Anti-frost and energy-saving transparent glass widows manipulated through solar-absorbing metamaterial coatings

William Tong\textsuperscript{1} and Alan Tong\textsuperscript{2}

\textsuperscript{1}Illinois Mathematics and Science Academy, Aurora, IL 60506, USA
\textsuperscript{2}Neuqua Valley High School, Naperville, IL 60564, USA
Corresponding author Email: colin.tong@hotmail.com

Accepted 16 December 2014

In this paper, possible approaches will be explored for designing transparent glass windows with anti-frost/anti-fog and energy-saving capabilities by coating nanostructure metamaterials on the widow’s outside surface. The metal-dielectric-metal nano-scale metamaterial structures with periodic metal-dielectric interfaces, when shined with light, acquire surface plasmons thus trapping light at subwavelength scales. When these metamaterials are coated on the outside of a glass window, they may lead to efficient solar radiation absorption, which can be used for anti-frost/anti-fog and energy-saving windows of transportation vehicles and modern buildings. The total thickness of the so-called metamaterial perfect solar absorber is a few tens of nanometer and its absorption band is broad, tunable and insensitive to the angle of incidence. This paper will present a concept to use the metamaterial coating on the window glass to absorb solar spectrum ($\lambda > 0.7 \mu m$) for anti-frost/anti-fog and energy-saving in the winter, meanwhile almost without lowering the luminous transmittance. In the summer, for a rotatable window, its opposite side with the perfect mirror function can be turn to face the sunlight to reflect the sunlight away. By adjusting bottom coating structure, perfect or non-perfect mirror can be formed for natural solar reflection or transmittance.

Keywords: metamaterial coating, transparent glass window, anti-frost, anti-fog, energy-saving, solar absorber, heat transfer, transportation vehicle, building

INTRODUCTION

The glass windows have been widely used for transportation vehicles and modern buildings. With taking aesthetic appearance characteristics of glass into consideration, more attention has also been paid on its abilities of anti-frost, anti-fog, energy-saving through heat control and sunlight projection. Therefore, multi-functional energy-saving glasses manipulated through specially designed coatings are getting more and more demands (Chen et al., 2011).

With respect to energy flows, a conventional window generally functions transmitting a controlled amount of luminous radiation for vision, and solar radiation for space heating at a specifically controlled heat transfer. The heat transfer covers contributions from thermal...
radiation, conduction in solids and gases, and gas convection. Radiation is relevant in three different wavelength regions (Voss et al., 2014): (a) the visual region from 0.4-0.7\,\mu m, (b) the solar region from 0.3-3.0\,\mu m, and (c) the thermal region with wavelengths larger than 2\,\mu m. Luminous, solar and thermal radiations are confined to these specific wavelength intervals, as can be seen in Fig.1 (Voss et al., 2014). Planck spectra for two temperatures of practical significance for windows can be seen in Fig.1 (Voss et al., 2014). Planck spectra for radiation that has passed already the earth's atmosphere. The curve has again a bell shape corresponding to the sun's surface temperature of about 6000°C. The minima in the spectrum are caused by atmospheric absorption, mainly by water vapor, carbon dioxide and ozone. The dashed curve shows the relative spectral sensitivity of the human eye in its light-adapted photopic state with the maximum at 0.555\,\mu m. In the darkness-adapted scotopic state, the latter one is displaced about 0.05\,\mu m towards shorter wavelengths (Voss et al., 2014).

With metamaterial coatings on the window glass surface, these spectra can be selectively absorbed, tuned, manipulated based on the specific design requirements. In this paper, a design concept of metamaterial coatings applied on the window glass would be presented to absorb solar spectrum (\lambda > 0.7 \, \mu m) for anti-frost/anti-fog and energy-saving almost without lowering the luminous transmittance.

