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Flat metallic surfaces coated with a dielectric grating: excitations of surface plasmon–polaritons and guided modes

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Abstract
The electromagnetic response of flat metallic surfaces coated with a dielectric grating is studied theoretically. We found that two kinds of optical modes, namely, surface plasmon–polaritons (SPPs) bound to the metallic/grating interfaces and guided modes (GMs) in the dielectric grating, can be excited by externally incident light. Both SPPs and GMs display well-defined band structures due to the introduced periodicity in the dielectric grating.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Over the past few years, there has been increasing interest in plasmonics, aiming to take advantage of surface plasmon–polaritons (SPPs) [1, 2]. SPPs are surface charge density oscillations at metallic/dielectric interfaces [3]. Owing to their subwavelength and low-dimensional nature, highly complex miniaturized SPP-based photonic devices can be accomplished. Analogous to photonic crystals [4–6], complicated band structures and even band gaps for SPPs can appear if propagating in periodic structures [1, 2]. The existence of complicated SPP band structures and gaps may offer promising ways in tailoring SPP dispersion and propagation. Up to now, most studies on SPP band structures have been focused on periodically textured or uneven metallic surfaces [7–13].

For flat metallic surfaces, SPPs cannot be excited directly by externally incident light. However, if a dielectric grating is introduced on flat metallic surfaces, SPPs can be excited [14, 15]. It was found that SPP band gaps can exist for metallic surfaces coated with a dielectric grating [16]. If a flat metallic film is coated symmetrically with a dielectric grating on both sides, enhanced transmission mediated by the excitation and coupling of SPPs can occur [17, 18], similar to metallic films perforated with periodic slits or holes [19, 20].

In this paper, we report a theoretical study on the electromagnetic response of flat metallic surfaces coated with a dielectric grating by externally incident light. We find that the systems under study can support two kinds of optical modes: SPPs and guided modes (GMs), depending on the thickness of the gratings. Moreover, both SPPs and GMs display well-defined band structures and even band gaps. Over periodically textured and uneven metallic surfaces these coated metallic surfaces may not only make the design and fabrication more amenable but also offer more degrees of tunability for SPP and GM band structures.

2. Structures and numerical method

In figure 1 a schematic view of the structure under study is shown. It is composed of a metallic surface coated with a periodic dielectric grating. The coating dielectric grating consists of alternating dielectric and air media. The dielectric grating has the following structural parameters: grating period a, width of the dielectric constituent d, and grating thickness t.

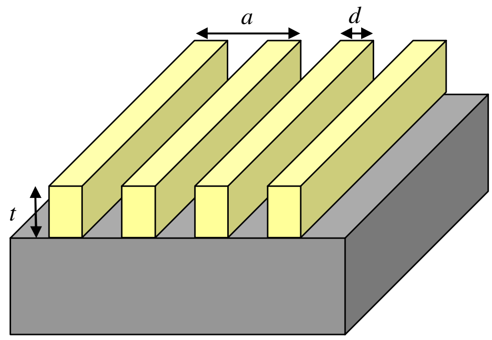

Figure 1. Schematic view of a metallic surface coated with a periodic dielectric grating.

