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Realization of an extraordinary transmission window for a seamless Ag film based on metal-insulator-metal structures

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A polarization-sensitive, wide-angle operating antireflection coating based on a metal-insulator-metal structure is investigated. In both visible and near-infrared regions, it dramatically reduces the reflection and enhances the transmission through a seamless Ag film near a specifically designed frequency due to the surface plasmon resonance. By achieving above 70% transmission through a 20 nm-thickness Ag film theoretically, this antireflection coating is able to open an extraordinary transmission window for a metallic layer without any slits or holes. © 2013 AIP Publishing LLC. [http://dx.doi.org/10.1063/1.4807734]

When incident light encounters a dielectric-metal interface, most of the energy is usually reflected, partial is absorbed, and the rest transmits through. The reflectance R, the absorbance A, and transmittance T always satisfy the following condition as \( R + A + T = 1 \). Nevertheless, with the help of resonance, it is possible to greatly enhance either absorption or transmission, depending on nanostructures. For instance, perfect absorbers1 have attracted vast attention due to their capability of cancelling all reflection and transmission inside nanostructures, and enhancing the light absorption.2–5 However, in many practical applications, absorption is unfavorable, and it is desirable to enhance and improve the transmission as high as possible. The phenomenon of extraordinary optical transmission through a metallic film perforated by nanohole arrays was observed by Ebbesen et al.,5 which has led to many advances in control of light at the nanoscale.7–11 While for a seamless thin metallic film, only a few attempts have been done to enhance its transmission.12,13 Recently, a symmetric multiple-layered nanostructure has been demonstrated to achieve broadband transparency for a continuous Ag film.14 In view of the fabrication, it is quite difficult to make highly symmetric structures on both sides of the Ag film.

In the present paper, we demonstrate a one-sided antireflection coating based on a metal-insulator-metal (MIM) structure, which can be more conveniently fabricated than the symmetric one. As shown in Fig. 1, the whole structure is on a glass substrate. It consists of a dielectric layer deposited on the seamless Ag film with a periodic Ag grating on the top. Geometrically, this structure is quite similar to a three-layer MIM component which generally functions as a high-efficiency absorber.2,3 However, in an absorber, the bottom metallic film is usually thick (\(~100\) nm) enough to prevent the light from transmitting through, while it is designed to be thin in our structure to allow the light to penetrate. In such way, we obtain an opportunity to open an extraordinary transmission window for a seamless metallic layer even without any help of nanoslits or nanoholes. The nanostructure is modeled using the commercial software COMSOL MULTIPHYSICS based on finite element method. The refractive indices of the substrate and dielectric are set as 1.55 and 1.50. Here, the thickness of the seamless Ag film is fixed to 20 nm. The permittivity of silver is extracted from the experimental data by Johnson and Christy.15 The whole structure is illuminated with a normal incident plane wave, which is linearly polarized with the electric field vector in y axis direction (TM mode) or z axis direction (TE mode). A set of optimized parameters for high transmission are given as \( a = 50 \text{ nm}, w = 45 \text{ nm}, h = 10 \text{ nm}, \) and \( d = 3 \text{ nm} \), where \( a, w, \) and \( h \) represent the period, width, and height of gratings, respectively, and \( d \) denotes the spacer thickness. The simulated results are shown in Fig. 2(a). For the TM wave, the maximum transmittance reaches 75% at 1030 nm. There is a notable enhancement comparing with the transmittance of the referenced Ag film at the same wavelength. In addition, a relatively flat transmission curve is observed under TE illumination and the transmittance is even lower than that of a single-layered Ag film, which is consequently evidence of the polarization-sensitivity of this antireflection coating.

![FIG. 1. Schematic of the MIM structure under the normal incident TM or TE light.](image-url)
tunability of the transmission band by adjusting grating parameters is also investigated. The corresponding results are presented in Fig. 2(b), by increasing the width of gratings $w$ from 30 nm to 45 nm with a step of 5 nm while keeping the other parameters unchanged. A remarkable red-shift of the transmission spectrum can be seen, meanwhile, the maximum transmittance still stays above 70%. These desirable features exhibit potential applications in spectrum filtering and polarization detecting. It is worth nothing that the optimized peak transmittance is related to the optical properties of Ag. If using Palik’s data of Ag\(^{16}\) (where the loss is higher), we find that the optimized peak transmittance can still be more than 60% while the peak wavelength is similar.

