Optical transmission through double-layer metallic subwavelength slit arrays

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We present measurements of transmission of infrared radiation through double-layer metallic grating structures. Each metal layer contains an array of subwavelength slits and supports transmission resonance in the absence of the other layer. The two metal layers are fabricated in close proximity to allow coupling of the evanescent field on individual layers. The transmission of the double layer is found to be surprisingly large at particular wavelengths, even when no direct line of sight exists through the structure as a result of the lateral shifts between the two layers. We perform numerical simulations using rigorous coupled wave analysis to explain the strong dependence of the peak transmission on the lateral shift between the metal layers.

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Subwavelength structures on the surface of a metal film can strongly modify its interaction with electromagnetic fields.[1] Recently metal films with periodic subwavelength structures have been shown to exhibit intriguing optical properties.[2] For instance, Ebbesen and co-workers[3] discovered that the transmission of light through an array of subwavelength holes on an optically thick metal film was significantly larger than the predictions of standard aperture theory at specific wavelengths. Since then other geometries, such as one-dimensional slit arrays,[4–11] annular apertures,[12] and a single hole or slit surrounded by periodic corrugations[13–15] have all been shown to possess extraordinary transmission and beaming characteristics. The excitation of surface plasmons and/or diffracted evanescent waves on the upper and lower surfaces of the metal films have been suggested to play a crucial role in the strong transmission.[3,16] For slits and annular apertures, excitation of guided modes can also lead to efficient transmission.[4]

While much progress has been made with subwavelength structures on a single layer of metal, the interaction between the strong evanescent fields on the surfaces of two or more nanostructured metal layers in close proximity[17–19] could lead to novel optical properties and offer new functionalities. In this Letter we report measurements of far-field optical transmission through two metal layers placed in close proximity. Each metal layer contains an array of subwavelength slits that supports transmission resonances in the absence of the other metal layer. The separation between the layers is chosen to be small enough to allow coupling of the evanescent fields on the surfaces of the two metal films. We find that the transmission is surprisingly large at particular wavelengths and depends strongly on the lateral shifts between the two layers. In some devices, the lateral displacement of the two metal layers permits no direct line of sight through the structure. Nonetheless, the transmission remains remarkably high at resonance, comparable with the single-layer case. We perform numerical simulations to explain the strong dependence of the peak transmission on the lateral shift between the layers. Our experimental data and numerical simulations indicate that the spatial distribution of the electromagnetic fields at the surface of a single, isolated metal layer plays an important role in determining the resonant mode and optical transmission in the double-layer structure.

Our samples consist of single- and double-layer aluminum films that are surrounded by silicon oxide. The aluminum structures were fabricated on a silicon wafer. Completed structures were attached by optical adhesives onto a quartz substrate, and the silicon was completely removed by a combination of wet etching and mechanical polishing. The left-hand inset of Fig. 1a shows the cross section of a single-layer grating (sample A) with a period of 2 μm, slit width of 0.4 μm, and aluminum thickness of 0.41 μm. The dotted curve in Fig. 1a shows the transmission spectrum for TM polarization (electric field perpendicular to slits) for single-layer sample A. To account for the absorption of the optical adhesive at 2.7 and 3.5 μm wavelengths, all transmission data have been normalized to the transmission through a clear area adjacent to the structure that consists of the quartz substrate, optical adhesive, and silicon oxide layer but no aluminum layer. The transmission through the single-layer slit array peaks at a wavelength of $\sim$3.1 μm, with maximum transmission as large as 38% even though the fractional area of the slits is less than 20% and the wavelength is about 10 times larger than the slit widths. Taking into account the