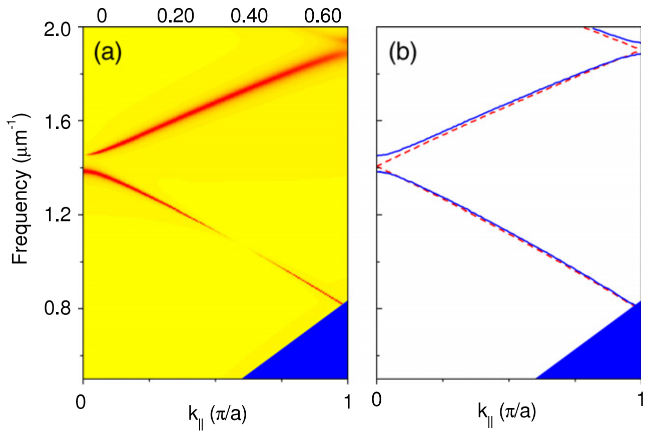

Figure 2. (a) Calculated absorption spectra for an Ag surface coated with a dielectric grating as a function of the in-plane wavevector of incident light and frequency in the color-scale form. (b) Dispersion defined by the loci of the absorption maxima (solid lines) and the folded SPP dispersion (dashed lines) of an effective homogeneous dielectric layer situated on an Ag surface. The parameters for the dielectric grating are $a = 0.6$ μm, $d = 0.36$ μm, and $t = 0.1$ μm. The shaded area in the lower right corner denotes the region below the light line of air.

Without loss of generality, the dielectric constituent is assumed to be characterized by a frequency-independent dielectric constant $\varepsilon = 2.3$, while the metallic medium is Ag, whose dielectric constant is described by the Drude model

$$\varepsilon_{\rm m}(\omega) = 1 - \frac{\omega_{\rm p}^2}{\omega^2 + {\rm i}\gamma\omega}, \qquad (1)$$

where $\omega_{\rm p}$ is the plasma frequency and γ is the collision frequency, related to energy loss. The parameters used in the Drude model for Ag are $\omega_{\rm p} = 1.37 \times 10^{16}$ rad s^{-1} and $\gamma = 7.29 \times 10^{13}$ rad s^{-1}, taken from [21]. To calculate the electromagnetic response of metallic surfaces coated with a dielectric grating, a plane-wave-based transfer matrix method [22, 23] is adopted. The central idea of this method is to divide the studied structure into small slices along the periodic direction. Electromagnetic waves on the left-hand and right-hand side of each slice can be associated by an S matrix whose elements are the function of the local wavevectors and Fourier components of the dielectric function. Since metallic surfaces are flat and without any structure, the convergence of this method is rather fast. Within the framework of this method it is possible to calculate reflectance, transmittance, and absorptance.

3. Results and discussions

In the present work, we only consider p-polarized incident light, namely, the magnetic field of incident light is perpendicular to the periodic direction of the dielectric grating. Figure 2 shows the calculated absorption spectra of an Ag surface coated with a dielectric grating in the first Brillouin zone of the dielectric grating as a function of frequency and the in-plane wavevector of incident light $k_\parallel = k_0 \sin\theta$ in the color-scale form, where k_0 is the wavevector of incident light in air and θ is the incident angle. The structural parameters of the dielectric grating are $a = 0.6$ μm, $d = 0.36$ μm, and $t = 0.1$ μm.

Owing to the interaction of incident light with the structure, for a fixed frequency the structure shows an absorption maximum at a certain in-plane wavevector. It is found that the absorption maxima are exactly coincident with the reflection minima since there is no transmission. Obviously, the loci of the absorption maxima show well-defined band structures. As will be shown later, the observed absorption maxima result from the excitations of SPPs. Therefore, the well-defined band structures are no other than the SPP band structures. Much information can be obtained from the absorption spectra. For instance, the quality factor of an absorption peak $\omega/\Delta\omega$ (ω is the peak frequency and $\Delta\omega$ is its half-width) can render the lifetime of SPPs, which is related to the intrinsic damping and radiation loss of SPPs. The propagation length can be also derived.

It can be found that SPP band gaps appear at the Brillouin zone center or boundary due to multiple Bragg scatterings when SPPs propagate along the periodic direction, similar to photonic band gaps in photonic crystals [4–6]. There exist two SPP band gaps in the displayed frequency range: the first one ranges in wavelength from 0.69 to 0.73 μm, while the second one from 0.52 to 0.53 μm. These two SPP band gaps are the second and third ones of the structure. The first SPP band gap cannot be observed since the first and part of the second SPP bands lie below the light line of air.

