# Fabrication and optical characterization of a 2D metal periodic grating structure for cold filter application

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## ABSTRACT

Cold filters, which simultaneously reflect infrared light and transmit visible light, prevent overheating in charge-coupled device cameras, microscopes, and other heat-sensitive equipment. This study proposes a cold filter based on a two-dimensional (2D) metal periodic grating structure. Conventional dielectric multilayer films with abrupt filtering characteristics are undesirably affected by incident angle, temperature, and polarization. To solve these problems, a 2D metal periodic grating structure, which does not depend on the polarization, was applied. The grating structure comprises an Au layer and an electron beam resist layer, and was fabricated by electron beam lithography. The optical characteristics of this structure in the visible light region were measured by a spectrometer, and the optical properties were related to structural parameters of the double-layer, 2D grating structure. In particular, the reflectance over the entire visible light spectrum decreased at periods of 800 nm and 1 μm. The wavelengths of minimum and maximum reflectance were shifted by changing the spacing between the upper and lower metal layers from 270 to 370 nm. Simulation results suggested that the interference between the upper and lower layers and the surface plasmon resonance between the metal and resist layers occur simultaneously. Therefore, in the visible light region, the reflectance and transmission spectra were controlled by altering the structure of the 2D metal periodic grating.

**Keywords:** cold filter, 2D metal periodic grating, electron beam lithography, interference, surface plasmon resonance

## 1. INTRODUCTION

Thermal radiation is a phenomenon in which thermal energy is emitted from the thermal source as electromagnetic waves. It is possible to effectively utilize the energy by spectral control of the thermal radiation. In recent years, microfabrication technologies have enabled the development of one- and two-dimensional (2D) diffraction gratings[1-3] and spectral emissivity with periodic microstructures, such as photonic crystals[4-6]. Alternatively, filters can be installed, which control the transmission and reflectance of electromagnetic waves at distances far from the thermal source. An example is the cold filter, which transmits visible light and reflects infrared light. Cold filters suppress the temperature rise in window glass, CCD cameras, and biological observation microscopes. Light in a cold filter is transmitted through dielectric multi-layer film with sharp rising characteristics, a wide wavelength spectrum, and a reflectance that can be altered by controlling the structure. However, the transmitted light is blue-shifted by oblique incidence and the temperature and polarization dependence of the reflectance and transmittance.

A general 2D metal grating structure admits light of wavelengths smaller than the opening and blocks (reflects) longer-wavelength light. Based on this concept, we propose 2D metal periodic grating structures to solve the problems of the dielectric multi-layer film. Ebbesen et al. demonstrated extraordinary optical transmission through periodic Ag subwavelength hole arrays.[7] This phenomenon is attributable to surface plasmon resonance combining with the transmitted light. Since then, surface plasmon polaritons have been exploited in several studies of high optical transmission.[8, 9] Klein–Koerkamp et al. fabricated periodic arrays of subwavelength holes[8], whereas Schouten et al. designed a double-slit structure.[9] These structures freely admit normally incident light. By the same phenomenon, we previously demonstrated extraordinary transmission through a double-layer wire grid polarizer.[10] In the present study, we apply this concept to a 2D metal grating structure targeted for cold filter applications. This structure is easily fabricated by electron-beam lithography (EBL) and sputtering. We report the transmission and reflectance spectra in the visible region by varying the period and the spacing between the upper and lower Au layers.

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## 2. EXPERIMENTAL METHOD

The 2D metal grating structures were fabricated on a glass substrate by EBL (CABL-8000, CRESTEC) and DC magnetron sputtering (SC-701MC, SANYU). The crossing line and space patterns were drawn by an EB resist (ZEP-520A, Zeon) on the glass substrate. The EBL process is described in.[11] After developing the resist layer, the Au layer was sputtered onto the EB resist pattern. In this study, we fabricated two types of 2D metal grating structures; single-layered (Figure 1 (a)) and double-layered (Figure 1(b)). The double-layered structure is more easily fabricated than the ordinal single-layered structures, because no lift-off process is required.[10] The thicknesses of the the Au layer was 30 nm. The spacing between the upper and lower Au layers ($\Delta h$) was controlled by the thickness of resist. The period $p$ of the WGP was varied as 800, 1000, and 2000 nm. The duty ratio of the line and space patterns was 0.5. The sample dimensions were ($1.5 \times 1.5$) $mm^2$. The structures of the samples were observed by scanning electron microscopy (SEM). The SEM images are shown in panels (c) and (d), respectively, of Figure 1.

