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Excitations of surface plasmon polaritons in double layer metal grating structures

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We study the light scattering properties of double layer gratings (DLGs) made from Au on SiO_2 substrates. It is found that surface plasmon polaritons (SPPs) can be excited in the DLGs for a separation of up to 150 nm between the two Au grating layers and the collective reflectance spectra exhibit a strong resonant peak and a closely lying dip as a result of the surface plasmon polariton excitations. It is also found that the angle-resolved specular reflectance spectra show a dip-peak pair structure, while the angle-resolved reflectance spectra of higher diffracted orders show a complementary peak-dip pair structure. Finally, operation of the DLGs for efficient wavelength demultiplexing is proposed and discussed in light of these results. © *2012 American Institute of Physics*. [http://dx.doi.org/10.1063/1.3690947]

Surface plasmon polaritons (SPPs) are electromagnetic surface waves at an interface between a metal and a dielectric.[1] A common method to enable and control the excitations of SPPs by incident light is to corrugate the interface periodically. The excitation of a SPP is then seen as a dip in the reflectance if only the zeroth diffracted order exists.[1,2] When additional diffracted orders are present, the excitations of SPPs can cause the appearance of both dips and peaks in the reflectance spectra of different diffracted orders depending on the geometry of the corrugation.[3–5] A corrugation structure can be realized, for example, by creating a single or a multiple layer grating. A double layer grating (DLG) consists of two parallel layers of metal wires and can offer additional geometrical tunings for the control of the scattering properties of light compared to a single corrugated metal layer. Subwavelength DLGs have been used as reflection polarizers[6,7] and to sensitively control the transmission properties of light.[8–13]

In this work, we study both experimentally and theoretically the light scattering properties of DLGs with a period comparable to the wavelength of the incident light. The DLGs are fabricated using Au on SiO_2 substrates by nanoimprint lithography. The scattering intensity of light is measured for the fabricated DLGs. Each measured spectrum shows a resonant peak whose wavelength position depends on the DLG period. It is also found that the peak is accompanied by a closely lying dip. The light scattering properties of the DLGs are also simulated by employing a scattering matrix method.[14] It is found that SPPs can be excited in the DLG systems with a separation of up to 150 nm between the two Au grating layers. It is also shown that the resonant scattering observed experimentally is caused by the excitation of SPPs at the top interface of the DLGs. Based on these experimental and theoretical findings, operation of a DLG as an efficient wavelength demultiplexer is proposed.

Our DLG devices are fabricated with nanoimprint lithography, reactive ion etching, and thermal evaporation of Au on thick SiO_2 substrates.[15] A schematic of a DLG is shown in Fig. 1(a) where the top side of the DLG is filled with air and the SiO_2 substrate is thick enough to be considered as optically infinitely thick. We denote by w the width of the Au wires in the top grating layer. The width of the wires in the bottom grating layer alternates between d_1 and d_2. The period of a DLG is then $L = d_1 + d_2 + 2w$ when $d_1 \neq d_2$ or $L = d_1 + w$ when $d_1 = d_2$. The thickness of the Au layers is h_1 and the separation between the top and the bottom Au grating layer is h_2. Light is incident on a DLG from the top air side at an angle θ_{inc}. A scanning electron microscope (SEM) image of one of the fabricated DLGs is shown in Fig. 1(b).

In the experiment, unpolarized light is incident on the DLGs at $\theta_{inc} = 62°$ and the scattered light is collected with an objective lens of numerical aperture of NA = 0.5 oriented normal to the grating structure [see Fig. 1(a) for a schematic]. The scattering intensity spectra, here defined as the intensity of the collected light after normalization by the