To demonstrate that the well-defined dispersion is from the SPP band structures, we also plot the folded SPP dispersion of an Ag surface coated with an effective homogeneous dielectric layer, shown in figure 2(b). The thickness of this homogeneous dielectric layer is the same as that of the dielectric grating and its dielectric constant is taken to be the average value of the constituents, namely, $\varepsilon_{\rm eff} = \varepsilon f + (1 - f)$, where $f = d/a$ is the filling fraction of the dielectric constituent. Obviously, the folded SPP dispersion for the Ag surface coated with the effective homogeneous dielectric layer coincides well with the band structures defined by the loci of absorption maxima. Deviations occur at the Brillouin zone center and boundary where band gaps appear due to strong Bragg scatterings as expected. We can thus conclude that the observed dispersion

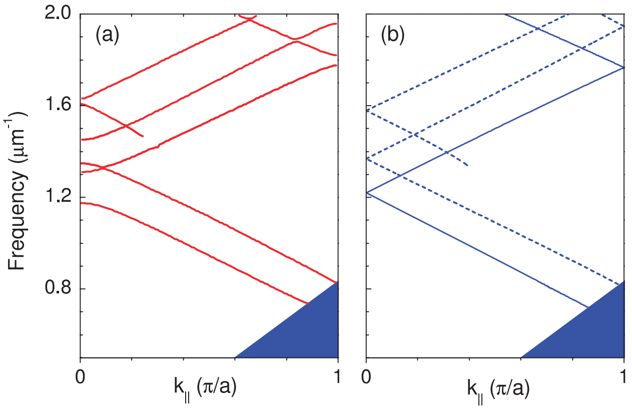

Figure 3. (a) Band structures derived from the loci of absorption maxima for an Ag surface coated with a dielectric grating. The structural parameters of the dielectric grating are the same as in figure 2 except for $t = 0.8\ \mu$m. (b) Folded dispersion of SPPs (solid lines) and GMs (dashed lines) for an Ag surface coated with an effective homogeneous dielectric layer. The shaded area in the lower right corner denotes the region below the light line of air.

defined by absorption maxima is from SPP band structures. Alternatively, this can be confirmed by inspecting the field distributions around the metallic/grating interface.

For a flat metallic surface, incident light cannot directly excite SPPs since the wavevector of SPPs is always larger than that of incident light [3]. After introducing a dielectric grating, however, SPPs can be excited by incident light [14, 15]. This is due to the fact that incident light is firstly scattered by the dielectric grating. As a result, the wavevector of scattered light should be imposed by the Bragg vectors resulting from the periodicity of the grating. If the wavevector of SPPs, k_{spp}, matches that of scattered light, namely

$$k_{\text{spp}} = k_{\parallel} + \frac{2\pi}{a}N, \qquad (2)$$

SPPs can be excited, where N is an integer. The excitations of SPPs are responsible for the observed absorption maxima or reflection minima. The existence of SPP band structures and band gaps for a metallic surface coated with a dielectric grating comes from a similar mechanism to those in photonic crystals and in periodically textured or uneven metallic surfaces. When propagating along the metallic/grating interface, SPPs will experience two different regions at the dielectric grating side, one dielectric and the other air. Consequently, SPPs will undergo multiple Bragg scatterings, leading to observed SPP band structures and gaps.

It is known that the dielectric grating can support GMs [24]. In figure 2 the thickness of the dielectric grating is rather thin such that no GMs can exist in the displayed frequency range. If we increase the grating thickness, GMs will appear as expected. In figure 3 the calculated band structures for an Ag surface coated with a dielectric grating defined by the loci of absorption maxima for $t = 0.8\ \mu$m are shown. Compared with structures consisting of thin dielectric gratings, the band structures defined by the loci of absorption maxima show more complicated features: additional bands appear. The existence of additional bands lies in the excitation of GMs in the dielectric grating. Besides SPPs, GMs can also give rise to enhanced absorption as an alternative mechanism. To show this, the folded dispersion of SPPs and GMs for an effective homogeneous dielectric layer situated on an Ag surface is also given for comparison. The derivation of the GM dispersion of a homogeneous dielectric layer on a metallic surface can be found elsewhere [25]. It is obvious that the newly arisen bands are of GM in nature. Interestingly, GMs also display band gaps since they also experience multiple Bragg scatterings.

