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Making a continuous metal film transparent via scattering cancellations

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Based on theoretical analyses and full-wave simulations, we propose a scheme to make a continuous metal film transparent in optical regime, with light scattered from the metal film cancelled by those from two composite layers consisting of metallic and dielectric stripes. Such a transparency fully retains the conductance of the targeted metal and is robust against incidence angle as well as structural disorders. As a proof of concept, we performed microwave experiments to verify all theoretical predictions. © 2012 American Institute of Physics.

Making a high-conducting metal transparent has drawn lots of attention recently. 1–8 The problem is of great scientific curiosity since a bare metal itself is opaque for light. On the application side, transparent conducting metals (TCMs) with both high DC conductivity (σDC) and high light transmission are desired in optoelectronic devices. 1–4 However, the problem is of great scientific curiosity since a bare metal itself is opaque for light. On the application side, transparent conducting metals (TCMs) with both high DC conductivity (σDC) and high light transmission are desired in optoelectronic devices. 1–4 However, the effective transparency of such TCMs are much smaller than that of a continuous metal film. 5 Transparency of a metal film can also be achieved with help of certain resonances such as surface plasmon polaritons (SPPs) 6 or Fabry-Perot (FP) resonances. 7 However, in such schemes, the targeted metals should be perforated with holes or slits. Moreover, the SPP approach is sensitive to structural order while the FP one requires samples with thicknesses comparable to wavelength, both are inconvenient for practical realizations. Making an opaque medium transparent was also demonstrated in low-frequency regime (e.g., GHz) based on metamaterials (MTMs), 8 but direct scaling of such MTMs to optical regime is proven invalid due to the saturation effect of LC resonators at high frequencies. 9,10 Here, we propose a scheme to make a continuous (apertureless) metal film transparent in optical regime. Our approach retains the full electric and mechanical properties of a natural metal, and the transparency is robust against structural disorder and incidence angle. We demonstrate the idea by full-wave simulations and proof-of-concept microwave experiments.

Figure 1(a) schematically depicts our proposed structure, in which the target continuous metal film C (with thickness hC and relative permittivity εC) is sandwiched by two identical composite layers (with thickness hAB) consisting of alternate dielectric (A) and metallic (B) stripes. To avoid electric shorting, C layer is separated from AB layers by small gaps (with thicknesses hA) filled with a medium with relative permittivity εA. As a pure theoretical model, we set εC = −110 and performed full-wave simulations based on the finite-element method (FEM) 11 to compute the transmittance (T) of the whole structure under illuminations of an x-polarized normally incident light. We depicted in Fig. 1(b) how T depends on two parameters εB and P = wA + wB (through varying wA only), with other parameters fixed as εA = 12, wB = 0.1λ, hA = hC = 0.02λ, εA = 1, hA = 0.01λ where λ is the incident wavelength. Although a standing-alone C layer is nearly opaque (with T < 2%), we note that such a sandwich structure can be perfectly transparent under

\[ \varepsilon_C = -110 \]

\[ T = \frac{w_A}{w_A + w_B} \]

\[ \lambda = \text{incident wavelength} \]

\[ \varepsilon_A = 12, \quad w_B = 0.1\lambda, \quad h_A = h_C = 0.02\lambda, \quad \varepsilon_A = 1, \quad h_A = 0.01\lambda \]

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certain conditions. The upper high-\(T\) band at \(P \sim \lambda\) is very narrow, and is easily identified as the SPP-aided extraordinary optical transmission (EOT).\(^6\) The lower high-\(T\) band is much broader, with governing physics explained below.

