Extraordinary transmission in a narrow energy band for metallic gratings with converging-diverging channels

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Transmission metallic gratings with narrow and deep slits having the shape of converging-diverging channel (CDC) can exhibit enhanced transmission resonances for wavelengths larger than the periodicity of the grating. Using finite element method, the authors show that, by varying the gap size at the throat of CDC, the spectral locations of the transmission resonance bands can be shifted close to each other and have high transmittance in a very narrow energy band. Also, the proposed shape can lead to almost perfect transmittance for any desired wavelength by carefully optimizing the metallic material, gap at the throat of CDC, and grating parameters. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2357037]

In late 1980s the concept of photonic crystals emerged, which initiated studies of metallic gratings, as examples of one-dimensional (1D) periodic media.[1] Although some theoretical studies have been done on the transmission gratings since then, they did not receive much attention because it has been thought that the transmission through the subwavelength apertures is very low in accordance to the standard aperture theory.[2] The finding of extraordinary transmission through subwavelength holes has sparked renewed interests in studying the transmission gratings (or slits), which are 1D version of the structure studied by Ebbesen *et al.*,[3] to explain the underlying physics for enhanced transmission.

The dielectric response, $\varepsilon(\omega)$, of a metal is governed mainly by its free electron plasma and for frequencies smaller than the plasma frequency the real part of $\varepsilon(\omega)$ is negative, which make it behaves like a photonic insulator at those frequencies. Negative ε has another consequence: the metal-dielectric interface can support surface electromagnetic modes called surface plasmon polaritons (SPPs). The dispersion relation of these modes for a flat interface does not cross the light cone and so SPP cannot be excited by a direct incident plane wave. However, if the metal-dielectric interface is modulated periodically, the SPP bands fold allowing the external radiation to excite the SPP modes.[4] Therefore, when the frequency ω and the in-plane wave vector $\mathbf{k}_{\parallel}$ of the light scattered by the grating vector match the surface mode (or SPP mode) of the structure, the transmittance and reflectance are modified.[5] Hence the physics behind the enhanced transmission in metallic subwavelength apertures was initially considered as the coupling of the incident light via diffraction to the SPP modes of the metallic structure.[2,6] This type of explanation was expected since surface plasmons are responsible for a type of grating anomalies, as was previously established.[7] The Wood-Rayleigh anomaly in the transmission spectra is due to the vanishing or emerging of a diffracted order above or below the grating in vacuum.[8] There is one more kind of anomaly that appears in TM-polarized reflection or transmission spectra of metallic gratings, which is called the resonance anomaly.[9] For this anomaly the SPP resonance modes on lower and upper surfaces of the gratings are excited when one of the diffracted waves is coupled to the SPP modes. However, there are other kinds of electromagnetic resonances, such as the cavity modes or waveguide resonances, which may also play an important role in enhanced transmission.[10] It was reported that in order to have high transmission through metallic gratings the waveguide mode resonance in the channel is the only effective way, even at the SPP resonance mode excitation wavelength.[11] It was also reported that for lamellar transmission metallic gratings there are two transmission resonances: coupled SPP modes on both the horizontal surfaces of the metallic grating for $\lambda \sim d$ and cavity or waveguide modes located inside the slits for $\lambda \gg d$.[12]

In this letter, we propose a change in the slit channel shape of the grating structure from a straight channel to converging-diverging channel (CDC) (Fig. 1). Gold lamellar gratings are considered. The dielectric function of gold described in this letter is from the tables reported in Ref. 13. The transmission for metallic lamellar gratings with transverse electric polarization suffers a cutoff wavelength.[14] Hence, we have analyzed the metallic gratings with only TM polarization in order to study whether the enhanced transmission could be achieved for any desired wavelength with the CDC structure. Commercially available finite element software (FEMLAB 3.1I) was used for solving the Maxwell equations. It is plausible to use Maxwell's equation when the absolute lower limit of the length of macroscopic domain is

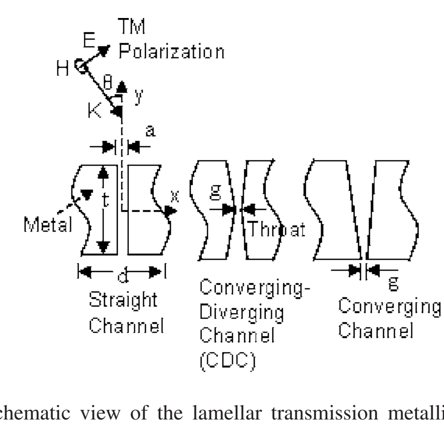

FIG. 1. Schematic view of the lamellar transmission metallic gratings in vacuum with grating parameters as period $d=3.5$ μm, aperture $a=0.5$ μm, and thickness $t=3.0$ μm.