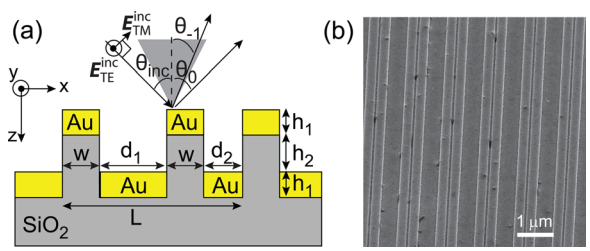

FIG. 1. (Color online) (a) Schematic of a DLG of period L. The (long) axes of the Au wires are parallel to the y direction. The direction of the incident light lies in the xz plane and is defined by θ_{inc}. As examples, the directions of the 0th and −1st diffracted orders are specified and marked by θ_0 and θ_{-1} in the figure. The shaded triangle indicates the cone of the light collected by an objective lens with NA = 0.5 oriented normal to the DLG. $E_{TE}^{inc} \parallel e_y$ and $E_{TM}^{inc} \perp e_y$ define the TE and TM polarized components of the electric field of the incident light. (b) SEM image (the top view) of a fabricated DLG with $d_1 = 500$ nm, $d_2 = 100$ nm, $w = 200$ nm, $h_1 = 60$ nm, and $h_2 = 30$ nm. The scale bar is 1 μm.

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emission spectrum of the light source, are shown in Fig. 2(a) for three DLGs with $d_1 = 500$ nm, $w = 200$ nm, $h_1 = 60$ nm, and $h_2 = 30$ nm, but with the three different values of $d_2 = 100$, 200, and 500 nm, respectively. A single resonant peak is clearly seen in the spectra of all the three DLGs. The peak is at $\lambda = 662$ nm when $d_2 = 100$ nm, at $\lambda = 688$ nm when $d_2 = 500$ nm, and at $\lambda = 721$ nm when $d_2 = 200$ nm. The peak height is the lowest at $\lambda = 662$ nm (the shortest wavelength) and the highest at $\lambda = 721$ nm (the longest wavelength). There is also an accompanied dip to the resonant peak in each scattering spectrum at a wavelength position slightly red-shifted from the peak.

To reveal the physical origin of the resonant behavior observed in the experiment, electrodynamic simulations using a scattering matrix method[14] are carried out. We use tabulated values for the wavelength dependent refractive index n of SiO_2 and Au.[16,17] For air, $n = 1.0$ is used. Due to the periodicity in the DLGs, the reflected light consists of the components of different diffracted orders that propagate in different but well defined directions. We use the reflectance R_m to denote the normalized intensity of the light scattered into the mth diffracted order and the angle θ_m to define the corresponding propagation direction of the scattered light. We integrate the intensity of the scattered light only over the scattering angles of $|\theta| < 30°$ corresponding to NA = 0.5 in the experimental setup. To meet the experimental condition of unpolarized light, we conduct two kinds of simulations, one with transverse-electric (TE) and the other with transverse magnetic (TM) polarized incident light, and average the results of the simulations. The obtained scattering intensity spectra are shown in Fig. 2(b). The spectra show, without any fitting parameters, peaks and accompanied dips whose positions match excellently with the experimental ones shown in Fig. 2(a). The overall shapes of the experimental spectra are also excellently reproduced by the simulations.

It is found from the simulations (not shown here) that the resonant peaks and dips are caused by the TM polarized component of the incident light. One of the differences between TM and TE polarized light is that SPPs can be excited only by TM polarized light in these DLGs.[1] Therefore, in the following, we focus our study on the scattering characteristics of TM polarized incident light.

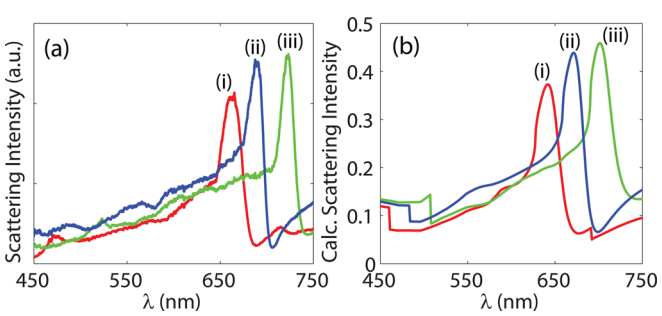

FIG. 2. (Color online) (a) Scattering intensity spectra measured for three DLGs with $h_1 = 60$ nm, $h_2 = 30$ nm, $d_1 = 500$ nm, and $w = 200$ nm, and (i) $d_2 = 100$ nm, (iii) $d_2 = 200$ nm, and (ii) $d_2 = 500$ nm. Here, unpolarized light is incident with $\theta_{inc} = 62°$ toward the DLGs and collected with an objective lens of NA = 0.5 oriented normal to the DLGs. (b) Simulated scattering intensity spectra for the same three DLGs and incident light conditions as in (a).