The transmittances and reflectances were characterized by illuminating the fabricated sample with a normally incident tungsten lamp. The wavelength dependences of the transmittance and reflectance were determined. The 0th-order transmission and reflectance was detected by a monochrometer.

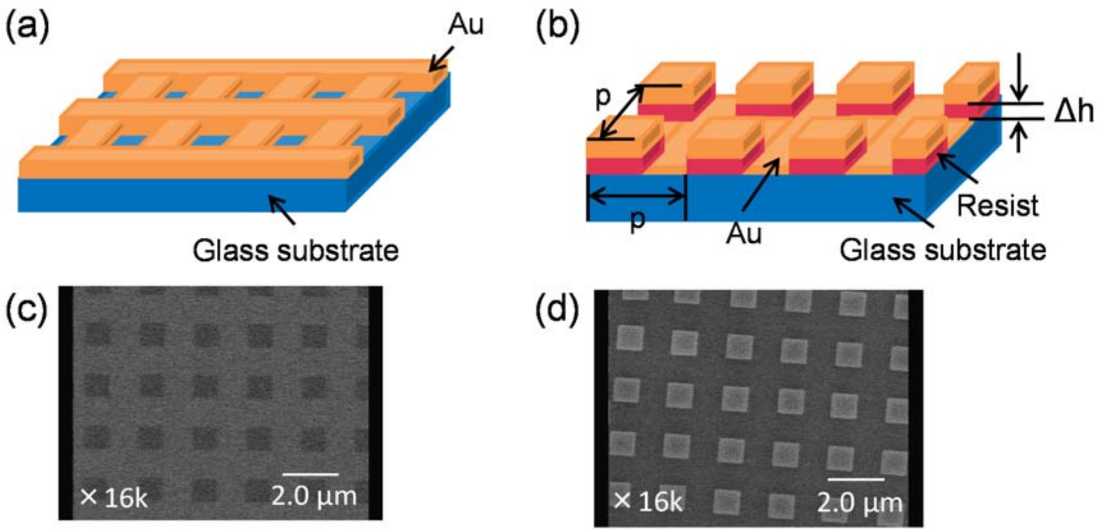


Figure 1. Schematics and surface SEM images: Schematics of (a) single-layer structure and (b) double-layer structure; SEM images of (c) single-layer structure and (d) double-layer structure.

## 3. EXPERIMENTAL RESULTS

### 3.1 Single-layer 2D metal grating structures

The reflection and transmission spectra of the 0th-order normally incident light were measured in single-layer 2D metal grating structures with different periods (2 µm and 1 µm). The reflectance spectra of both grating structures and of Au thin film are presented Figure 2. At wavelengths longer than 517 nm, corresponding to the gold plasma frequency, the reflectance of the 2D metal grating structures is lower than that of Au thin flat film, but the decrease is not remarkable.

To elucidate the reason for the similar reflectances, we conducted a rigorous coupled-wave analysis (RCWA) of the magnetic field amplitude distribution in a simulation study. Although light was transmitted through the lattice opening, more than 40% of the light was reflected by the 2D metal grating structure. We conclude that such a structure cannot transmit sufficient visible light. Moreover, on account of the lift-off process, single-layer gratings are difficult to fabricate on subwavelength scales. To overcome this problem, we fabricated the double-layer 2D diffraction grating, which omits the lift-off process.