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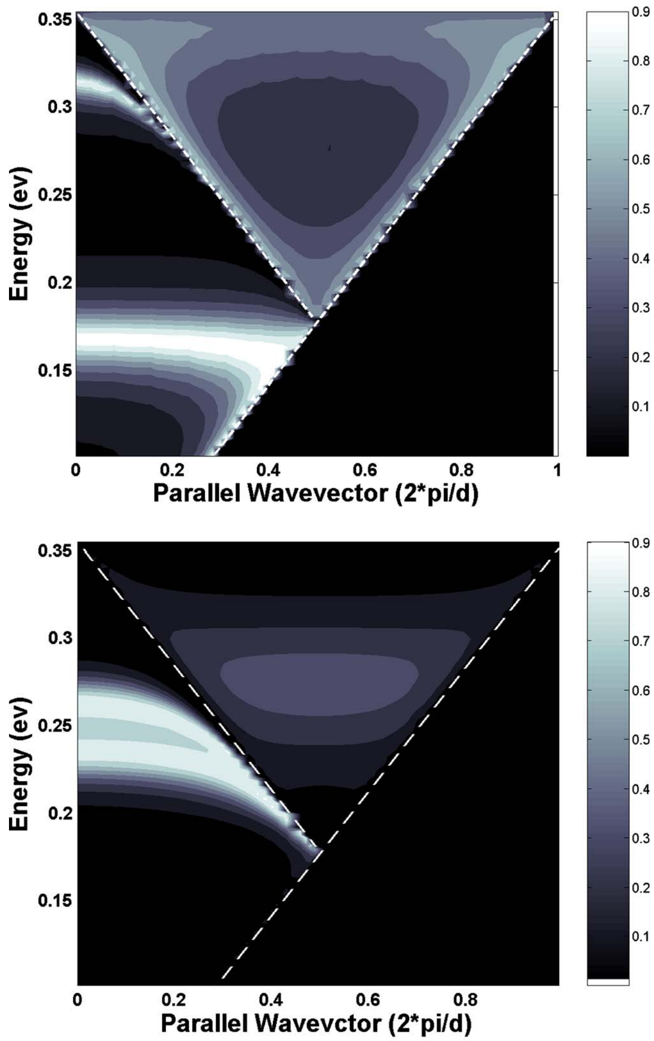

FIG. 2. (Color online) Photonic band structure of the surface plasmons responsible for the transmission resonances of gold gratings in vacuum with slit shape as (a) straight channel and (b) CDC with $g=5$ nm. The grating parameters are fixed at $d=3.5$ μm, $a=0.5$ μm, and $t=3.0$ μm. Also seen in figures are energetic positions (white dashed lines) of the SPP modes.

10 nm.[15] A two-dimensional computational domain surrounded by periodic boundary conditions and perfectly matching layer[16] were used.

In Fig. 2(a) we show the photonic band structure of a grating with straight channel in vacuum. Also, we show the energetic positions of the SPP modes (white dashed lines) for a nearly flat metal surface. Figure 2(a) shows that there are two transmission resonance bands, with the higher energy band following close to the SPP mode energetic positions and the lower energy band present at (~0.17 eV) is almost independent of "θ." The transmission resonances close to the SPP dispersion and at 0.17 eV correspond to coupled SPP mode and a waveguide resonance mode, respectively, as reported in Ref. 12. It is shown in Fig. 2(b) that when the channel shape is changed to CDC the resonance of coupled SPP mode is redshifted and the waveguide resonance mode is blueshifted. In addition, the two resonance bands have now almost merged together. This means that there would be only one transmission band at a particular gap near the throat where the previous high and low energy bands mix to give a single "hybrid band."

