Ultraviolet and Infrared Blocking Meta-glasses for Electric Vehicles

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***Abstract*—The air-conditioning systems installed in electric vehicles (EVs) consume a significant portion of battery power, thus, limiting EVs' operating mileage. A design of an automobile windshield that can passively control the heat and light transmitted through it, could improve EV's performance by reducing the need for air-conditioning. Here, we present a 'meta-glass' coating design that could block nearly 90% of ultraviolet and infrared radiations while transmitting 60% of visible radiation. Vehicle windows coated with our meta-glasses could provide thermal and visual comfort to passengers.**

***Index Terms*—metallic nanoparticles, smart windows, thin-films**

I. INTRODUCTION

THE operation of traditional vehicles requires burning of fossil fuels that causes carbon emissions leading to global warming. Keeping in view the sustainable development goals, electric vehicles (EVs) have emerged as a promising solution for the future. Unfortunately, limited operating speed, long battery recharge time, and short driving range remain fundamental challenges in the EV industry [1]. A study reveal that passengers' demand for air-conditioning reduces the driving range by 53% and 18% in winter and summer, respectively [2]. A design of passive windows that can block the undesired ultraviolet and infrared radiations while allowing the transmission of visible radiation could improve EV's performance by reducing the need for air conditioning [3], [4].

To address this challenge, we introduce 'meta-glass' coatings to passively control the portion of solar radiation transmitted through it. This coating comprises a two-dimensional (2D) hexagonal array of metallic nanoparticles (NPs) embedded inside the dielectric layer of a metal–dielectric–metal (MDM) multilayer thin-film stack. We use silver (Ag) as the top and bottom metallic layers and silica (SiO_2) as the middle dielectric layer. We explore five different choices of metallic NPs and compare their figure of merit based on industry standards.

II. DESIGN, RESULTS AND DISCUSSIONS

Figure 1(a) shows a 3D perspective view of our proposed meta-glass coating. It comprises a 45 nm thick SiO_2 dielectric layer sandwiched between 8 nm thick top and bottom Ag metallic layers. A 2D hexagonal array of molybdenum (Mo) NPs with a 6 nm radius is embedded inside the dielectric layer. The incident wave is a plane wave of transverse-magnetic polarization propagating along the z-direction. We use a finite element method solver to compute over 200–1800 nm spectral window covering more than 95% of the solar irradiance received on the earth's surface [5]. This spectral range comprises ultraviolet (UV; 200–400 nm), visible (VIS; 400–750 nm), and a portion of infrared (IR; 750–1800 nm) radiations [6]. Figure 1(b) depicts the top view of the design where the shaded region represents the unit cell considered for full-wave simulations. The unit cell parameters are specified in the Fig. 1 caption. Figure 1(c) shows that the simulated spectral response through our meta-glass design. We could block ∼90% UV and IR radiations while maintaining 60% standard visible transmission. Figure 1(d) shows strong localization of the electric field between the NPs at 1000 nm wavelength. Around this wavelength, incident light sees the entire assembly of NPs as a reflective plane–leading to high reflection in near-IR.

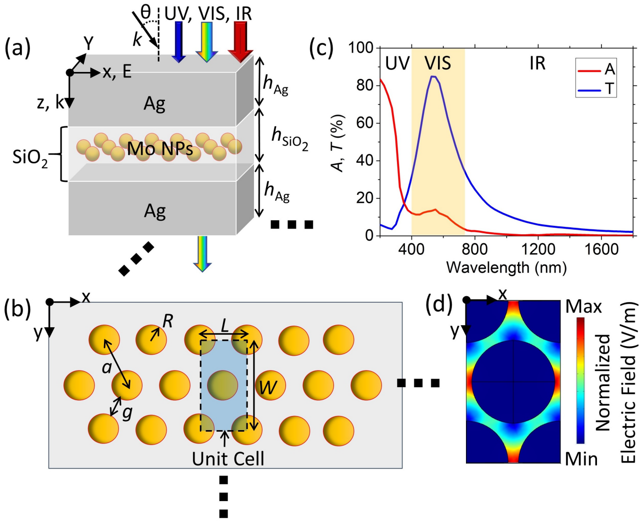

Fig. 1. (a) A three-dimensional (3D) geometry of meta-glass based on an infinite 2D array of metallic nanoparticles (NPs), (b) top view of the design depicting a unit cell using the shaded region, (c) spectral response showing transmittance (T) and absorbance (A), and (d) normalized electric field distribution of the unit cell at 1000 nm wavelength. In (a) and (b), thickness of top and bottom silver metallic layers, h_{Ag} = 8 nm, thickness of silica dielectric layer, $h_{\mathrm{SiO_2}}$ = 45 nm, radius of each NPs, R = 6 nm, gap between NPs, g = R/4, lattice constant, a = $2\times R+g$, Width of the unit cell, L = 2asin30°, and length of the unit cell W = 2acos30°.