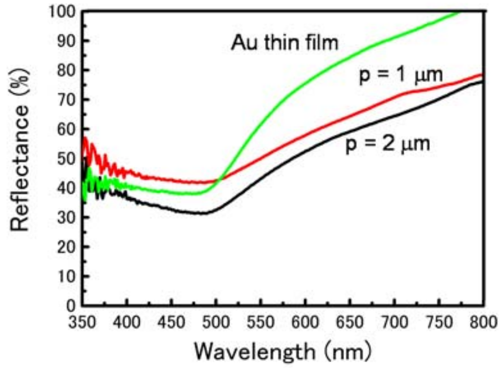


Figure 2. Reflectance spectra of the single-layer 2D metal grating structures (*p* denotes the period of the structure).

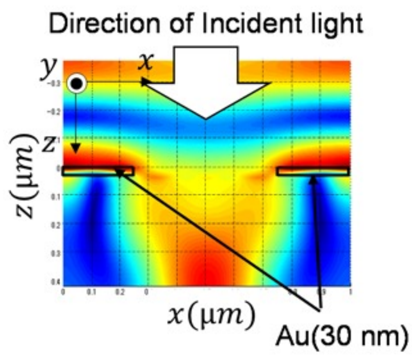


Figure 3. Magnetic field distribution in the single-layer 2D metal grating structure, calculated by the RCWA method (Wavelength = 803 nm; $p$ = 1μm).

### 3.2 Double-layer 2D metal grating structures

Next, we characterized the transmittance and reflectance spectra of the double-layer 2D metal grating structures (see Figure 1 (d)). The spacing between the upper and lower Au layers ($\Delta h$) was fixed at 370 nm, and $p$ was varied as 800, 1000, and 2000 nm. The spectra of the three grating structures and Au thin film are presented in Figure 4. The visible light reflectance of the double-layer 2D metal grating structures is lower than that of Au thin film, and even below that of single-layer 2D metal grating structures when $p$ is small (<1 μm). These results imply that the double-layer 2D metal grating structure effectively reduces the reflectance of visible light.

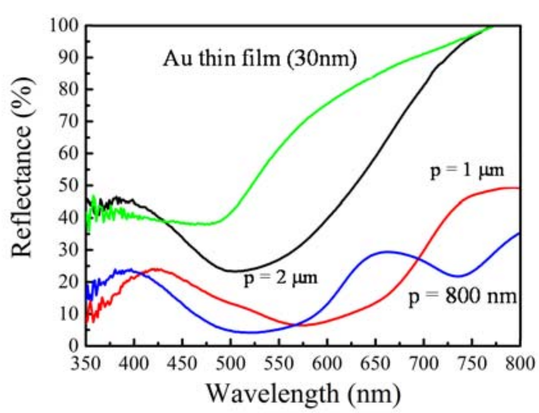


Figure 4. Reflectance spectra of double-layer 2D metal grating structures with different period *p*.

Finally, we related the reflectance and transmittance to the layer spacing Δ*h*, fixing *p* at 800 nm. The resulting reflectance and transmittance spectra are presented in Figure 5. As Δ*h* decreases, the reflectance characteristics approach those of Au thin film. This result is expected, because as Δ*h* reduces, the double-layer 2D metal grating structurally resembles the Au thin film. As Δ*h* increases, the reflectance peaks and troughs shift to longer wavelengths, for reasons discussed in the next section. The new peak (~600 nm) in the transmittance spectra of the grating with Δ*h* = 370 mm is currently being investigated. These results indicate that the reflectance spectra can be controlled by varying the *p* and Δ*h* of the double-layer 2D metal grating structure.