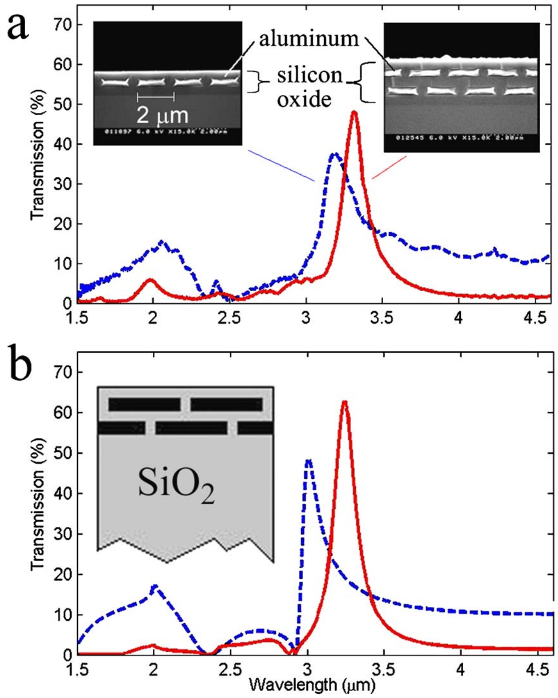

Fig. 1. (Color online) a, Insets, scanning electron micrograph of (left) the cross section of single-layer sample A and (right) double-layer sample B1. Measured transmission of TM polarized light through (dotted curve) sample A and (solid curve) sample B1. b, Transmission calculated by RCWA. Inset, cross-section schematic of the double-layer structure used in the calculations.

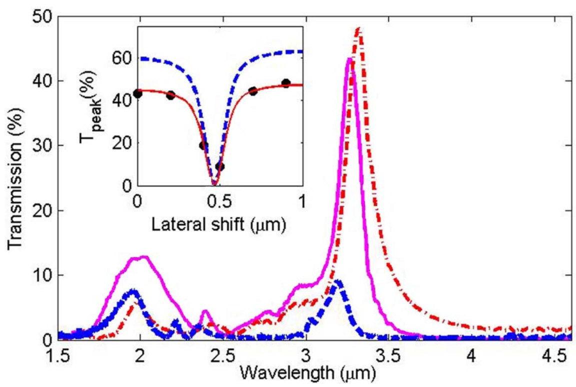

Fig. 2. (Color online) Measured transmission for samples B1, B2 and B3 with lateral shifts of (dashed–dotted), 0.9, (dashed) 0.5, and (solid) 0 μm respectively, between the two aluminum layers. Inset (filled circles) measured and (dotted curve) calculated peak transmission as a function of lateral shift. The solid curve is the calculated transmission scaled by a factor of 0.75.

refractive index of silicon oxide (1.53), peak transmission occurs at a wavelength slightly higher than the 2 μm periodicity of the structure. This transmission peak has been studied in detail by a number of investigators and was attributed either to the coupled surface-plasmon mode[4,8,10] of transmission through narrow slits or to the excitation of evanescent diffracted waves.[16]

The solid curve in Fig. 1a shows the measured optical transmission for sample B2 (right-hand inset in Fig. 1(a)) that contains two metal layers in close proximity to each other. The arrays of slits on the two metal layers are displaced laterally by 0.9 μm, an amount equal to about half the grating period. Even though no direct line of sight exists from the input surface to the output surface, the peak optical transmission exceeds the single-layer case, with the transmission peak shifted to slightly longer wavelengths. The peaks do not arise from ordinary etalon effects between two partially transmitting metallic layers, because the layer spacing (0.5 μm) is much smaller than the wavelength of light in silicon oxide ($\sim$2 μm). We also emphasize that the period of the grating is smaller than the peak wavelength in silicon oxide, so that normally incident light produces no propagating diffractive orders emerging from individual single layers.

To elucidate the origin of the efficient transmission through the double-layer structures, we fabricated a set of samples with different lateral shifts between the two metallic layers. We find that transmission through the double-layer structure depends strongly on the lateral shifts of the pattern on the two metal layers. Figure 2 compares the transmission spectrum for samples B1, B2 and B3 with lateral shifts of 0, 0.9, and 0.5 μm, respectively. The transmission efficiency of sample B3 is significantly lower than samples B1 and B2. The filled circles in the inset of Fig. 2 show the dependence of the peak transmission (T_{peak}) on the lateral shifts of the two metal layers for six different samples. When the lateral shift between the two layers is close to zero (perfect alignment) or is 1 μm (half the grating pitch), the peak transmission is large. The smallest peak occurs at lateral shifts around 0.5 μm, corresponding to a quarter of the grating period.

