surface-plasmon polaritons (SPP's), different types of waveguiding modes in holes or slits, localized plasmons, and various combinations of the above.[4–11] One of the proposed mechanisms relies on the resonant tunneling of light via states of localized surface plasmons in narrow grooves[7] or surface-plasmon polariton Bloch waves excited on the periodically nanostructured film interfaces.[9,10] The tunneling does not require any apertures in a metal film since the resonant energy transfer can occur directly through a continuous film. However, in the presence of holes in a film this effect can be hidden because of the other mechanisms being directly related to the holes, and its contribution to overall transmission and its dependence on the structure parameters have not been clarified yet.

In this paper we present numerical studies of optical transmission through a continuous (without holes), optically thick metal film with ridge gratings on one or both film interfaces. In the optimal conditions, the resonant transmission through such a film at the wavelengths of surface polariton Bloch modes can be enhanced by more than 100 times compared to the transmission of a smooth film of the same average thickness. Dielectric ridges on the metal film can provide even higher transmission enhancement. This transmission occurs due to the resonant tunneling via surface-plasmon polaritons excited on periodically structured interfaces and can be controlled by adjusting the relative position of the ridges on the opposite interfaces.

We have studied a one-dimensional grating (Fig. 1) consisting of a silver film of thickness H with a periodic set of rectangular ridges (D is the grating period, d is the ridge width, and h is the ridge height). Since there are no apertures in a film, all effects related to one or another mechanism of light transmission directly through the slits are absent, and the resonant tunneling through a metal film is the only mechanism responsible for the enhanced transmission. In all calculations below, the structure is illuminated at normal incidence with light polarized perpendicularly to the grating ridges. However, the discussed transmission mechanisms are valid for any angle of incidence.

Numerical modeling was performed using differential method with the R algorithm taking into account the Li remarks.[12,13] The latter two modifications allow modeling of deep gratings. The electromagnetic field above and below the structure was presented as an expansion over the Rayleigh waves. The structure under consideration is considered as three zones: two modulated zones (the gratings of the ridges) and one homogeneous layer (the continuous metal film). The complex amplitudes of the Rayleigh waves are obtained by solving the propagation equations with the boundary conditions at the interfaces.

First we have studied the optical properties of a free standing metal film in air with the metal ridges of width $d = D/2$ on both film interfaces. The two sets of ridges can be laterally shifted with respect to each other. The shift is described by the phase difference between the gratings: $\Delta\phi = 2\pi dx/D$, where dx is the distance between the ridge edges of the gratings on the opposite interfaces (Fig. 1). Reflection, absorption, and transmission of such metal structures depend on the phase difference between the gratings. In all cases it is easy to identify the spectral ranges with suppressed reflection and corresponding to it strong absorption and transmission (Fig. 2). These spectral ranges correspond to the excitation of one or another surface-plasmon polariton mode on the film interfaces for which the diffraction grating provides conservation of wave vector needed for light coupling to SPP's.

Relatively thick films exhibit only one peak in reflection/absorption in the spectral range corresponding to the lowest

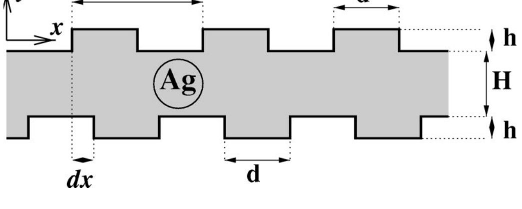

FIG. 1. Geometry of a structured film.