**Design principle of metamaterial absorbers**

Metamaterial absorbers can selectively absorb or emit electromagnetic waves by exciting plasmonic resonances at particular wavelengths inside the material structures (Watts et al., 2012). The absorbing metamaterials are generally made of micro/nanostructures with subwavelength metallic patterns on a metal film separated by a dielectric spacer. Between the metallic pattern and the metal film, strong electromagnetic coupling could occur at selected wavelengths due to electric and magnetic responses of the metamaterial (Wang and Wang, 2013).

Considering a slab of magneto-dielectric metamaterial structure with thickness d, which can be described by both the magnetic permeability $\mu(\omega) = \mu_0 \mu_r(\omega)$ and the electric permittivity $\varepsilon(\omega) = \varepsilon_0 \varepsilon_r(\omega)$, and backed by a highly conductive opaque metallic ground plane, here $\varepsilon_0$ and $\mu_0$ are the permittivity and permeability of free space; the reflectivity (R) and reflection coefficient (r) of an interface, for transverse electric (TE) and transverse magnetic (TM) polarized waves can be expressed as (Watts et al., 2012)

$$R_{TE} = |r_{TE}|^2 = \frac{\cos^2 \theta - \mu_r^2 \sin^2 \theta}{\cos^2 \theta + \mu_r^2 \sin^2 \theta}$$

$$R_{TM} = |r_{TM}|^2 = \frac{\varepsilon_r \cos \theta - \sin^2 \theta}{\varepsilon_r \cos \theta + \sin^2 \theta}$$

where $\theta$ is the angle of incidence, and $n = \sqrt{\mu_r \varepsilon_r}$ is the index of refraction of the magneto-dielectric medium. In case of normal incidence angle ($\theta = 0$), the Eq. (1) and (2) reduces to (Watts et al., 2012):

$$R_{TE} = \frac{1 - n}{1 + n}$$

$$R_{TM} = \frac{\varepsilon_r - n}{\varepsilon_r + n}$$

If it is intended to have no reflectivity for both polarizations, $R_{TE}$ and $R_{TM}$ should be equal to zero, which is equivalent to $\mu_r = \varepsilon_r$. This indicates that impedance of the metamaterial ($Z = \sqrt{\mu_r / \varepsilon_r}$) should match that of air ($Z_0 = \sqrt{\mu_0 / \varepsilon_0}$) in order to reduce the reflection loss down to zero (Watts et al., 2012). According to Kirchhoff's rule (Mehdi et al., 2014), the sum of the transmittance T, reflectance R, and absorbance A should be equal to 1 in the absence of scattering and diffraction, that is, the absorbptivity can be written as (Watts et al., 2012)

$$A = 1 - R = 1 - \left[\frac{2 - Z_0}{Z + Z_0}\right] = 1 - \left[\frac{\mu_r - n}{\mu_r + n}\right]^2$$

Therefore, the light can be absorbed totally if the impedance of metamaterial matches to that of the free space, and the back metallic film or ground plane is opaque for zero light transmission (acts as a mirror). However, lowering the reflectivity by impedance matching is not sufficient and presence of lossy materials is obligatory for realization of high absorbptivity (Mehdi et al., 2014). For instance, if the metamaterial slab thickness d is not sufficiently thick and the constituent material is not lossy enough, the wave which is bounced back off the back metal film can reflect back into free space (Watts et al., 2012). As a result, the challenge to design a perfect metamaterial absorber is to structure it with lossy materials and meet the condition of the impedance matching the free space (Mehdi et al., 2014).

Metals are electromagnetically lossier in high frequency, in particular at optical realm, due to electron transitions from the filled d bands into the surface plasmon (SP) conduction bands, which is base of wave absorption (Callaway, 2014). However, at lower frequency especially when the frequency is below terahertz or near-infrared range (Reza, 2008), most metals can be assumed acting as a perfect conductor with small loss, since the corresponding Ohmic loss fraction, the ratio of the skin depth over wavelength, is only 0.1% or less (Mehdi et al., 2014). As a result, for the electromagnetic absorbing metamaterials designed for below terahertz or near-
infrared, the main loss is resulted from the dielectric. Therefore, lossy dielectric is usually incorporated in the metamaterial design. In contrast to low frequency, contribution of metallic absorption through Ohmic loss and surface plasmon decay is more than dielectric when the operating frequency is near-infrared (NIR) or visible. As a result, absorption within the metallic part in metamaterial absorbers for visible frequency reduces the role of dielectric absorption, and hence relatively thinner dielectric is sufficient for high frequency purposes (Mehdi et al., 2014).

