Research article

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Optically and radio frequency (RF) transparent meta-glass

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Abstract: We propose a radio frequency (RF) and visibly transparent composite metasurface design comprising newly developed transparent multilayer conductive coatings. Detailed experimental and theoretical analysis of the RF/visible transparency of the proposed meta-glass is provided. The proposed nature-inspired symmetrical honeycomb-shaped meta-glass design, alters the electromagnetic properties of the glass substrate in the RF spectrum by utilizing visibly transparent Ag-based conductive coatings on each side. Furthermore, the competing effect of the Ag thickness on optical and RF transparency is discussed. We show that using multilayer dielectric-metal coatings, specifically 5-layered spectrally selective coatings, RF transparency of the meta-glass can be enhanced while preserving visible transparency. Herein we demonstrate high transparency meta-glass with 83% and 78% peak RF and optical transmission at 28 GHz and 550 nm, respectively. The meta-glass yields enhanced RF transmission by 80% and 10% when compared to low-emissivity glass and bare glass, respectively. The meta-glass design presented here is amenable to a variety of 5G applications including automobile radar systems. This work provides a superior alternative to the standard indium-tin-oxide (ITO) transparent material which is becoming scarce. Moreover,

this study paves the way for the design of new visibly transparent metamaterials and artificial dielectrics.

Keywords: 5G communication; metamaterials; metasurfaces; radomes; transparency.

1 Introduction

Recent years have witnessed a growing interest in thin metallic nano-films that can simultaneously offer high electrical conductivity and optical transparency, owing to their promising potential in realizing various optically transparent electromagnetic (EM) devices and low-emissivity materials. In this regard, conductive oxides (e.g., indium tin oxide (ITO), aluminum-doped zinc oxide (AZO)) and dielectric-metal-dielectric (DMD) designs (usually comprising silver nano-films) have been extensively studied [1–18] for a variety of applications. These include low-emissivity optical coatings [1–3, 16, 19, 20], transparent conductive oxides (TCOs) in photovoltaic devices [2–4], transparent circuit components [4], antennas [5], metamaterials [7–10, 17, 20, 21], and various flexible devices and sensors [11, 12, 18]. Moreover, there has been a focus on the design and fabrication of visibly transparent low-emissive radio frequency (RF) absorbers for IR, acoustic and RF bistable applications [18–22], where researchers exploit the low conductivity of thin films (e.g., ITO) for high RF absorption. Despite their successful integration in a multitude of device constructs, the limited electrical conductivity offered by these material systems along with their scarcity (e.g., ITO) prevents the realization of transparent EM devices that can also operate in the high radio frequency (RF) range (GHz–THz).

To overcome these constraints, spectrally selective coatings have been proposed recently that can offer high electrical conductivity in the microwave regime while also offering high optical transparency [15, 23]. As such, they serve as a promising steppingstone in the development of transparent EM devices, particularly for next generation 5G communication applications. These 5G communication technologies which are based on microwave frequencies

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extending up to 100 GHz require the consideration of energy-efficient designs in light of the higher RF ohmic losses in this frequency range.

Among the various potential applications associated with 5G communication, transparent meta-glasses that maximize both the optical and RF transparencies are of particular interest given that RF reflection from ordinary glass is high due to its high permittivity in the RF region, especially for transverse electric (TE) polarization due to the lack of a Brewster's angle. Further, RF reflection is exacerbated by the wide use of low-emissivity coatings on windows (low-emissivity glass), where these coatings can completely block the RF signal and preclude the use of communication devices [16, 24]. It is from the recognition of these constraints that we take inspiration to develop the idea of a meta-glass that maximizes both optical and RF transparencies.

To realize such a meta-glass, we hereby utilize a cascade of dielectric (D) and metal (M) layers at the nanometre thickness scale to design a composite of metasurfaces on a glass substrate. High optical transparency is achieved via optimal utilization of multilayers (m) of oxide-free dielectric aluminum nitride (AlN) and nano-thin silver (Ag) films, while the metasurfaces are obtained by design to realize low RF reflections and minimize ohmic losses. In particular, these metasurfaces comprise of arrays of subwavelength-sized unit cells that interact with an incident RF wave such that the structure is impedance matched to the surrounding medium, thereby minimizing the RF reflections. The prototypical meta-glass structure proposed herein opens the prospect of a manifold of new optically transparent metamaterial designs.