We applied a mode-expansion theory\(^\text{12,13}\) to analytically solve the scattering problem of the present system under two approximations. First, we retain only the zero-order diffraction modes in air regions, and only the fundamental Bloch modes inside the two periodic AB layers. Second, we homogenize layer C plus two tiny gaps as an effective medium with a volume-averaged \(\tilde{\varepsilon}_C\) and a modified thickness \(h_C = h_C + 2h_u\). The first approximation is well justified for the lower high-\(T\) band since \(P \ll \lambda\), and the second is also reasonable since \(h_C, h_u \ll \lambda\). With material loss neglected in the model, perfect transparency is equivalent to zero reflection, leading to the following equation:

\[
\frac{Z_0}{Z_{AB}} - \frac{Z_{AB}}{Z_0} 2\tan(k_C h_{AB}) - \frac{\varepsilon_C}{\varepsilon_C + 1}\tanh(\varepsilon_C h_C) \\
- \left(\frac{\varepsilon_C Z^2_{AB}}{k_0 Z_{AB}} + \frac{k_0 Z^2_{AB}}{\varepsilon_C Z^2_{AB}}\right) \tan^2(k_{AB} h_{AB}) \tanh(\varepsilon_C h_C) = 0,
\]

(1)

where \(k_0 = \omega / c, Z_0 = \sqrt{\mu_0 / \varepsilon_0}, \varepsilon_C = \sqrt{\varepsilon_C} k_0\). \(k^2_{AB}\) is obtained by solving the Bloch mode equation of the AB structure (setting Bloch wavevector \(K_x = 0\)),

\[
2\cos(k^2_A w_A + k^2_B w_B) - \frac{\varepsilon_B k^2_A}{\varepsilon_A k^2_B} \left(\frac{\varepsilon_B k^2_A + \varepsilon_A k^2_B}{\varepsilon_B k^2_B} - 2\right) \\
\times \sin(k^2_A w_A)\sin(k^2_B w_B) = 2,
\]

(2)

in which both \(k^2_A\) and \(k^2_B\) are implicit functions of \(k^2_{AB}\):

\[
k^2_A = \sqrt{\varepsilon_A k^2_A - (k^2_{AB})^2}, \quad k^2_B = \sqrt{\varepsilon_B k^2_B - (k^2_{AB})^2}.
\]

\(Z_{AB}\) is the effective impedance of the AB layer which is given by

\[
Z_{AB} = Z_0 \kappa_{AB} S_E / (k_0 S_H),
\]

(3)

where

\[
S_H = P^{-1} \int_0^p H^0_y(x) \, dx,
\]

\[
S_E = P^{-1} \left[ \int_0^{\omega_A} e_A^{-1} \cdot H^0_y(x) \, dx + \int_0^{\omega_B} e_B^{-1} \cdot H^0_y(x) \, dx \right],
\]

(4)

are two overlapping integrals between the incident wave and the fundamental Bloch mode inside the AB layer (with eigen wavefunction described by \(H^0_y(x)\)). We numerically solved Eq. (1) for the present structure and depicted the obtained perfect transparency solutions in Fig. 1(b) by two solid lines. As \(\varepsilon_B < -60\), Eq. (1) ceases to have perfect transparency solutions, but we can still find the high-transmission solutions by minimizing the reflections from the entire system (denoted by the dashed line in Fig. 1(b)). The analytical results well reproduced all salient features of the lower high-\(T\) band, although quantitative deviations do exist due to neglecting the higher-order contributions in our theory.

The analytical model established a clear picture for the noted transparency. The first two terms in Eq. (1) can be understood as the reflections from individual AB layers and C layer, while the third term represents the multiple scattering effects. While the C layer is always highly reflective [see the 2nd term in Eq. (1)], if the reflection from the AB layer [the 1st term in Eq. (1)] is strong enough to cancel the reflection from the C layer, the whole structure can still be perfectly transparent. For this to be true, we need a mechanism to tune the scatterings from the two AB layers. Since \(\varepsilon_A\) and \(\varepsilon_B\) have opposite signs, Eq. (4) shows that the two terms in \(S_E\) can largely cancel each other so that \(S_E\) can be made very small. Therefore, via adjusting the AB structure, one can tune the effective impedance \(Z_{AB}\) very efficiently and, in turn, to tune the scatterings from two AB layers so that Eq. (1) can be exactly satisfied under certain conditions. Obviously, such a scattering cancellation mechanism (SCM) needs not structuring the metal C, so that full DC conductivity of metal C can be retained. We note that the SCM band is very broad and becomes almost independent on \(P\) in the region \(-90 < \varepsilon_B < -30\), indicating that such a transparency is robust against structure disorder, a character that many other transparency schemes do not possess.