For example, ultra-thin (~20 nm) plasmonic nanocomposite made of metal nanoparticles dispersed randomly in polymeric or generally dielectric matrix, a
highly dispersive material with a high refractive index contrast to the interlayer, could give rise to perfect absorption of light in a broad range of frequency from deep ultraviolet (UV) up to visible and NIR (Etrich et al., 2014). Once again, this verify that impedance matching of the metamaterial to free space, multi-reflection of light between different structural layers, light trapping and absorption by the tiny metallic particles /period metallic structures/metallic films enable realization of almost unity absorption of light in wide range of spectrum from UV to NIR (Mehdi et al., 2014).

Perfect metamaterial absorber coatings on glass windows

Initially, perfect metamaterial absorbers were made of electric ring resonators coupled to metal wires, exhibiting selective absorption in the terahertz region. By replacing the metal wires with a continuous film, as shown in Fig. 2a, the design was improved to achieve wide-angle absorption for both transverse electric (TE) and magnetic (TM) polarized waves (Landy et al., 2008). Moreover, different top-layer pattern structure designs such as chiral metamaterial, fishnet structure, and cut-wire array were proposed to achieve omnidirectional and polarization-independent absorption in the terahertz regime. Thereafter, by shrinking the sizes of the metamaterial absorbers, the near-perfect selective absorption can be obtained in the infrared and visible region. For instance, 97% absorption was demonstrated at the wavelength of 6 μm in a subwavelength perfect absorber made of a film-coupled crossbar structure, as shown in Fig. 2b (Tao et al., 2008). Fig. 2c shows a plasmonic absorber made of a layer of gold patch array with the width less than 200 nm on a thin Al₂O₃ layer over an Ag film, demonstrating an absorption peak of 88% at the wavelength of 1.58 μm (Liu et al., 2010). As shown in Fig. 2d, by depositing a two dimensional (2D) Ag grating with a period of 300 nm on a 60-nm SiO₂ over an Ag film, an ultra-thin plasmonic absorber was made in the visible spectrum (Hao et al., 2010). Strong visible light absorption has also been achieved by film-coupled colloidal nanoantennas, circular plasmonic resonators, and nanoparticles, by exciting magnetic resonance inside the metamaterial absorbers. In addition, selective absorption can also be
used for controlling thermal emission (Wang and Wang, 2013).

**Tungsten-silica-tungsten metamaterial solar absorbers**

This paper will attempt to use tungsten-silica-tungsten solar absorbers, proposed by Hao Wang and Liping Wang (Wang and Wang, 2013), as metamaterial coatings for design of anti-frost/anti-fog and energy-saving transparent glass windows. Fig. 3 shows typical structures of the metamaterial solar absorbers made of 2D periodic tungsten gratings on a thin SiO$_2$ spacer over a tungsten thin film (Wang and Wang, 2013). A unit cell of the metamaterial structure with single-sized tungsten patches is shown in Fig. 3a. The geometric parameters include grating period $\Lambda$, tungsten patch width $w$, grating height (or patch thickness) $h$, and SiO$_2$ spacer thickness $t$. The opaque tungsten thin film could be a couple of hundred nanometers thick. The three-layer-structural metamaterial would be deposited on outside surface of a glass window to obtain the anti-frost/anti-fog and energy-saving capabilities. The 2D periodic gratings are designed with the same geometric parameters (i.e., $\Lambda$ and $w$) in the $x$ and $y$ directions, since the geometric symmetry is crucial to realize the polarization independence at normal direction. Here wavevector $K_{\text{inc}}$.
represents the electromagnetic wave with a free-space wavelength \( \lambda \) incident onto the metamaterial structure at a polar angle or incidence angle \( \theta \), polarization angle \( \psi \), and azimuthal angle \( \varphi \). The polar angle \( \theta \) denotes the angle between \( \mathbf{K}_{\text{inc}} \) and the surface normal of the structure (z direction). The polarization angle \( \psi \) is by \( \mathbf{K}_{\text{inc}} \) and the structure surface normal, between electric field vector \( \mathbf{E} \) and the plane of incidence. \( \psi = 0^\circ \) indicates the transverse magnetic (TM) polarized wave while \( \psi = 90^\circ \) gives the transverse electric (TE) polarized wave. Azimuthal angle \( \varphi \) is the angle between the x axis and the plane of incidence, and can be taken as \( \varphi = 0^\circ \) here for simplicity by ignoring conical diffraction due to the non-zero wavevector components in both x and y directions for the incident wave (Wang and Wang, 2013).