We perform numerical simulations by using rigorous coupled-wave analysis (RCWA)[20] to investigate the origin of the large transmission through the double layers and its dependence on the lateral shift between the layers. RCWA is a numerical method that analyzes the transmission and reflection of periodic structures. The structure is divided into multiple layers, and the calculation involves spatial Fourier expansion of the electromagnetic field and dielectric functions in each layer. By requiring that the electromagnetic fields satisfy Maxwell's equation within each layer as well as the boundary conditions between adjacent layers, RCWA reduces the electromagnetic field calculation to an algebraic eigenvalue problem. We used the tabulated values[21] for the dielectric function of aluminum and a refractive index of 1.53 for the silicon oxide layers. The layer geometries of the samples are slightly simplified in the calculations. At the output side of the metal film, the silicon oxide–air interface is taken into account, whereas at the input side the small mismatches among the refractive indices of silicon oxide, the optical adhesive, and the quartz substrate is neglected. In other words, the silicon oxide is assumed to extend through all space at the input side, as shown in the inset of Fig. 1b. We kept 100 orders in the Fourier expansion of the electromagnetic field and dielectric

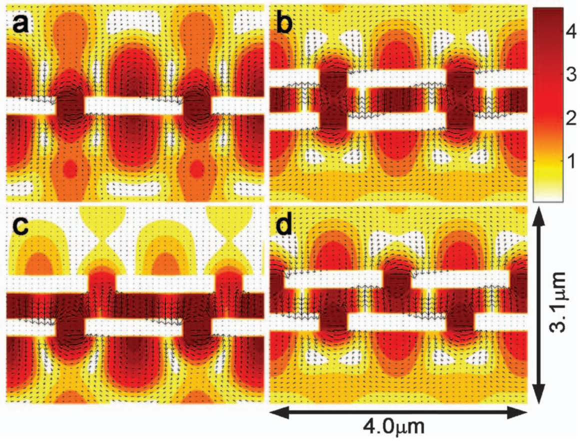

Fig. 3. Electromagnetic field distribution at resonance for, a, a single metal layer and, b–d, double layers with lateral shifts of 0, 0.5, and 1 μm, respectively. Light is incident from the bottom with unit amplitude. The magnetic fields are directed out of the page, and the magnitude is represented by the color scale, whereas the arrows represent the electric fields. For simplicity, the silicon oxide layers are assumed to extend through all space above and below the metal layer.

function. Figure 1b plots the calculated zero-order transmission spectrum for TM-polarized light through samples A and B1. The location of the transmission peaks at ~3.1 μm, and other details are in good agreement with our data. In addition, the RCWA calculations reproduced the dependence of the peak transmission as a function of the lateral shift between the two metal layers, as shown by the dotted curve in the inset of Fig. 2. Although the agreement between data and calculations is not exact, probably due to additional losses in samples and to the simplification of the sample geometry in the calculations, the RCWA calculation reproduces all the main features of our measurement, including the minimum in peak transmission at a lateral shift of about 0.5 μm between the two layers.

Figure 3 shows the electromagnetic fields obtained from RCWA calculations. The field distribution in a single metal layer (Fig. 3a) provides useful insights in understanding the dependence of the peak transmission on lateral shifts. When the two metal layers are far apart, each layer has electromagnetic field distribution at resonance similar to Fig. 3a. As the two layers are brought closer, the evanescent fields of the two layers begin to couple. If the top layer is perfectly aligned (Fig. 3b) or misaligned (Fig. 3d) with the bottom layer, the positions with maximum magnetic and electric field on the two layers overlap, leading to strong coupling and high transmission. In contrast, when the top layer is misaligned with the bottom layer by one quarter of the period (Fig. 3c), the field maxima on the bottom layer now coincide with the field minima on the top layer. As a result, the evanescent field coupling between the two layers is weak and the transmission is low. Our experimental data and numerical simulations indicate that the spatial distribution of the electromagnetic fields at the surface of a single, isolated metal layer is crucial in determining the resonant mode and the coupling of evanescent fields for two metal layers in close proximity.

The strong transmission of light through bilayer subwavelength metallic slits opens up a new dimension in the design and operation of plasmonic devices. It appears likely that under the appropriate conditions high transmission also occurs in other multilayer geometries, such as subwavelength hole arrays[3] or annular corrugations.[12] Understanding the coupling of evanescent waves in complex multilayer metallic nanostructures is of fundamental interest and practical importance in designing optical devices that could become important building blocks in future nano-optical systems.[2]

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