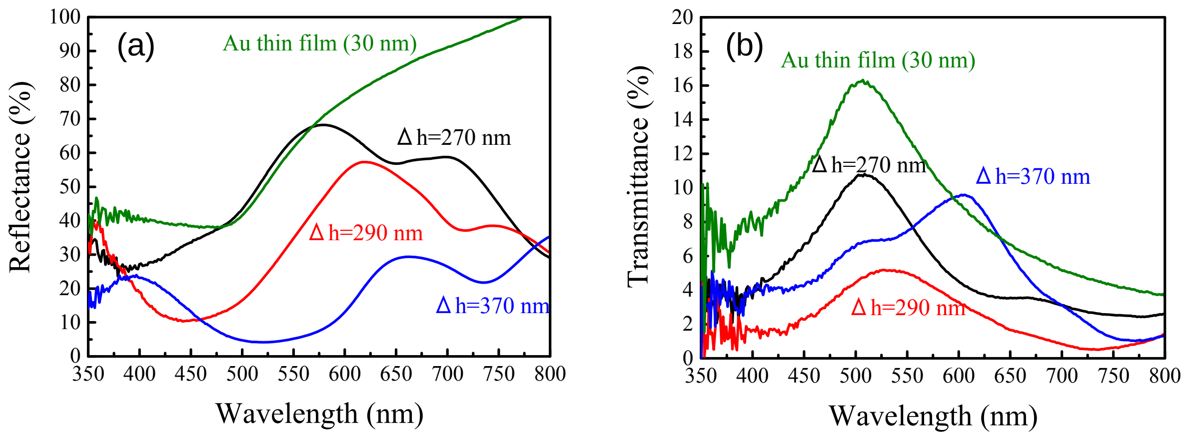


Figure 5. (a) Reflectance and (b) transmission spectra of double-layered metal gratings with different spacing Δ*h*.

## 4. DISCUSSION

This section investigates the longer-wavelength shifts in the reflectance and transmittance spectra as Δ*h* increases. In the double-layer WGP, the transmittance characteristics have been attributed to interference between the reflectances of the top and bottom gold layers and the surface plasmon resonance between the metal and insulator layers.[13, 14] We assume similar interference in our double-layer 2D metal grating structures. First we discuss the interference between the two gold layers considering the model in Figure 6 (a). The wavelengths of the peaks and troughs were extracted from Figure 4 and are plotted as functions of Δ*h* in Figure 6 ((b) and (c)). The interference patterns of the light reflected by the upper and lower Au films are given as

$$\text{Strong: } 2\,(t + \Delta h) = m\lambda \tag{1}$$
$$\text{Weak: } 2\,(t + \Delta h) = (m + 1/2) \tag{2}$$
$$m = 0, 1, 2, \dots .$$

The experimental data are matched to Equations (1) and (2) with *m* = 1. Initially, we attributed the peak shift in Figure 4 to interference imposed by the upper and lower Au thin films.

However, the peak shift cannot be wholly explained by the simple interference model, because the double-layer 2D metal grating structure has a subwavelength structure in the vertical direction. Thus, we examined the intensity of the magnetic field $|H_y|$ distribution by the RCWA method by fixing Δ*h* at 270 nm and varying the wavelength as 403 nm, 503 nm, 603 nm, and 703 nm. The distributions of the magnetic field amplitudes are displayed in Figure 7. The 403 nm light undergoes a phase shift when reflected by the lower layer (Figure 7 (a)). These out-of-phase reflections of the 0-th order light mutually weaken each other, yielding a minimum reflection characteristic. Moreover, a strong magnetic field exists in the vicinity of the upper Au layer. In the quantitative simulation analysis, 50.2% of the incident light was absorbed by the Au layer or converted to an evanescent wave in the resist layer. In the case of 503 nm light (Figure 7(b)), no strong magnetic field occurred near the upper Au layer, indicating that incident light of this wavelength is easily transmitted. The 603 nm light reflected below the upper layer is in phase with the non-reflected light, so the 0th-order light is mutually enhanced to yield a maximum reflection characteristic (Figure 7 (c)). Furthermore, unlike 403 mm light, 603 mm or 703 mm light induces a strong magnetic field at the interface between the upper Au layer and the EB resist layer (Figure 7(d)), which attenuates in the z-direction. As the surface plasmon propagates in the z direction, it is weakened by partial absorption by the metal. The plasmon propagation length is increased at longer wavelengths.[12] Therefore, we consider that surface plasmon resonance concentrates the magnetic field near the interface between the upper Au layer and the resist layer.