Next, the unit cell parameters are tuned to obtain the desired optical response from these meta-glasses. Figure 2(a) shows a redshift in the peak transmittance with an increase in the radius (R) of NPs. This is because the larger the NP radius, the resonance is likely to take place at a longer wavelength. Next, when we increase the gap (g) between the NPs, there is a slight blue shift and increase in peak transmittance, as

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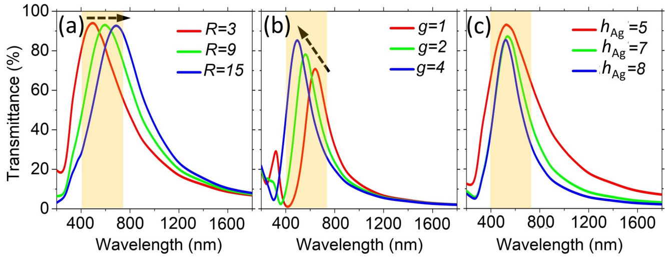

Fig. 2. Tuning transmittance spectrum by varying the unit cell parameters (all dimensions in nm): (a) radius of NPs, R, (b) gap between NPs, g, and (c) thickness of the top and bottom metallic layers, h_{Ag}.

shown in Fig. 2(b). This is because light can now see the gaps and easily penetrate through the structure. In Fig 2(c), we could see a slight drop in the peak transmittance and narrowing of spectra with an increase in the top and bottom metallic layer thicknesses (h_{Ag}). This is obvious because the larger the thickness of the metallic layer, the lesser will be the transmission of electromagnetic waves through it [7]. Finally, after manually optimizing our design in its parametric domain, we found that R = 6 nm, h_{Ag} = 8 nm , and g = 1.5 nm could be an optimal choice for our meta-glass design.

The portion of UV, VIS, IR, and total solar heat transmitted through a window over a given spectral range is defined as ultraviolet transmittance (UVT), visible transmittance (VT), infrared transmittance (IRT), and solar heat gain coefficient (SHGC), respectively. A general expression for FOM is given by [6]:

$$\mathrm{FOM} = \frac{\int_{\lambda_{\min}}^{\lambda_{\max}} I_{\mathrm{solar}}(\lambda) T(\lambda) \mathrm{d}\lambda}{\int_{\lambda_{\min}}^{\lambda_{\max}} I_{\mathrm{solar}}(\lambda) \mathrm{d}\lambda} \tag{1}$$

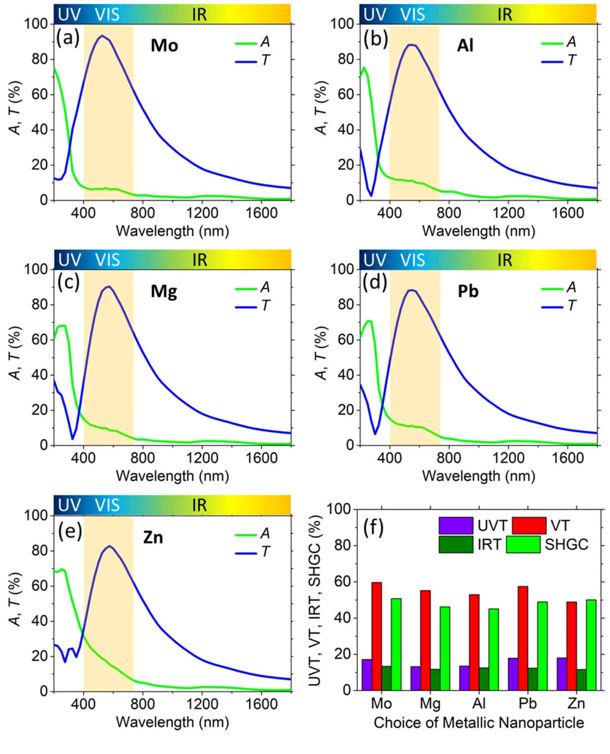

Fig. 3. Numerically calculated spectral characteristics of meta-glasses for different choices of NPs: (a) molybdenum, (b) aluminium, (c) magnesium, (d) lead, and (e) zinc. Figure of merit comparison among our designs depicted in (a)–(e). Note: ideal values of ultraviolet transmittance (UVT), visible transmittance (VT), infrared transmittance (IRT), and solar heat gain coefficient (SHGC) are 0, 1, 0, and 0.43 over 200–1800 nm spectral range.

where $I_{\mathrm{solar}}(\lambda)$ and $T(\lambda)$ are termed as solar irradiance of sun at sea level and wavelength dependent transmission, respectively [5]. The spectral window for UVT, VT, IRT, and SHGC are 200–400 nm, 400–750 nm, 750–1800 nm, and 200–1800 nm, respectively [4]. Since, we optimized our window for typical hot weather condition, ideal values are FOM are: UVT = 0, VT = 1, IRT = 0, and SHGC = 0.43.

Figures 3(a)–3(e) show numerically obtained spectral response for different choices of metallic NPs: molybdenum (Mo), aluminium (Al), magnesium (Mg), lead (Pb), and Zinc (Zn). In Fig. 3(f), we compared their performance by introducing the figure of merit (FOM) used in the industry [8]. Based on these parameters, we find that Mg or Al NPs based meta-glasses are suitable for efficiently blocking the UV portion of the solar radiation. If blocking IR radiation is a priority, then Zn NPs based meta-glasses could be the best choice. However, since we want to maintain standard visible transmittance around 60%, Mo NPs based meta-glasses could be considered as the best choice among all.

III. CONCLUSION

We presented a design of meta-glasses capable of blocking ultraviolet and infrared radiations efficiently. By introducing different choices of metallic nanoparticles inside the dielectric layer of a metal–dielectric–metal cavity, we could achieve more than 90% UV and IR blocking while maintaining 60% visible transmittance. Our thin-film coatings may be applied on vehicle windows to provide ambient indoor temperature and brightness and improve the vehicle's performance. Apart from vehicles, these meta-glasses could find wide application in residential buildings, greenhouses, sunglasses, solar panels, advertising screens, just to name a few.

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