In contrast, it is important to recognize that over the last decade various concepts on optical transparency have been explored to advance the design of visibly transparent metamaterial structures [25]. Structures with balanced loss and gain, such as those embracing parity-time symmetry, have been proposed to attain low scattering response from a metamaterial layer or a single meta-atom using active elements [26, 27]. The potential of designing transparent meta-atoms using only passive elements has also been explored [27]. Exceptional properties of such photonic structures have been studied at length [28]. A recent study shows that densely packed metallic nanospheres and nanorods act as artificial dielectrics in the optical region and it is possible to fabricate thick transparent metallic structures [29]. However, the proposed approaches lack simplicity and present fabrication challenges that make large scale fabrication impractical. Further, the use of low conductivity layers in these constructs prevents the

structures from being ideal candidates for the design of RF metamaterials even though they provide transparency in the visible region.

In this work, we propose and experimentally demonstrate a meta-glass that significantly enhances the RF transmission at the operating frequency of 28 GHz and which is amenable for various 5G applications such as radomes in automobile radar systems. The prototypical meta-glass structure offers increased RF transparency and minimal ohmic losses by simultaneously inducing both electric and magnetic responses such that the intrinsic impedance of the meta-glass is matched to that of free space. The underlying physics defining the balance between RF and optical transparency is examined in detail. In the following section, we present the theory and design of the RF transparent meta-glass. We then show how RF transparency is constrained by the competing properties of optical transparency and electrical conductivity of the nano-thin silver film layer(s). Subsequently, we present and discuss the RF and optical response of the designed and fabricated meta-glass structure. We conclude by pondering opportunities in the field of transparent metamaterials.

2 Theory

The aim of this study is to realize an optically transparent meta-glass that also offers a wide-band, wide-angle, high RF transparency near 30 GHz. We commence by demonstrating the design of the highly visible and electrically conductive optical coating (Figure 1c). We then utilize this optical coating as a conductive surface to design a metasurface which offers high RF transparency near 30 GHz.

Here below, we elaborate on the theory behind the optical transparency of multilayered dielectric-metal (m-DM) optical coatings and the physics of RF transparency of the honeycomb-shaped composite metasurface structure (Figures 1 and 2). We analyse the design procedures for optical and RF transparency separately given the huge difference between optical and RF wavelengths.

2.1 Design of the multilayered optical coating

To obtain high optical transparency as well as high electrical conductance, we consider spectrally selective coatings comprising multilayered dielectric-metal (m-DM) films (Figure 1c). These m-DM coatings offer much design versatility where the integrated wave-interference effects,

Figure 1: (a) Meta-glass: a symmetrically layered structure made of identical metasurfaces on both faces of the glass substrate. (b) Unit cell view of the meta-glass comprising aligned honeycomb meshes on both sides. (c) Honeycomb mesh made of a cascading multilayered dielectric-metal (m-DM) spectrally selective coating.

due to the modulation in dielectric and metal film thicknesses at nanometre scales, yield the desired optical transparency while the composite structure provides significant electrical conductance [15]. Here, we optimize the m-DM stack using the transfer matrix method [30, 31] to achieve high optical transparency and high electrical conductance, where the latter is then availed for the desired EM response in the RF region. High electrical conductance is achieved by virtue of being able to integrate multiple nano-thin layers of metal films within the m-DM

stack and simultaneously being able to optimize the dielectric layers to maintain a high level of optical transparency. The optimal optical performance is achieved through the maximization of T_{vis} . T_{vis} is a weighted transmission coefficient – that is, the transmittance is weighted by the photopic sensitivity function where the latter represents the spectral response of an average human eye

$$T_{vis} = \int V(\lambda) T_{m-DM \text{ coated glass}}(\lambda) d\lambda \quad (1)$$