Fig. 3b illustrates a unit cell for the metamaterial absorber with double-sized tungsten patches of different widths \( w_1 \) and \( w_2 \). The patches with the same width are arranged diagonally such that the structure behaves exactly the same at normal incidence for either TE or TM waves. Each patch is centered in its quadrant, and the period \( \Lambda' \) of the double-size metamaterials is twice that of single-sized ones, i.e., \( \Lambda' = 2\Lambda \) (Wang and Wang, 2013).

As shown in Fig. 3c, SiO\(_2\) spacer thickness \( t \) yields a similar effect as the tungsten grating height \( h \) on the normal absorptance of the single-sized metamaterial solar absorber. When the spacer thickness increases from 40 nm to 150 nm, the magnetic polariton (MP) peak shifts to shorter wavelength, while the peak amplitude first increases to a maximum close to 1 with \( t = 80 \) nm and then drops with further thicker spacers. The surface plasmon polariton (SPP) peak locations do not change with spacer thickness but the amplitudes change with different \( t \) values. The coupled magnetic polariton (CMP) peak separates from the SPP peak around \( \lambda = 0.6 \) \( \mu \text{m} \), and shifts slowly towards the longer wavelength with increasing \( t \). As a result, the absorbance in the spectral region between 0.6 \( \mu \text{m} \) to 1.8 \( \mu \text{m} \) is greatly enhanced, with the minimum value of spectral absorbance increases from 0.6 at \( t = 40 \) nm to 0.92 at \( t = 120 \) nm. However, the absorbance starts to decrease with further thicker spacers (Wang and Wang, 2013). Therefore, a SiO\(_2\) spacer thickness range of 60 nm to 120 nm is preferable when coating the spacer layer on the window glass.

Fig. 3d shows the absorptance of both single-sized and double-sized metamaterial absorbers with the same geometric parameters of \( \Lambda = 600 \) nm, \( h = 150 \) nm and \( t = 60 \) nm but different patch widths \( w_1 = 250 \) nm and \( w_2 = 300 \) nm, respectively (Wang and Wang, 2013). The tungsten grating height \( h \) can be optimized to make the single-sized metamaterial have close-to-unity absorptance in the partial or full visible and near-infrared region, or in the near-infrared region only to let the visible light transmit through the window glass for luminous. The single-sized metamaterial absorber with smaller patch width \( w_1 = 250 \) nm has a narrower band of absorption but a little bit higher absorptance in the near-infrared, than the one with larger patch width of \( w_2 = 300 \) nm (Wang and Wang, 2013). By comparison, the double-sized metamaterial is more preferable for coating on the window glass because of its broader absorption band than the single-sized one with \( w_1 = 250 \) nm, and higher absorbance than the single-sized one with \( w_2 = 300 \) nm. The minimum absorptance of the double-sized metamaterial is higher than 0.95 in a wide spectral range from 0.6 \( \mu \text{m} \) to 1.8 \( \mu \text{m} \) (Wang and Wang, 2013), meanwhile the geometry design with a couple hundred of total thickness of the metamaterial coating would almost not result in lowering the luminous transmittance.