Further studies about the influences of other geometric parameters on the transmission property are shown in Fig. 3. Based on the optimal structure mentioned above, dual-peak transmission spectra appear when the spacer thickness $d$ becomes quite large. Taking $d = 245$ nm as an example, the transmittances are simultaneously higher than 80% at two different optical wavelengths in the visible region, 460 nm and 770 nm, indicating the realization of transmission windows in both “blue” and “red” areas, thanks to the antireflection coating. Similarly, two transmission peaks are also redshifted evidently with increasing $d$, as illustrated in Fig. 3(a). To describe the characteristic more distinctly, electric field intensity enhancements inside the MIM structure at different wavelengths and a reference wavelength are presented in Fig. 3(b). The strong surface plasmon (SP) coupling emerges around the top metallic grating at all above wavelengths, which will be guided or localized depending on whether the resonant mode is excited. Thus, the guided SP coupling makes a contribution to the transmission enhancement at 460 nm and 770 nm, yet the localized stops further transmitting of light at 600 nm.

For this type of antireflection coating, the extraordinary transmission effect is robust and highly polarization-sensitive for oblique incidence. Simulations are performed to verify this effect with the optimal dimensions which are the same as those in Fig. 2(a). The transmittances as functions of incident wavelengths and angles under different polarized waves are shown in Fig. 4. There is no obvious transmittance enhancement within concerned wavelength region in the cases of H\(_{xz}\) and E\(_{xy}\). However, when the electric field is parallel to the $xy$ plane, the extraordinary transmission window is open around resonant wavelength regardless of incident planes. For the E\(_{xy}\) case [Fig. 4(a)], when incident light is parallel to the $xz$ plane, even if the angle of incidence is up to $75^\circ$, the maximum transmittance remains 70%, with a slightly narrower bandwidth. For the H\(_{xz}\) case [Fig. 4(d)], the transmittance also remains high while the oblique incident angle becomes very large.

In order to reveal the underlying physics of extraordinary transmission through a seamless Ag film based on MIM structures, we extract the effective optical parameters from reflection and transmission coefficients. The general method to retrieve the constitutive parameters is using scattering parameters ($S$ parameters),\(^{17,18}\) which has been widely applied in both numerical simulations and experimental measurements. To guarantee the validity of the method, it is necessary to keep the maximum possible symmetry in geometry in the design process, so as to make the whole structure better approximate an isotropic material. Although in the previous reports, the standard retrieval method is also suitable for the asymmetric structures, such as absorbers.\(^{3,19}\) That is mainly

![Figure 2](image2.png)

**FIG. 2.** (a) Reflectance (red) and transmission (blue) as a function of wavelength. REF: a 20 nm Ag film on a glass substrate as the reference, $S$: the MIM structure under TE mode, $P$: the MIM structure under TM mode. (b) Transmission spectra under TM mode with different grating widths.

![Figure 3](image3.png)

**FIG. 3.** (a) Transmission spectra under TM mode with varying spacer thickness $d$. The inset shows a unit of the dual-peak MIM structure. (b) Electric field enhancement (plotted on a log scale) in the MIM structure with $d = 245$ nm at both resonance wavelengths and a reference wavelength. The white rectangle represents the position of a seamless Ag film.
attributed to the near-zero transmission, leading to an absorber being undoubtedly considered as an imaginary symmetric structure along the propagating direction of light. Whereas our present MIM structure obviously lacks inversion symmetry and holds high transmission, a more complex method will be used to retrieve the effective constitutive parameters of the structure which exhibits bi-anisotropy.20–22