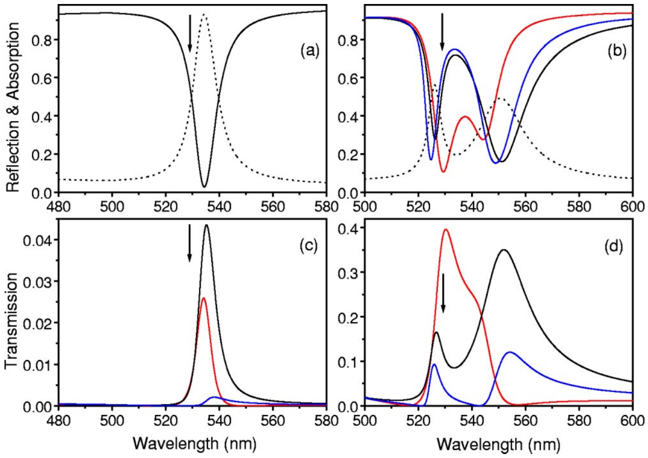

FIG. 2. (Color online) Reflection (solid lines), absorption (dotted lines), and transmission spectra of the silver film with the silver ridges ($d = 250$ nm and $D = 500$ nm) on both film interfaces: (a),(c) $H = 100$ nm, $h = 20$ nm; (b),(d) $H = 40$ nm, $h = 20$ nm. The relative position of the gratings is $\Delta\phi = 0$ (black), $\Delta\phi = \pi/2$ (blue), and $\Delta\phi = \pi$ (red). The absorption spectra are shown only for the $\Delta\phi = 0$ grating configuration. The reflection spectra for different grating configurations are indistinguishable in (a). Arrows indicate the excitation resonance of the SPP propagating on the smooth surface of a thick film.

(first) diffraction order of light coupling to the SPP modes on the grating, while thinner films have two different peaks related to the film SPP modes. At normal incidence these SPP modes are the standing Bloch waves ($k_x = 0$) corresponding to the bottom edge of the second band gap (the top edge of this band gap corresponds to nonradiative SPP mode at normal incidence; it results in the double peaks of transmission, reflection, and absorption at oblique illumination).[10] For a relatively thick metal film, the interaction between the SPP modes on the opposite film interfaces is weak and the position of the resonances observed in reflection, absorption, and transmission corresponds well to the band-gap edge which lies on the long-wavelength side of the SPP resonance on a smooth surface (Fig. 2). Variation of the relative position of the gratings on the opposite interfaces does not have a significant effect on the spectral position of the SPP modes [Fig. 2(a)] but significantly influences the peak transmission of the structure [Fig. 2(c)].

In the case of a thin metal film with a strong coupling between SPP modes on the opposite interfaces, the situation is more complex. The strong coupling between the SPP modes on the different interfaces of a thin film leads to a significant modification of the SPP dispersion relations.[14–16] First, one should consider a formation of the film SPP modes resulting in splitting of the degenerated SPP frequencies and appearance of the two SPP modes: a long-wavelength mode (compared to SPP on a thick-film surface) with a symmetric distribution of the electric field in the film and the short-wavelength mode with an antisymmetric field distribution.[14] The latter mode has a longer propagation range and thus stronger field enhancement associated with it, compared to a symmetric SPP mode [Fig. 2(b)]. On the periodically structured metal film these two modes form two sets of the Bloch modes. Moreover, this is accompanied by a complex interplay between symmetry of the SPP modes related to the film mode structure and the Bloch mode symmetry. This is especially evident in the SPP band-edge shift in the case $\Delta\phi = \pi$ for which the structure can be seen as a locally ‘‘smooth’’ one, and the symmetric (long-wavelength) mode is much less influenced by the grating structure [Figs. 2(b,d)]. This can be understood taking into account that there is no variation of the local metal thickness in such a structure.[17]

At the resonant SPP mode wavelengths, the reflection of the structure is small, while there is a strong absorption due to the Ohm losses in metal. At the same time a significant transmission is observed exceeding the transmission of a smooth film of the same thickness by more than two orders of magnitude. Although the total average thickness of the metal structure does not depend on the phase difference between the gratings, the relative position of the ridges significantly modifies the transmission enhancement.