In addition to the absorptance enhancement of MP, CMP and SPP resonance modes around particular wavelengths, the utilization of high intrinsic loss of
tungsten is another important factor for the broadband high absorption. Compared with relatively low losses such as Ag and Au, Tungsten has several interband transitions around the wavelengths of 0.4 µm, 0.6 µm and 1.4 µm (Voss et al., 2014). For solar thermal applications, its high intrinsic loss is actually beneficial to enhance the absorption of solar radiation across a wide spectral range. Therefore, the most important approach to achieve almost perfect absorption in a broad spectral band from visible to the near-infrared region with the designed metamaterial absorber is use of the coupling effect between different resonance modes and interband absorption of tungsten. In other words, the absorptance of the metamaterial solar absorber strongly depends on the geometric parameters (such as the tungsten patch width, grating period, grating thickness, and the spacer thickness), the coupling between MP, CMP and SPP modes as well as the intrinsic loss of tungsten. The peak wavelengths of the MP and CMP modes also strongly depend on the patch width w, grating period Λ, grating height h, and spacer thickness t, which could be potentially employed to further broaden the absorption.

Figure 7. Variation of the window outside surface temperature vs. solar absorption time for (a) general building window; (b) a car window, assuming initial outside and inside surface temperatures of the window are the same.

Figure 8. Variation of the building window inside surface temperature vs. solar absorption time for (a) Initial outside temperature -15°C; (b) Initial outside temperature -30°C.
peak. As a result, the absorption could be also maximized by optimizing the geometric parameters (Wang and Wang, 2013).

Applications on window glass

As shown in Fig.3, the solar absorber used for coating on window glass consists of three-layer structures. The top layer is constructed based on the top one-dimensional (1D) tungsten planar stack, the dielectric SiO$_2$ spacer functioned as an optical cavity, and the bottom metallic film sandwiching the cavity with the top tungsten stack, functioning as non-perfect or perfect mirrors (Wang and Wang, 2013). The three-layer absorber structure can be deposited on one side of a rotatable window glass surface, as shown in Fig. 4, for instance. The profile of the three-layer structured coating can be designed to allow proper proportion of visible light transmit through the window glass for enough lightening in the room, while maximum infrared waves can be absorbed for heating. For example, the bottom metal film can be made thick enough to block near-infrared and infrared light transmission, while the top metal layer is deposited to be ultrathin (close to the radiation penetration depth) to enable transmission of the incident sunlight wave into the cavity and further generate resonance to maximize absorption (Voss et al., 2014).

In the summer, another side of the window functioning as perfect metal film mirror will face the sunlight to reflect the sunlight away. By adjusting bottom metal film coating structure, perfect or non-perfect mirror can be formed for natural solar reflection or transmittance. Here the spectral transmittance can be weighted and averaged over the whole solar spectrum between 300-2500nm (Voss et al., 2014). The light transmittance and reflectance are manipulated based on the requirement of visual evaluation and daylighting systems.

The three-layer absorber structure coating can be deposited using closed field magnetron sputtering (CFM). As shown in Fig.5, CFM sputtering offers a flexible and high throughput deposition process for metamaterial absorber and other optical coatings (Monaghan et al., 1993), (Gibson et al., 2006). During CFM, two or more different material targets can be used to deposit multilayers structures comprising a wide range of dielectrics, metals and conductive oxides. Moreover, CFM can produce films over a large surface area at high deposition rate with excellent and reproducible optical properties, attributed to its advantages of room temperature deposition, high ion current density, and low bias voltage and reactive oxidation in the entire volume around the rotating substrate drum carrier. CFM has been used for various optical coatings, including anti-reflection, IR blocker and color control and thermal control filters, graded coatings, narrowband filters as well as conductive transparent oxides such as indium tin oxide (Gibson et al., 2006).