The general discussion for bi-anisotropic behavior is beyond the scope of this paper. Here, only the particular 2D situation will be considered. When a plane wave is polarized vertically to the grooves of the MIM structure, the constitutive relationships in the Maxwell equations can be simplified to

$$
\begin{pmatrix}
D_y \\
B_z
\end{pmatrix} =
\begin{pmatrix}
\varepsilon_0 \varepsilon \gamma & -i \varepsilon_0^{-1} \gamma \\
+i \varepsilon_0^{-1} \gamma & \mu_0 \mu
\end{pmatrix}
\begin{pmatrix}
E_y \\
H_z
\end{pmatrix}.
$$

\(\varepsilon_0\) and \(\mu_0\) are the permittivity and permeability of the vacuum, respectively, and \(c_0\) is the speed of light in vacuum. A bi-anisotropy parameter \(\xi\) is introduced to describe the interaction between electric and magnetic components of the electromagnetic field. The retrieved material parameters satisfy the following relationship, \(n^2 = \varepsilon \mu - i\xi^2\), where \(n, \varepsilon, \mu\) are the effective refractive index, permittivity, and permeability.

We extract the equivalent parameters of the dual-peak MIM structure with \(d = 245\) nm using the method from Ref. 22 as an example. However, the most interesting and prominent feature of bi-anisotropic material is that reflectances are different for the wave propagating in the two opposite directions. The calculated reflection coefficients when illuminating from both free space \((S_{11})\) and the substrate \((S_{22})\) are shown in Fig. 5. We note that even \(|S_{11}|\) is close to \(|S_{22}|\) at most wavelengths, there is a really big disparity in the phases of these two parameters, hence bi-anisotropy can still occurs. Based on \(S\) parameters, the characteristic impedance \(z\) for the wave propagating from air to the substrate is shown in Fig. 6(a). At two resonant wavelengths, \(z_1 = 0.77 - 0.2i\) and \(z_2 = 1.13 - 0.2i\), whose real parts approach to one and imaginary parts approach to zero. The resulting retrievals imply that the impedances are well matched to that of free space, leading to very low reflections. Meanwhile, the rather small imaginary parts of \(n_1\) and \(n_2\) (see Fig. 6(b)) bring out low losses generated in the structure and consequently result in high transmissions. This is also confirmed in Figs. 6(c) and 6(d) that the real parts of \(\varepsilon_{1,2}\) and \(\mu_{1,2}\) are all close to one with rather small imaginary parts. The same results can also be obtained in the MIM structure with an ultrathin spacer layer \((d = 3\) nm\), giving a more intuitive explaining of the phenomenon of extraordinary optical transmission through a seamless Ag film.

In summary, our work demonstrates a polarization-sensitive antireflection coating based on a metal-insulator-metal (MIM) structure, opening an extraordinary transmission window for a seamless Ag film in both visible and near-infrared regions. Theoretical results reveal that the high transmission peak can be tuned by changing the grating width and spacer thickness. Even under a large-angle incidence, the extraordinary transmission effect remains robust and highly polarization-sensitive. Since the fabrication of this antireflection coating only requires a single patterning step, which can be easily fabricated by focused ion beam etching or E-beam lithography technique. Furthermore, it can also be expected that a polarization-independent antireflection coating will be achieved by extending this design principle to a 3D structure. Overall, all these coatings provide high transmission without any nanoslits or nanoholes perforated on a metallic layer, which would have significant impacts and potential applications in nanophotonic devices.

![Figure 4](image1)

**FIG. 4.** Transmittance as a function of wavelength and the angle of incidence for different polarization incident radiations, where \(a = 50\) nm, \(w = 45\) nm, \(h = 10\) nm, and \(d = 3\) nm. (a) E.L.Sxz, when the angle of incidence is up to 75°, the maximum transmittance remains 70%; (b) H.L.Sxz and (c) E.L.Sxy, no obvious transmittance enhancement occurs; (d) H.L.Sxy, for incident angle to 50°, the maximum absorption is 70%.

![Figure 5](image2)

**FIG. 5.** \(S\) parameters of the dual-peak MIM structure. The vertical dashed lines indicate the wavelengths of peak transmittances.
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FIG. 6. Real (blue) and imaginary (red) parts of the effective constitutive parameters. The vertical dashed lines indicate the wavelengths of peak transmittances.