The enhanced optical transmission through apertureless metal films has been recently modeled in the case of deep gratings for which it is related to tunneling via localized surface plasmons in the deep grooves.[7] For weakly corrugated films the enhancement was predicted considering photon tunneling via surface-plasmon polariton states on one or both film interfaces.[10] In the latter case which is appropriate for a structure embedded in a symmetric environment so that the SPP modes on both film interfaces occur at the same wavelength, the efficiency of tunneling depends on the spatial overlapping of the SPP Bloch modes on the opposite interfaces:[10]

$$T \sim \int_0^D dx \int_{+\infty}^{-\infty} |E_{SP}^{(1)} E_{SP}^{(2)}| dy, \tag{1}$$

where $E_{SP}^{(i)}(x,y)$ is the surface polariton field on the interfaces $i = 1$ and 2, and the integration along the surface (x direction) is performed over the grating period. The integral related to this lateral overlapping depends on the phase difference between the gratings since they determine the SPP field distribution along a periodically structured surface.[18] Strongest lateral overlapping is achieved in the case $\Delta\phi = 0$ corresponding to the strongest transmission enhancement in a weak-coupling regime [Fig. 2(c)]. In this case the SPP fields on the opposite interfaces are symmetric with respect to the film. With the increase of the phase difference and thus mismatch in the field distributions of the SPP modes on the opposite interfaces, the transmission decreases reaching minimum at $\Delta\phi = \pi/2$. However further increase of the phase difference between the gratings leads to the increase of the transmission probably due to the increase of the overlap in a y direction. In a strong-coupling regime [Fig. 2(d)], the strongest enhancement is observed at $\Delta\phi = \pi$ for which the symmetry considerations discussed above provide most favorable conditions [Eq. (1)] for antisymmetric SPP film modes in which energy is accumulated more effectively.

The role of these effects is clearly seen in the dependencies of the transmission on width and height of the ridges (Figs. 3 and 4). The optimal ridge width is approximately a

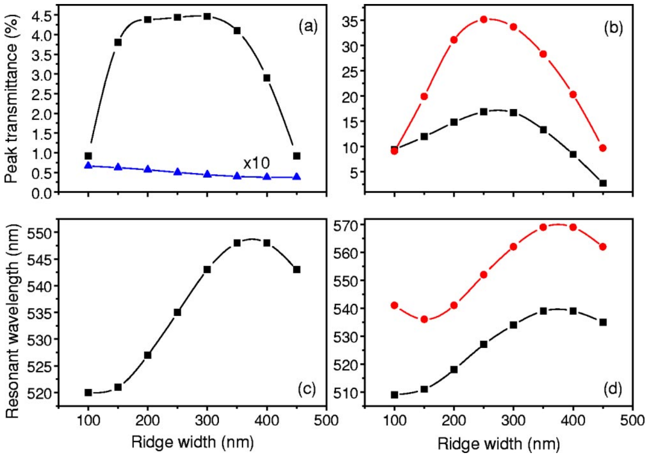

FIG. 3. Dependencies of the resonant wavelength of the enhanced transmission and the peak transmittance on the width of the silver ridges (cf. Fig. 2). The structure parameters are (a), (c) $D = 500$ nm, $H = 100$ nm, $h = 20$ nm, $\Delta\phi = 0$ and (b), (d) $D = 500$ nm, $H = 40$, $h = 20$ nm, $\Delta\phi = 0$, symmetric (circles) and antisymmetric (squares) film SPP modes. Triangles in (a) show the transmittance of a smooth silver film normalized on an average film thickness at the wavelengths corresponding to the resonant wavelengths in (c).

half of the grating period that provides most effective formation of the SPP Bloch modes and overlapping conditions [Eq. (1)]. With the increase of the ridge height the resonant wavelength (and thus the band-gap edge) shifts in the long-wavelength range as is expected, however the overall transmittance decreases after reaching maximum. The optimal ridge height which depends on the structure parameters is determined by a trade-off between the SPP excitation efficiency, the SPP field overlap, and the SPP radiative losses. For small ridge heights, the coupling of photons to SPP Bloch modes is low. With the increase of the ridge height, the y-direction overlap of the SPP modes decreases since the mode profile roughly follows the topographic profile. The radiative losses due to SPP coupling to photons increase with the ridge height. The competition between these processes leads to the maximum observed in Fig. 4. Similar behavior is observed in the strong-coupling regime. The width and height of the ridges on the opposite film interfaces can be chosen independently as long as the resonant conditions are satisfied. In general, the ridge parameters on the illuminated interface of the film are more important for absorption of light in the structure.