We designed realistic TCMs based on Fig. 1(a), in which both C and B are assumed as Ag, material A is set as air, and the spacers between AB and C are assumed as A12O3. Figure 2(a) presents the FEM calculated transmission spectra for two of our designs, with silver described by a Drude model \(\varepsilon_{Ag} = 5 - \omega^2_p / (\omega^2 + i \Gamma)\) with \(\omega_{p} = 1.37 \times 10^{16}\) Hz and \(\Gamma = 2.73 \times 10^{13}\) Hz according to Ref. 14. For the \(h_C = 40\) nm design, we found \(T \sim 75\%\) at \(~700 nm which is remarkable since the transmittance through a bare C layer is less than 3\%. The transmittance at 776 nm is enhanced to 90\% with a much larger bandwidth for the \(h_C = 25\) nm design.

There are other models in literature\(^\text{15,16}\) to describe \(\varepsilon_{Ag}\), which adopted \(\Gamma\) values 3-4 times larger than ours. We took those models to re-perform the calculations and found that the qualitative transparency behaviors did not change. In particular, the
peak transmittance can still be as high as \(~70\%\) for the \(h_C = 25\)nm designs calculated with enhanced \(\Gamma\) values.\(^9\)\(^\ast\) The transmission spectra exhibit Fano-like resonant behaviors since Eq. (1) is satisfied only at a particular frequency due to the intrinsic dispersion of metal C. We emphasize that these designs are practically realizable with current technology, particularly noting the recent exciting achievements in multilayer fabrications.\(^7\)\(^\ast\) Via changing \(w_B\) from 50nm to 150nm with \(w_A = 50\)nm fixed, we show in Fig. 2(b) that the transparency wavelength changes from 700nm to 1600nm, demonstrating the flexibility of our design. We plotted in Fig. 2(c) the distributions of H-field and the energy flux inside the \(h_C = 40\) nm structure studied in Fig. 2(a), right at \(\lambda = 726\)nm. Clearly, the incident photons are squeezed into material A and then coupled through layer C aided by strongly enhanced H fields localized in the gaps between B and C. Figure 2(c) showed that the second AB layer played an important role to make the SCM work. In fact, with only one AB layer attached to the C layer, the whole structure is much less transparent but strongly absorb light instead, resembling recently realized optical absorbers.\(^8\)\(^\ast\) In addition, replacing the Ag stripes by Ag patches, we found an isotropic TCM working for both \(\mathbf{E} \parallel \hat{x}\) and \(\mathbf{E} \parallel \hat{y}\) polarizations.

We performed proof-of-concept experiments in microwave regime to verify the proposed scheme. In microwaves, metals behave as perfect conductors and do not exhibit finite negative \(\varepsilon\). However, metallic meshes with subwavelength openings are shown to exhibit Drude-like \(\varepsilon\) in microwave regime,\(^9\)\(^\ast\) and therefore, we designed mesh-based MTMs to mimic the plasmonic metals B and C at optical frequencies. In our designs, the unit air-hole is a \(2 \times 15.5\) mm\(^2\) rectangle in mesh B and is a \(3.5 \times 3.5\) mm\(^2\) square in mesh C, and each metallic line is 0.5 mm-wide and 0.05 mm-thick. Mesh B was put on a 0.6 mm-thick substrate with \(\varepsilon_A = 5\), and mesh C was sandwiched between two such substrates. We fabricated realistic B and C samples [see insets of Figs. 3(a) and 3(b) for pictures], and measured their transmission spectra.\(^9\)\(^\ast\) Figures 3(a) and 3(b) show that the measured spectra are in excellent agreement with FEM simulations. From the calculated spectra, we derived\(^9\)\(^\ast\) the effective permittivity of the two materials as \(\varepsilon_B = 5 - 580/\omega^2\) and \(\varepsilon_C = 5 - 2300/\omega^2\), with \(\omega\) denoting linear frequency measured in GHz. At \(\omega \sim 4.5\) GHz, we have \(\varepsilon_C \approx -109, \varepsilon_B \approx -24\) indicating that our MTMs can indeed well mimic plasmonic metals in optical regime.