The dispersion relation of the in-plane k vector of a SPP at an interface between a dielectric of permittivity ϵ_d and a metal of permittivity ϵ_m is[1,14]

$$k_{spp}(\lambda) = \frac{2\pi}{\lambda}\sqrt{\frac{\epsilon_m(\lambda)\epsilon_d(\lambda)}{\epsilon_0[\epsilon_m(\lambda)+\epsilon_d(\lambda)]}}, \tag{1}$$

where ϵ_0 is the permittivity of vacuum. The wavelengths λ_p for which SPPs could be excited in a periodic system can be obtained, to a good approximation, by the matching[1,14]

$$\left|\frac{2\pi\sqrt{\epsilon_{inc}(\lambda_p)/\epsilon_0}}{\lambda_p}\sin(\theta_{inc}) + \frac{2\pi p}{L}\right| = \mathrm{Re}[k_{spp}(\lambda_p)]. \tag{2}$$

Here, p is an integer and ϵ_{inc} is the permittivity of the dielectric on the side from which the light is incident. We consider the case in which $\epsilon_{inc} = \epsilon_{air} = \epsilon_0$. The positions of the peaks in Fig. 2(b) match excellently with the predicted wavelengths of $\lambda_{-3} = 642$ nm for $d_2 = 100$ nm ($L = 1000$ nm), $\lambda_{-2} = 672$ nm for $d_2 = 500$ nm ($L = 700$ nm), and $\lambda_{-3} = 702$ nm for $d_2 = 200$ nm ($L = 1100$ nm), respectively, for which SPPs could be excited at an air-Au interface.

To further study the relation between the resonant light scattering behavior and the excitation of SPPs in the DLGs, we explore theoretically the effect of varying θ_{inc} on the reflectances. We concentrate on the DLG with $d_1 = d_2 = 500$ nm, $w = 200$ nm, $h_1 = 30$ nm, and $h_2 = 60$ nm. Figures 3(a) and 3(b) show the θ_{inc} dependencies of the specular reflectance R_0 and of the reflectance into all higher diffracted orders ($R - R_0$), respectively. In these figures, we have indicated with two curves the wavelengths λ_p for which SPPs of $p = -2$ and $p = 1$ at an air-Au interface could be excited according to Eq. (2). Figure 3(a) shows that there exist two clear dips in R_0 in the region of $\lambda > 550$ nm, while Fig. 3(b) shows that there exist two prominent peaks in $R - R_0$ in the region of $\lambda > 600$ nm. The positions of these dips and peaks fall nicely on the two curves predicted according to Eq. (2) for possible SPP excitations at an air-Au interface. In the region of $\lambda < 550$ nm, neither R_0 nor $R - R_0$ shows signs of strong resonances at positions where SPPs could be excited. This could be due to the fact that Au becomes more absorbing at these shorter wavelengths,[17] which makes it less possible to excite the SPPs resonantly. In addition, we note that weak peak features are observable in R_0 in the region of

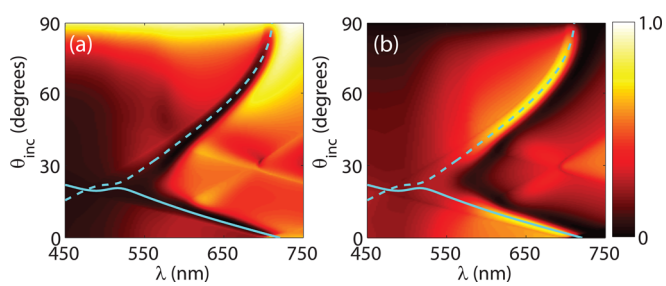

FIG. 3. (Color online) (a) Simulated R_0 (specular reflectance) as a function of θ_{inc} and λ for a DLG with $d_1 = d_2 = 500$ nm, $w = 200$ nm, $h_1 = 60$ nm, and $h_2 = 30$ nm. The incident light is TM polarized. The curves show the wavelengths for which the SPPs of $p = -2$ (dashed line) and $p = 1$ (solid line) could be excited at an air-Au interface according to Eq. (2). (b) Same as in (a) but for $R - R_0$, the reflectance into all higher diffracted orders.