Heat exchanges of glass windows with perfect metamaterial absorber coatings

Taking the metamaterial solar absorber (Fig.3 and 4) as
an example, the total solar absorptance or the fraction of absorbed solar energy at the normal incidence can be calculated by (Wang and Wang, 2013):

\[ \alpha_{\text{total}} = \frac{\int_{\lambda \text{min}}^{\lambda \text{max}} I_{\lambda}(\lambda) d\lambda}{\int_{\lambda \text{min}}^{\lambda \text{max}} I_{\lambda}(\lambda) d\lambda \cdot A_{\text{abs}}} \]  

(6)

Here, \( I_{\lambda}(\lambda) \) is the spectral intensity of solar irradiation in the US continent (Air Mass 1.5 Spectra, American Society for Testing and Materials (ASTM), 2014). The total absorptance at normal incidence for the single-sized metamaterial absorbers with \( w_1 = 250 \text{ nm} \) and \( w_2 = 300 \text{ nm} \), and the double-sized one with \( w_1 \) and \( w_2 \) are 88.06%, 87.96%, and 88.72%, respectively (Wang and Wang, 2013).

While the total absorptance represents the performance to collect solar energy, the total emittance should also be considered as a measurement of thermal energy loss from the thermal emission of the absorber itself, which can be calculated at normal direction by (Wang and Wang, 2013):

\[ \varepsilon_{\text{total}} = \frac{\int_{\lambda \text{min}}^{\lambda \text{max}} I_{\lambda}(\lambda) \cdot \varepsilon_{\lambda} d\lambda}{\int_{\lambda \text{min}}^{\lambda \text{max}} I_{\lambda}(\lambda) d\lambda} \]  

(7)

where \( \varepsilon_{\lambda} \) is the blackbody spectral intensity at the solar absorber temperature \( T_A \). The total emittance strongly depends on the absorber temperature. Assuming that the absorbers operate at \( T_A = 100^\circ\text{C} \), the total emittance at normal direction for all above three metamaterial solar absorbers are 2.76%, 3.20% and 2.97%, respectively. Therefore, the metamaterial structure coatings as shown in Fig.4 could potentially be highly efficient selective solar absorbers with more than 88% solar absorptance and less than 3% total emittance at 100°C (Wang and Wang, 2013).

By neglecting convection and conduction heat loss and assuming 1 sun condition, the total photon-to-heat conversion efficiency of the solar absorbers can be calculated by (Wang and Wang, 2013):

\[ \eta = \frac{\alpha_{\text{total}} G - \varepsilon_{\text{total}}(G - \alpha_{\text{sky}})}{G} \]  

(8)

where \( G = 1000 \text{ W/m}^2 \) is the incidence heat flux of solar irradiation (Green et al., 2011), and \( T_{\text{sky}} = 0^\circ\text{C} \) is the sky temperature. The total conversion efficiencies are 85.90%, 85.45%, and 86.40% for the optimized single-sized structures with \( w_1 = 250 \text{ nm} \) and \( w_2 = 300 \text{ nm} \), and the double-sized one, respectively (Wang and Wang, 2013).

As shown in Fig. 6, for a solar absorber/building glass window system (glass/air space/glass), the heat energy balance can be expressed as

\[ \Delta \varepsilon_j \cdot t_d \cdot \eta = \alpha_c L_w d_w c_w (T_{\text{Outside}} - T_{\text{Inside}}) + n_{\text{total}} - T_{\text{Inside}} - T_{\text{Outside}} \]  

(9)

where \( \alpha_c \) and \( L_w \) are the area surface of the solar absorber coating and window glass, separately, m²; \( t_d \) is standard solar radiation at the earth’s surface, 1000 W/m² (Green et al., 2011); \( \eta \) is working hours per day of the solar absorber; \( \eta \) is thermal efficiency of the solar absorber; \( K_g \) and \( K_a \) are thermal conductivities of the window glass, and the air space, W/mK; \( h_i \) and \( h_o \) are the convective coefficient of the inside glass surface and out surface of the window, W/m²K; \( T_{\text{Inside}} \) and \( T_{\text{Outside}} \) are the inside surface temperature and the out surface temperature of the window glass, °C; \( L_g \) and \( L_a \) are the thickness of the window glass and the air space, m; \( d_w \) is density of tungsten coating, 19300kg/m³; \( L_w \) is the thickness of the tungsten coating, and \( c_w \) is the specific heat of the tungsten coating, 132 J/kgK.