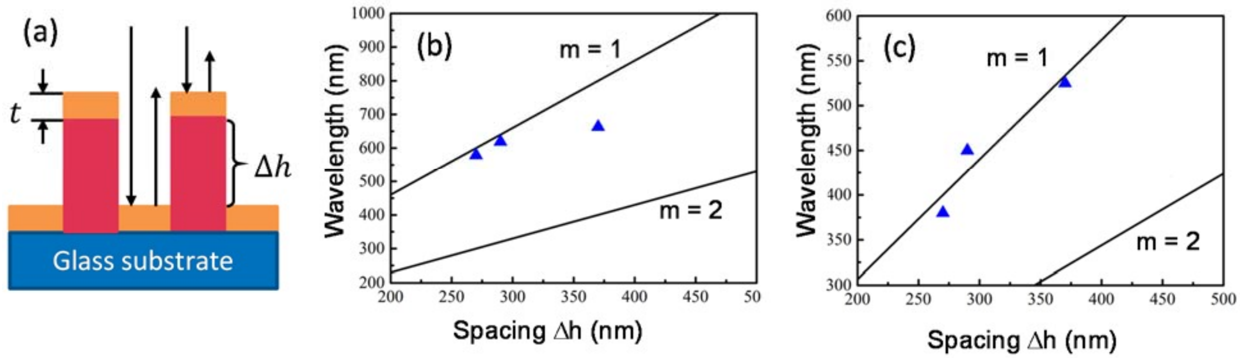


Figure 6. (a) Interference model and (b) wavelengths of maximum reflectance and (c) minimum reflectance as functions of spacing $\Delta h$

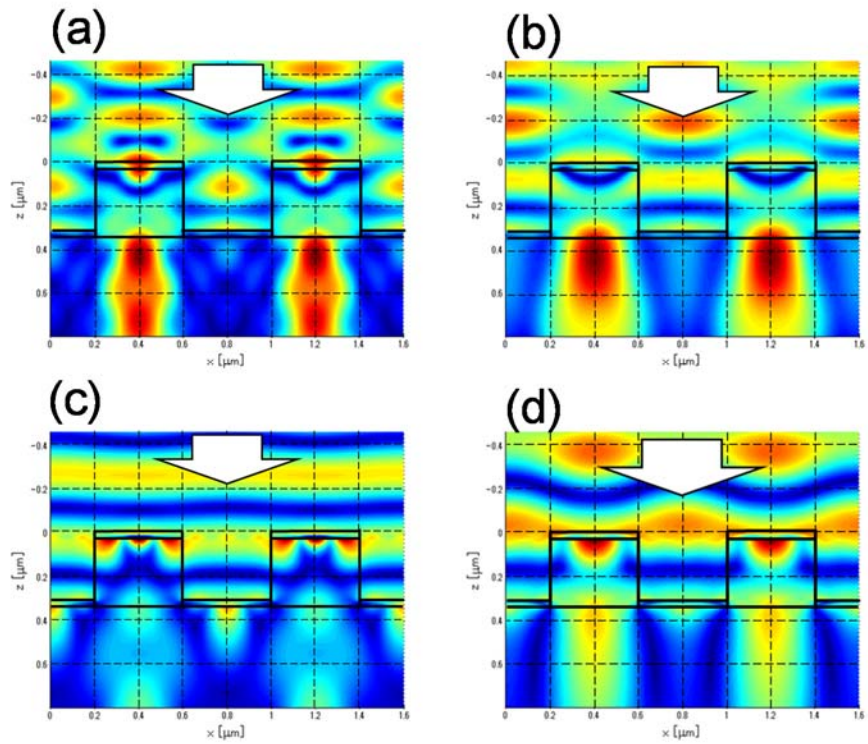


Figure 7. Magnetic field distributions at $\Delta h$ = 270 nm and different incident wavelengths calculated by the RCWA method: (a) 403 nm, (b) 503 nm, (c) 603 nm, and (d) 703 nm.