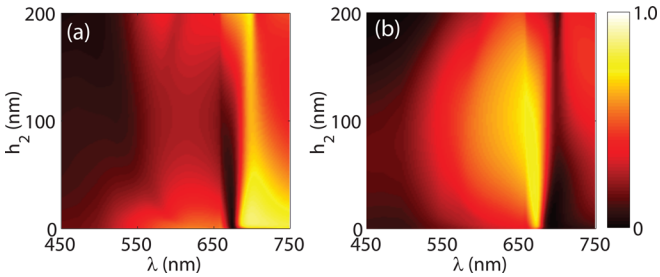

FIG. 4. (Color online) (a) Simulated R_0 (specular reflectance) as a function of λ and h_2 for a DLG with $d_1 = d_2 = 500$ nm, $w = 200$ nm, and $h_1 = 60$ nm. The incident light is TM polarized and $\theta_{inc} = 62°$. (b) Same as in (a) but for $R - R_0$, the reflectance into all higher diffracted orders.

600 nm $< \lambda <$ 750 nm and $10° < \theta < 40°$. These features can be attributed to the Rayleigh anomalies[5] caused by diffraction of the SiO_2 substrate.

Evidently, we find that the wavelengths for which SPPs can be excited at an air-Au interface match excellently with the positions of the dips in R_0 and the peaks in $R - R_0$. This shows that SPPs can be excited at the interface between the air and the top side of the DLGs. The dispersion relation of these SPPs follows very closely that of SPPs at a planar air-Au interface given by Eq. (1).

Figures 4(a) and 4(b) show R_0 and $R - R_0$ for varying h_2 at $\theta_{inc} = 62°$. For $h_2 < 150$ nm, there is a dip in R_0 at $\lambda = 675$ nm. This wavelength is close to the wavelength of $\lambda_{-2} = 672$ nm for which a SPP of $p = -2$ at an air-Au interface could be excited. R_0 rises to a high value at $\lambda = 700$ nm. $R - R_0$ shows a complementary behavior with a peak at $\lambda = 675$ nm and a dip at $\lambda = 700$ nm. The resonance at $\lambda = 675$ nm caused by the excitation of the SPP disappears when h_2 is increased beyond 150 nm. This indicates that an electromagnetic near-field coupling between the top and the bottom Au grating layer is needed for the excitation of a SPP in these DLGs.

It is clearly seen in Figs. 4(a) and 4(b) that when $h_2 < 150$ nm, R_0 shows a dip and R_{-1} shows a peak at $\lambda = 675$ nm, while R_0 shows a peak and R_{-1} shows a dip at $\lambda = 700$ nm. Here, we note that for $\lambda > 659$ nm, only the –1st and the 0th diffracted orders exist in the DLGs and then, $R_{-1} = R - R_0$. The above complementary dip-peak and peak-dip behaviors can be employed for wavelength demultiplexing. Light of $\lambda = 675$ nm is reflected mainly into the -1st diffracted order with $\theta_{-1} = -4.7°$, while light of $\lambda = 700$ nm is reflected mainly into the 0th diffracted order with $\theta_0 = \theta_{inc} = 62°$. Consequently, the DLGs offer a large angular separation (i.e., demultiplexing) of 66.7° of these two closely lying wavelengths. The operational wavelength of the DLG demultiplexer is tunable and Eq. (2) can be used to guide the demultiplexer design.

In summary, we have studied both experimentally and theoretically the scattering properties of DLGs made from Au on SiO_2 substrates. We find that the DLGs support the excitations of SPPs for the separation of up to 150 nm between the top and the bottom Au grating layer. These excitations cause resonant peaks and accompanied dips in the measured collective reflectance spectra. We have also found that the excitation of a SPP can cause a dip and a closely lying peak in the specular reflectance spectrum, and a complementary peak and a closely lying dip in the reflectance spectrum of a non-specular diffracted order. Based on these complementary dip-peak and peak-dip behaviors of the reflectances, the operation of the DLGs as efficient wavelength demultiplexers has been proposed. In fact, we have found that this SPP assisted demultiplexing works also at telecommunication wavelengths and also when the Au wires are completely surrounded by SiO_2, i.e., in the conditions relevant for integrated optics applications. However, these topics are still under extensive investigations and the results will be reported elsewhere later.

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