With materials C and B both available, we choose the substrate as material A, cut A and B layers to stripes with \(w_A = 1\)mm and \(w_B = 3\)mm, and then construct an ABC structure based on the design shown in Fig. 1(a). Here, we set \(h_a = 1\) mm after optimizations. Figure 3(c) depicts the measured and simulated transmission spectra through such an ABC structure, where a transparent band is identified at \(\sim 4.4\) GHz with peak transmittance \(\sim 100\%\)! This is quite counter-intuitive at first glance, since a bare layer C is nearly opaque here (with \(T < 5\%\)). However, by adjusting the AB configuration based on Eqs. (3) and (4), we can make the scatterings from the two AB layers strong enough to perfectly cancel the scattering by the C layer alone, leading to perfect transparency of the whole structure. Calculations on model systems with meshes replaced by homogenous stripes/slabs described by retrieved parameters \(\varepsilon_B, \varepsilon_C\) are in good agreement with those on realistic structures.\(^9\)\(^\ast\)

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**FIG. 3.** Measured (open circles) and simulated (solid lines) transmission spectra of (a) layer B, (b) layer C, and (c) the designed ABC structure. FEM-calculated transmittance as functions of incident angle and frequency for (d) \(S\)- and (e) \(P\)-polarized incident waves, with open circles representing the measured maximum-transmittance positions.

**FIG. 4.** Measured (open circles) and simulated (solid lines) transmission spectra of (a) a disordered ABC structure supporting the SCM transparency and [(b) and (c)] two designed structures supporting EOT-like transparencies. Here, the AB-stripes arrangement is perfectly ordered in (b) and is disordered in (a) and (c).
The discovered transparency possesses several attractive properties. Shown in Figs. 3(d) and 3(e) are the simulated $T$ versus incidence angle $\theta$ and frequency $f$ of the input EM waves with S- (keeping $\hat{E} \parallel \hat{x}$) or P-polarizations (keeping $\hat{H} \parallel \hat{y}$). Experimental data of peak-$T$ positions are denoted as open circles in the same figures. Clearly, our transparency is rather stable against varying $\theta$. Meanwhile, our scheme is also insensitive to structural disorder. We purposely re-designed and fabricated the AB layers to let $w_A$ randomly located within $1.0 \times (1\pm10\%)$ mm and measured the transmission spectrum through such a disordered ABC structure. Figure 4(a) shows that the transparency is still there. As a comparison, we also designed and fabricated microwave samples that can support EOT-like transparency (upper high-$T$ band in Fig. 1) at a similar frequency. Both experiments and simulations show that, while the peak transmittance for a perfectly ordered sample can be as large as 80% (see Fig. 4(b)), such an EOT transparency is almost killed when the same structural randomness is imposed, as shown in Fig. 4(c).

To summarize, we proposed a scattering cancellation scheme to make a continuous metal film transparent at optical frequencies, and demonstrated the concept by microwave experiments. Our mechanism retains all electric and mechanical properties of the targeted metal and is robust against incidence angle and structural disorder.

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10. See supplemental materials at http://dx.doi.org/10.1063/1.4764945 for saturation effect of electric MTM, the influences of damping parameter on the discovered transparency, and comparisons between calculations on realistic structures and their corresponding model systems.
20. All microwave spectra were measured by a vector network analyzer (Agilent E8362C PNA). Two identical microwave horns were used to generate and receive the signals separated by a distance of 100 cm. The sample was placed on a stage, 50 cm from the receiving horn. The transmittance is normalized to that without the samples.
22. The structure is similar to that for Fig. 3(c), but with $w_A = 12$ mm and $w_B = 36$ mm. Also, the size of the unit square hole in mesh C is changed to $9.5 \times 9.5$ mm$^2$. 

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