The evolution of hybrid band can be seen in Fig. 3, where the transmittance of CDC as a function of wavelength

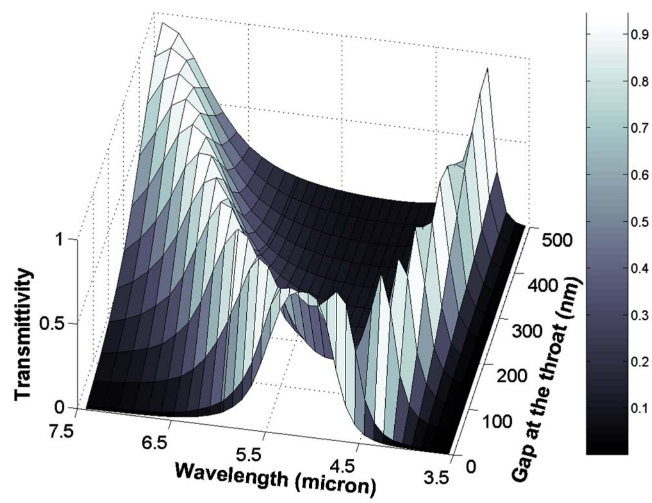

FIG. 3. (Color online) Transmittance of the gold gratings in vacuum for CDC as a function of the wavelength and distance at the gap of throat with constant grating parameters as $d=3.5$ μm, $a=0.5$ μm, and $t=3.0$ μm.

and gap size at the throat is shown. We can see that at ~7.4 μm wavelength the decrease in gap size at throat would result in the decrease of the transmittance. At smaller wavelengths the transmittance which was low for the straight channel would increase when gap size decreases and reach a maximum before decreasing with any further decrease in gap sizes. Also, it is shown in Fig. 3, around 5 μm wavelength the transmittance keeps increasing until the gap at throat is very small. At wavelengths smaller than 5 μm, the transmittance increases and decreases with the gap sizes as before. This trend continues until the wavelength is close to 3.9 μm wavelength where the transmittance variation with the gap sizes is same as that of at 7.4 μm. This indicates that the change in the channel shape from straight to CDC would lead to lower transmittance at wavelengths where already a waveguide resonance condition in the channel exists.

The transmittance of a channel with only converging shape is also calculated with the gaps at throat decreasing. Figure 4 shows the transmittance at ~6.35 μm incident wavelength for both CDC and converging channel with different gaps near the throat. It is shown that the transmittance

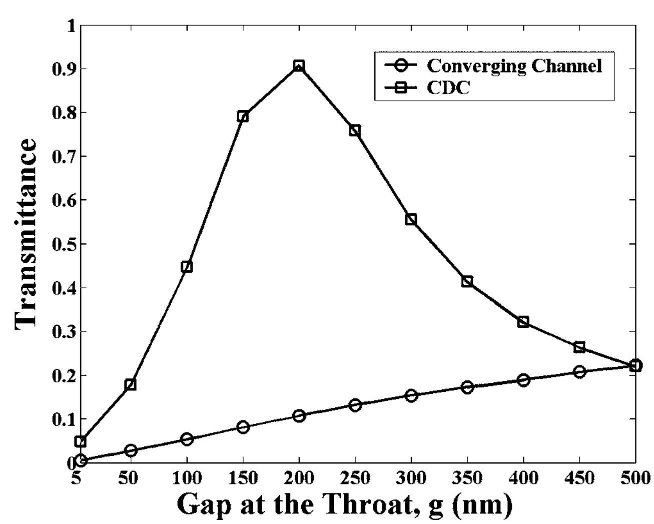

FIG. 4. Transmittance of a gold grating in vacuum with channel shape as CDC and converging at incident wavelength of 6.35 μm and with the grating parameters as $d=3.5$ μm, $a=0.5$ μm, and $t=3.0$ μm.