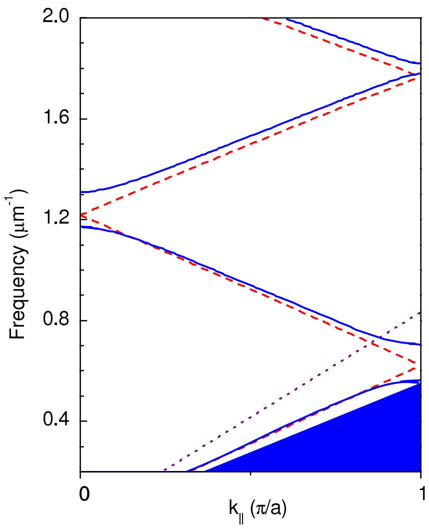

Figure 4. The same as in figure 3(a) but for light incident from a dielectric background with a dielectric constant of 2.3. Solid lines stand for derived SPP band structures from the loci of absorption maximum and dashed lines are the folded SPP dispersion for a flat Ag surface coated with an effective homogeneous dielectric layer. The dotted line is the light line of air and the shaded area denotes the region below the light line of the dielectric background.

It can be seen from figure 3 that SPP bands shift systematically to lower frequency and SPP band gaps become larger compared with thin dielectric gratings. This can be understood by the fact that the vertical components of SPP fields decay exponentially away from the metallic/grating interface. For thin dielectric gratings, the field tails of SPPs still exist in the air region above them. As a result, for a given wavevector the corresponding SPP frequency of a metallic surface coated with a dielectric layer shifts to lower frequency as the thickness of the dielectric layer increases. Likewise, SPPs experience stronger Bragg scatterings for a metallic surface coated with a thicker dielectric grating, leading to a broadening of SPP band gaps. It is worth noting that anti-crossing occurs when an SPP crosses a GM band, leading to a mini-gap. This can be seen by carefully checking the corresponding bands at the crossing points. At some crossing points, anti-crossing is not obvious due to the weak coupling between SPP and GM modes, leading to very small mini-gaps.

It can be found in figures 2 and 3 that the low-frequency bands cannot be excited since they are below the light line of air. To reveal low-frequency bands that are behind the light line of air, one can lower the light line by choosing light incident from a dielectric background. Figure 4 shows the band structures defined by the loci of absorption maxima for the same structure in figure 3 but incident from a dielectric background with a dielectric constant of 2.3. The dielectric background is on top of the dielectric grating and light is incident from the dielectric background. Obviously, we can clearly observe the low-frequency bands since they lie above the light line of the dielectric background. It is interesting to note that GM bands disappear. This is due to the fact that a dielectric layer can support GMs provided that the dielectric constant of the cladding layers on both sides is smaller than that of the dielectric layer. For light incident from the dielectric background, the dielectric grating cannot support GMs anymore since the dielectric constant of the dielectric background is larger than the effective dielectric constant of the dielectric grating.

4. Conclusions

In summary, we show that flat metallic surfaces coated with a dielectric grating display well-defined SPP and GM band structures and even band gaps. The appearance of SPPs and GMs depends strongly on the thickness of dielectric gratings. Over textured and uneven metallic surfaces, flat metallic surfaces coated with a dielectric grating are appealing in many aspects. First, both SPP and GM band structures and gaps can be tailored easily by modifying the material and structural parameters of dielectric gratings. Second, SPP and GM defect states can be obtained simply by introducing point or line defects in dielectric gratings, leading to the trapping and guiding of SPPs or GMs. Third, the constituents of dielectric gratings can be nonlinear materials so that nonlinear effects and devices could be obtainable.

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