When \( A_c = A_g \), Eq. (9) can be changed as

\[ T_{\text{outside}} = \frac{J_{\text{s}} d \alpha (1 + d_{\text{w}} + \frac{1}{h_i}) + L_w d_w c_w (1 + d_{\text{w}} + \frac{1}{h_i}) + \frac{1}{h_o} T_{\text{inside}}}{1 + L_w d_w c_w (1 + d_{\text{w}} + \frac{1}{h_i}) + L_w d_w c_w (1 + d_{\text{w}} + \frac{1}{h_i}) + \frac{1}{h_o} T_{\text{outside}}} \]  

(10)

\[ T_{\text{inside}} = T_{\text{outside}} \]  

(11)

For a car window with one layer-glass window, Eq. (9) can be simplified as

\[ A_c \cdot J_{\text{s}} \cdot t_d \cdot \eta = A_c L_w d_w c_w (T_{\text{outside}} - T_{\text{OIL}}) + \frac{T_{\text{outside}} - T_{\text{inside}}}{1 + \frac{1}{X_g} (1 + d_{\text{w}} + \frac{1}{h_i})} \]  

(12)

When \( A_c = A_g \), Eq. (11) can be changed as

\[ T_{\text{outside}} = \frac{J_{\text{s}} d \alpha (1 + d_{\text{w}} + \frac{1}{h_i}) + L_w d_w c_w (1 + d_{\text{w}} + \frac{1}{h_i}) + \frac{1}{h_o} T_{\text{outside}}}{1 + L_w d_w c_w (1 + d_{\text{w}} + \frac{1}{h_i}) + L_w d_w c_w (1 + d_{\text{w}} + \frac{1}{h_i}) + \frac{1}{h_o} T_{\text{outside}}} \]  

(12a)

With calculation results according to Eq. (10) and Eq.(12), Fig.7 shows the variation of the window outside surface temperature vs. solar absorption time for (a) general building window; (b) a car window, assuming initial outside and inside surface temperature of the window is the same. With the proposed metamaterial solar absorber coating, the frost and fog on the windows in a cold winter can be evaporated and removed quickly. With calculation results according to Eq.(10a) and Eq.(12a), Fig. 8 and Fig. 9 provide the variation of the inside surface temperature of building/car window vs. solar absorption time. With proper design, the window surface temperatures can be well controlled for efficient anti-frost, anti-fog and energy-saving. Here the tungsten coating thickness is assumed as 300 nm, which would not generate apparent effect on the transparency of the window glass. Moreover, the transparency can be adjusted by changing the tungsten coating thickness; meanwhile the absorption performance of the solar absorber has no significant variation.
CONCLUSION

The nano-scale metamaterial structures with period array metal-dielectric interfaces, when shined with light, acquire surface plasmons thus trapping light at subwavelength scales. When these metamaterials are coated on outside of a rotatable or switchable glass window, they lead to efficient light absorption, which can be used for window anti-frost/anti-fog and energy saving of transportation vehicles/airplanes and modern buildings. Based on this paper’s analysis, tungsten-SiO$_2$-tungsten metamaterial solar absorber coating can be efficiently provide or improve the window glass’ anti-frost/anti-fog and energy-saving capabilities, meanwhile its transparency has no evident variation. In addition, if the transparency needs to be adjusted, it can be done easily by variation of the tungsten coating thickness without apparent effect on the solar absorption performance. In the summer, for a rotatable window, its opposite side with the perfect mirror function can be turn to face the sunlight to reflect the sunlight away. By adjusting bottom coating structure, perfect or non-perfect mirror can be formed for natural solar reflection or transmittance.

REFERENCE