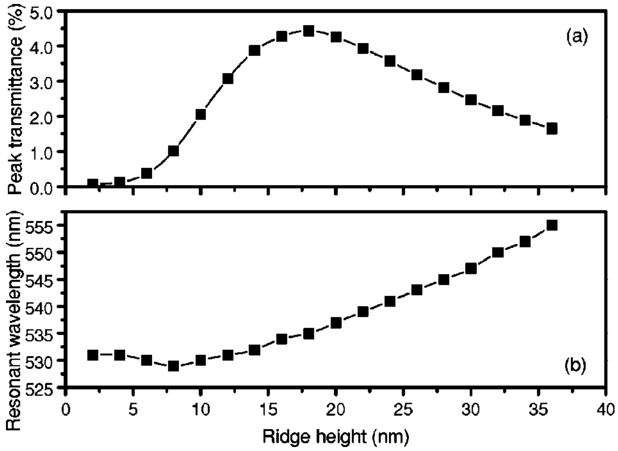

FIG. 4. Dependencies of the peak transmittance (a) and the resonant wavelength of the enhanced transmission (b) on the height of the silver ridges. The structure parameters are $D = 500$ nm, $d = 250$ nm, $H = 100$ nm, and $\Delta\phi = 0$.

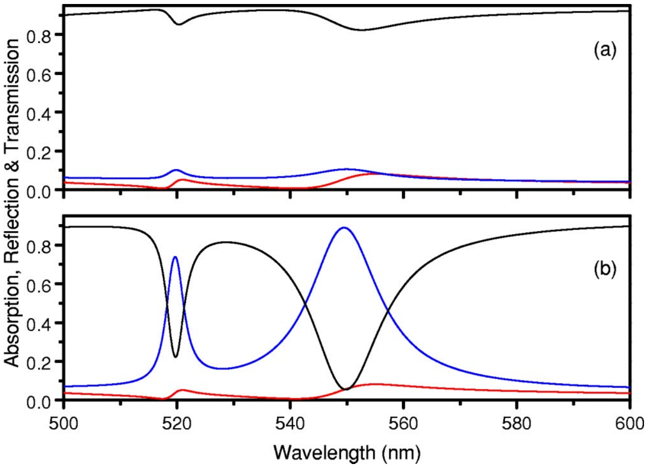

FIG. 5. (Color online) Reflection (black), absorption (blue), and transmission (red) spectra of the silver film with the silver ridges on one of the film interfaces: (a) the smooth interface is illuminated and (b) the structured interface is illuminated. The structure parameters are $D = 500$ nm, $d = 250$ nm, $H = 40$ nm, and $h = 20$ nm [cf. Figs. 2(b) and 2(c)].

Even if only one interface is periodically structured, transmission of the metal film is significantly enhanced. In a strong-coupling regime, a periodic structure on one of the interfaces is enough to provide the SPP Bloch mode excitation related to the film SPP modes. The transmission of such structures does not depend on whether smooth or structured interface is illuminated (Fig. 5). (It should be noted that for the structures of different parameters the zero-order transmission spectra can be different depending on the illuminated side, however the total transmission is always the same.) At the same time, absorption of the structure strongly depends on the illuminated side: efficient absorption is observed if the ridges are illuminated but absorption is low if the smooth surface is illuminated. This behavior is obvious if one considers the transmission mechanism described above. The SPP tunneling probability [Eq. (1)] obviously does not depend on the illumination conditions. At the same time, the absorption which is related to the Ohm losses during SPP propagation on a metal surface depends on the efficiency of the SPP excitation which is stronger when a structured interface is illuminated.

