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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 SiO2 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.

Our DLG devices are fabricated with nanoimprint lithography, reactive ion etching, and thermal evaporation of Au on thick SiO2 substrates. A schematic of a DLG is shown in Fig. 1(a) where the top side of the DLG is filled with air and the SiO2 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 d1 and d2. 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 \( \theta_{inc} \). 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 \( \theta_{inc} = 62^\circ \) 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 incident light intensity, of a DLG is then

\[
\frac{I_{sc}}{I_{inc}} = \frac{1}{\cos \theta_{inc}} \frac{d}{d_1 + d_2 + 2w} \frac{d_1 + w}{d_1 + w} \frac{1}{\cos \theta_{eye}}
\]

for the zeroth diffraction order and

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for the -1st diffraction order. The excitation of a SPP is then seen as a dip in the reflectance if only the zeroth diffracted order exists. 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 and to sensitively control the transmission properties of light.

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 SiO2 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. 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.

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mental spectra are also excellently reproduced by the scattering angles of corresponding propagation direction of the scattered light. The peak height is the lowest 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\textsuperscript{14} are carried out. We use tabulated values for the wavelength dependent refractive index of SiO\(_2\) and Au.\textsuperscript{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 \(m\)th diffracted order and the angle \(\theta_m\) to define the corresponding propagation direction of the scattered light. We integrate the intensity of the scattered light only over the scattering angles of \(|\theta| < 30^\circ\) 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.\textsuperscript{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 \(d_1 = 500\) nm, \(w = 200\) nm, \(h_1 = 60\) nm, and \(h_2 = 30\) nm, \(d_1 = 500\) nm, and \(w = 200\) nm, \(h_1 = 30\) nm, and \(h_2 = 60\) nm, and \(d_2 = 100\) nm, \(d_2 = 200\) nm, \(d_2 = 500\) nm, and \(d_2 = 500\) nm. Here, unpolarized light is incident with \(\theta_m = 62^\circ\) 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).](image)

The dispersion relation of the in-plane \(k\) vector of a SPP at an interface between a dielectric of permittivity \(\varepsilon_d\) and a metal of permittivity \(\varepsilon_m\) is\textsuperscript{11,14}

\[
k_{\text{spp}}(\lambda) = \frac{2\pi}{\lambda} \sqrt{\frac{\varepsilon_m(\lambda)\varepsilon_d(\lambda)}{\varepsilon_0(\lambda)\varepsilon_m(\lambda) + \varepsilon_d(\lambda)}},
\]

where \(\varepsilon_0\) is the permittivity of vacuum. The wavelengths \(\lambda_p\) for which SPPs could be excited in a periodic system can be obtained, to a good approximation, by the matching\textsuperscript{1,14}

\[
2\pi R_{\text{inc}}(\lambda_p)/\lambda_p \sin(\theta_{\text{inc}}) + 2\pi p/L = \text{Re}[k_{\text{spp}}(\lambda_p)].
\]

Here, \(p\) is an integer and \(\epsilon_{\text{inc}}\) is the permittivity of the dielectric on the side from which the light is incident. We consider the case in which \(\epsilon_{\text{inc}} = \epsilon_{\text{air}} = \epsilon_0\). The positions of the peaks in Fig. 2(b) match excellently with the predicted wavelengths \(\lambda_{-3} = 642\) 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 \(\theta_{\text{inc}}\) 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 \(\theta_{\text{inc}}\) 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 \(\lambda_p\) 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,\textsuperscript{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 \(\theta_{\text{inc}}\) and \(\lambda\) 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.](image)
600 nm < \lambda < 750 nm and 10^\circ < \theta < 40^\circ. These features can be attributed to the Rayleigh anomalies caused by diffraction of the SiO_2 substrate.

Evidently, we find that the wavelengths for which SPPs can be excited can be well matched with the positions of the dips in \( R_0 \) and the peaks in \( \Delta R_0 \). 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-air and the top side of the DLGs. The dispersion relation shows that SPPs can be excited at the interface between the Au on SiO_2 substrates. We find that the DLGs support 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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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 \( \Delta R_0 \). 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 \( \theta_{inc} = 62^\circ \). For \( h_2 < 150 \) nm, there is a dip in \( R_0 \) at \( \lambda = 675 \) nm. This wavelength is close to the wavelength of \( \lambda = 672 \) 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 \( R - R_1 \) shows a peak at \( \lambda = 675 \) nm, while \( R_0 \) shows a peak and \( R - R_1 \) shows a dip at \( \lambda = 700 \) nm. Here, we note that for \( \lambda > 659 \) nm, only the \(-1\)-st and the 0th diffracted orders exist in the DLGs and then, \( R - R_1 = R - R_0 \). 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 \(-1\)-st diffracted order with \( \theta_{-1} = -4.7^\circ \), while light of \( \lambda = 700 \) nm is reflected mainly into the 0th diffracted order with \( \theta_0 = \theta_{inc} = 62^\circ \). 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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