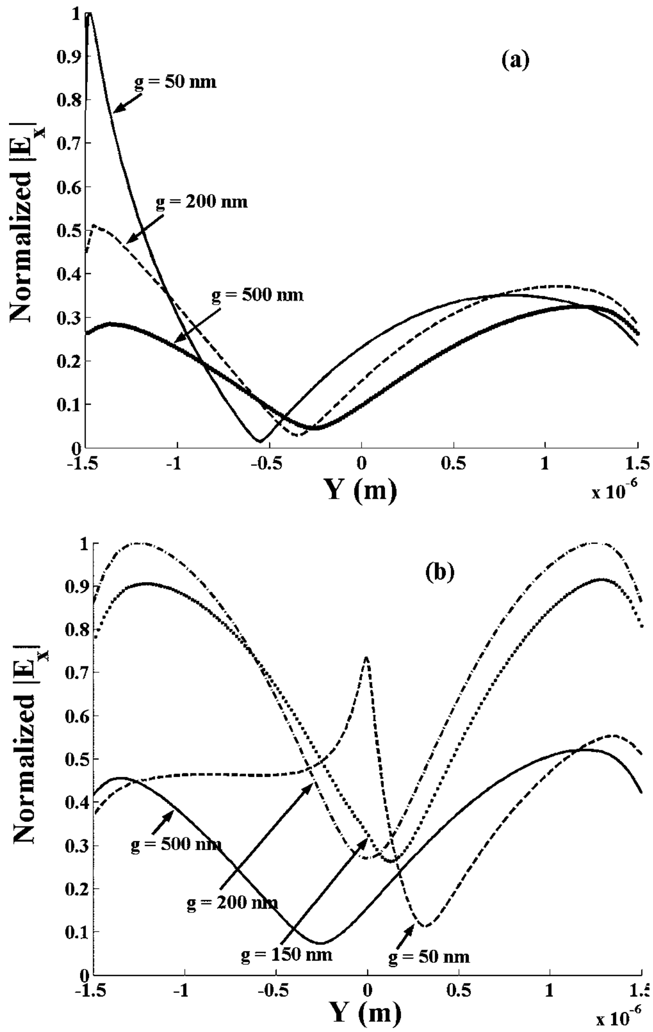

FIG. 5. Normalized electric field x component ($|E_x|$) at an incident wavelength of 6.35 μm along the channel centerline of a gold grating in vacuum with (a) converging channel and (b) CDC for different gaps at the throat and grating parameters as $d=3.5$ μm, $a=0.5$ μm, and $t=3.0$ μm.

for the converging channel decreases with the decrease in gaps at throat, whereas for CDC the transmittance increases until a certain gap at throat ($\sim$200 nm) and then decreases after that point, but remains higher than the converging channel transmittance for all gaps. This shows that changing the channel shape from straight to only converging would not result in higher transmittance.

The normalized magnitude of the x-component electric field intensity ($|E_x|$) along the centerline of the channel at $\sim$6.35 μm wavelength for the converging channel and CDC are shown in Fig. 5. In Fig. 5(a), we show that when the gap for converging channel is 500 nm or for straight channel, the wave inside the channel is an out-of-phase standing wave. The dipoles at channel ends have unequal strength which could be due to the destructive interference of the wave inside the channel.[14] With the decrease in gap near the throat the standing wave goes more out-of-phase. Also, when the gap near the throat keeps decreasing, the dipole at the throat starts to gain in strength and become stronger than the dipole at the other end of channel. This causes very less net energy to flow out of the channel. Similarly, from Fig. 5(b), we show that the wave inside the channel of CDC is a standing wave for different gaps near the throat. As the gap near throat in CDC keeps decreasing, the node keeps moving toward the center of channel. Also, the magnitudes of $|E_x|$ at two antinodes are increasing and becoming equal. This shows that the CDC shape of the channel is aiding the wave inside the channel to become an in-phase standing wave. The condition for an in-phase resonance inside the channel is given by[11] $2Kt+\Delta\phi=m2\pi$, where K is the wave vector of the resonance and $\Delta\phi$ is the phase change on the aperture of the slits. For the coupled SPP resonance the phase change of standing wave is π and so, the increase in length of the channel surface would need a higher wavelength for the above in-phase condition to be satisfied. Whereas for the waveguide resonance the phase change of standing wave is 2π and so the increase in length of channel surface would change an out-of-phase condition at a particular wavelength into an in-phase condition and this would cause the resonance to be blueshifted. Figure 5(b) shows that a small increase in length of channel surface or for a small decrease in the gap from 200 nm could make an in-phase standing wave go out of phase. In addition, the smaller gap throats could make the charges at throat gain in strength, just like in the case of converging channel [Fig. 5(a)].

In conclusion, we have shown that with CDC metallic gratings the transmission peaks can be selected by varying the width of gaps at the throat. This would then lead to high transmittance at any wavelength by carefully engineering the array material and CDC grating parameters. Also, high transmission resonances in a very narrow band can be achieved. This can have important applications, for example, in optical communications and optoelectronics where electromagnetic radiation with minimum diffractive effects is required.

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