The electromagnetic field distribution of the transmitted light above a smooth interface indeed reveals periodic structure of the tunnel-coupled transmitted field (Fig. 6). As is expected, the near-field is strongest in the transmission resonance corresponding to an antisymmetric short-wavelength SPP mode and much smaller at off-resonance and for symmetric SPP mode wavelengths. In the case of a symmetric

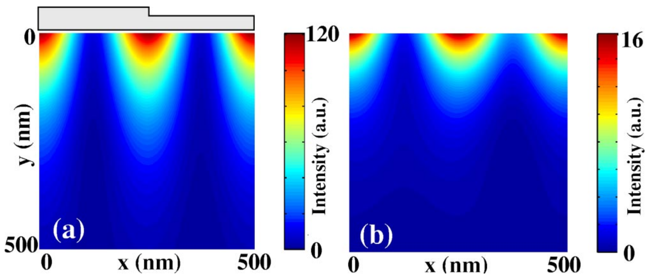

FIG. 6. (Color online) The intensity distributions of the electromagnetic field over a flat surface of the structure corresponding to different transmission resonances in Fig. 5(b): $\lambda = 520$ nm (a) and $\lambda = 550$ nm (b). The position of the ridges on the opposite interface is shown.

SPP mode, the electric field extends significantly in the metal film and thus is subjected to strong losses leading to the relatively small near-field intensity.

Coupling of light to the SPP modes and respective tunneling through a metal film require any kind of periodic modulation of the surface. Dielectric ridges on a smooth metal film can also play this role providing the modulation not only of topographical profile but also the boundary conditions. Compared to the case of the ridges made of the same metal as the film, the spectral behavior of the SPP modes in the case of dielectric ridges is more complex since the SPP's can exist on dielectric/metal as well as air/metal regions of the structured metal surface. At the same time, the observed transmission enhancement (Fig. 7) is even higher than for metallic ridges since the SPP Bloch modes exist directly on the "smooth" metal film interface, increasing the y direction overlapping compared to the case of metallic ridges when the SPP's more strongly follow the structure profile. For a 100 nm silver film the transmission can be more than three times higher with TiO_2 ridges than with silver ridges. The transmission behavior with the relative shift of the gratings is similar as for metallic ridges confirming the role of the SPP Bloch mode overlap as discussed above.

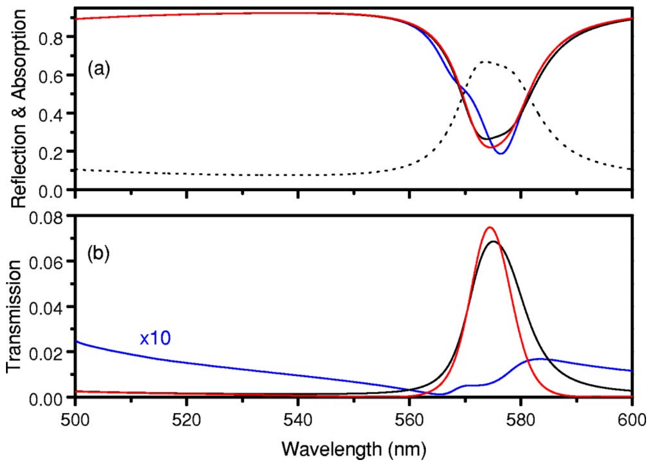

FIG. 7. (Color online) Reflection (solid lines), absorption (dotted lines), and transmission spectra of the silver film with the dielectric ridges ($n = 2.4$) on both film interfaces. The structure parameters are $D = 500$, $d = 250$ nm, $H = 100$, and $h = 20$ nm. The relative position of the gratings is $\phi = 0$ (black), $\Delta\phi = \pi/2$ (blue), and $\Delta\phi = \pi$ (red). The absorption spectra are shown only for the $\Delta\phi = 0$ grating configuration.

In conclusion, light tunneling via SPP modes through an apertureless metal film with the ridge gratings has been studied in weak- and strong-coupling regimes. This mechanism provides a significant enhancement of the light transmission through a metal film with the metal and dielectric ridge structures on one or both film interfaces and can be used to efficiently control the optical properties of the continuous metal films governed by surface-plasmon polaritons. The similar effects of SPP-enhanced transmission through a continuous metal film have been observed and described in the case of randomly rough interfaces where their efficiency is much smaller than in periodic structures due to less effective SPP excitation.[19]

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