## 5. CONCLUSIONS

This study reports the visible-light filtering characteristics of a 2D metal periodic grating structure intended for cold-filter applications. The double-layered structure suppresses the reflectance in the visible region, relative to its single-layered counterpart. As the spacing between the upper and lower metal layers increased from 270 to 370 nm, the wavelengths of minimum and maximum reflectance were shifted to the longer side. The simulation results were consistent with interference between the reflectance from the upper and lower layers and the surface plasmon resonance between the metal and resist layers. Therefore, in the visible light region, the reflectance and transmission spectra can be controlled by altering the parameters of the structure double-layer 2D metal periodic grating.

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## REFERENCES

[1] Greffet, J.-J., Carminati, R., Mulet J.-P., Mainguy, S. and Chen, Y., "Coherent emission of light by thermal sources," Nature 416 (6876), 61-64 (2002).
[2] Maruyama, S., Kashiwa, T., Yugami, H. and Esashi, M., "Thermal radiation from two-dimensionally confined modes in microcavities," Appl. Phys. Lett. 79 (9), 1393-1395 (2001).
[3] Sai, H., Kanamori, Y. and Yugami, H., "High-temperature resistive surface grating for spectral control of thermal radiation," Appl. Phys. Lett. 82 (11), 1685-1687 (2003).
[4] Fleming. J. G., Lin, S. Y., Kady, E., Biswas, R. and Ho, K. M., "All-metallic three-dimensional photonic crystals with a large infrared bandgap," Nature 417(6884), 52-55 (2002).
[5] Zoysa, M. D., Asano, T., Mochizuki, K., Oskooi, A., Inoue, T. and Noda, S., "Conversion of broadband to narrowband thermal emission through energy recycling," Nat. Photonics 6 (8), 535-539 (2012).
[6] Inoue, T., Zoysa, M. D., Asano, T. and Noda, S., "Single-peal narrow-bandwidth mid-infrared thermal emitters based on quantum wells and photonic crystals," Appl. Phys. Lett. 102 (19), 191110 (2013).
[7] Ebbesen, T. W, Lezec, H. J., Ghaemi, H. F., Thio, T., Wolff, P. A., "Extraordinary optical transmission through sub-wavelength hole arrays," Nature 391 (6668), 667-669 (1998).
[8] Klein Koerkamp, K. J., Enoch, S., Segerink, F.B., van Hulst, N.F. and Kuipers, L., "Strong influence of hole shape on extraordinary transmission through periodic arrays of subwavelength holes," Phys. Rev. Lett. 92 (18), 183901 (2004).
[9] Schouten, H. F., Kuzmin, N., Dubois, G., Visser, T. G., Gbur, G., Alkemade, P. F. A., Blok, H., 't Hooft, G. W., Lenstra, D., Eliel, G., "Plasmon assisted two-slit transmission: Young's experiment revisited," Phys. Rev. Lett. 94 (5) 053901, (2005).
[10] Motogaito, A., Morishita, Y., Miyake, H. and Hiramatsu, K., "Extraordinary Optical Transmission Exhibited by Surface Plasmon Polaritons in a Double-Layer Wire Grid Polarizer," Plasmonics, DOI 10.1007/s11468-015-9980-8 (2015).
[11] Motogaito, A., Hiramatsu, K., "Fabrication of binary diffractive lenses and the application to LED lighting for controlling luminosity distribution," Opt. Photon. J. 3 (1), 67-73 (2013).
[12] William, L. B., Dereux, A. and Ebbesen, T. W., "Surface plasmon subwavelength optics," Nature 424 (6950), 824-830 (2003).
[13] Ekinci, Y., Solak, H. H., David, C. and Sigg, H., "Bilayer Al wire-grids as broadband and high performance polarizers," Opt. Express 14 (6), 2323-2334 (2006).
[14] Ye, Z., Peng, Y., Zhai, T., Zhou, Y. and Liu, D., "Surface plasmon mediated transmission in double-layer metallic grating polarizers," J. Opt. Soc. Am. B 28 (3), 502-507 (2011).