where the $T_{m-DM \text{ coated glass}}(\lambda)$ is the net transmission of the uniformly coated (m-DM optical films on) glass substrate, which is calculated using the transfer matrix method [30, 31], while $V(\lambda)$ is the photopic sensitivity function of the average human eye [15]. Which means, the higher the T_{vis} value is, the more transparent the structure appears to the average human eye; the optimal optical response ($T_{m-DM \text{ coated glass}}^{opt}(\lambda)$) considered here is for a 5-layered m-DM coated glass structure. The optimal m-DM stack design comprises two metal (Ag) layers and three dielectric (AIN) layers, that is, DMDMD, with respective thicknesses of 42 nm-15 nm-48 nm-15 nm-42 nm. Figure 3 shows the calculated and measured optical response for this structure. Here, we used the refractive indices presented in [32]. The modelled results are in good agreement with the measured data. The rationale behind the design of the honeycomb-shaped meshes is explained below, where the electrical conductance of the optimal m-DM layer stack on glass serves as the basis of achieving the desired RF transparency. However, the effective optical transmission of the meta-glass is calculated by considering the fact that the honeycomb-shaped m-DM mesh covers only 25% of the meta-glass surface, that is, the ratio of surface areas covered by the m-DM to that of the entire honeycomb unit cell (Figure 1 a and b). To calculate this, we first determine the spectral response of the glass substrate which is

Figure 2: Meta-glass (cross-sectional view: a conceptual illustration of RF and visible performance, and RF Fresnel's reflection and transmission at 28 GHz).

Figure 3: Comparison between the modelled data based on the transfer matrix method and the measured data for the transmission and reflection of the glass substrate uniformly coated with the designed m-DM stack (DMDMD) on one side where the total Ag thickness is 30 nm and the respective thicknesses of 42 nm-15 nm-48 nm-15 nm-42 nm.

entirely/uniformly coated with the m-DM layer stacks on both sides using the transfer matrix method [30, 31].

The effective spectral optical transparency of the meta-glass is calculated using the fractional surface area weighted average of optical transmission associated with the m-DM coated glass (25%) and the bare glass (75%): $T_{vis}^{eff} = 0.25 \times T_{vis}^{coated-glass} + 0.75 \times T_{vis}^{bare-glass}$. Given the high transparency of the bare glass, the optical transmission of the meta-glass is significantly enhanced compared to the entirely/uniformly coated low-emissivity glass.

2.2 Design of the meta-glass structure

We now present the design of a metamaterial structure comprising identical metasurfaces on both faces of a glass substrate with the objective of enhancing the RF transparency of this composite metamaterial, that is, the meta-glass structure, at 28 GHz.

Metasurfaces permit the engineering of artificial electromagnetic response through subwavelength patterning of a given surface. Examining possible periodic patterns on 2D surfaces, we observe that the naturally occurring honeycomb mesh provides the highest level of geometric symmetry which is of relevance in this study. Using this honeycomb mesh unit cell design (Figure 1) we show that it is possible to modify the EM properties of glass such that the new meta-glass is effectively impedance-matched with its surroundings. For example, each of the honeycomb m-DM meshes on the glass substrate is a metasurface capable of possessing negative electric polarizability. The polarizability of each mesh can be tuned by changing the density of the meshes, that is, the denser the m-DM meshes are, the more negative it becomes.

Here, we would like to highlight that the effective permittivity ϵ_t and permeability μ_t were extracted by viewing the whole mesh-substrate-mesh topology as one metamaterial layer. In addition to the electric response, the magnetic response of the structure was viewed as a result of the coupling between the two meshes that are separated by the glass substrate with finite thickness. As such, the permeability which we utilize to characterize the magnetic response of the structure is not that of the 2D mesh, but that of the whole mesh-substrate-mesh structure. In this regard, the finite thickness of the meta-glass layer allows us to use average polarization in the meta-glass structure and as a result characterize the structure with effective permeability and permittivity. As mentioned above, the long inductive mesh wires give rise to an electric dipole response with a negative electric polarizability which can be engineered to lower the permittivity of the bare glass to make it equal to the effective permeability, thus leading to impedance matching [33].

The principal functional consideration in the design of a meta-glass is that the composite metasurface supports enhanced omnidirectional RF transmission while being polarization independent. In this regard, the symmetry of the meta-structure is a critical design parameter given the fact that it helps sustain RF transparency under different angles of incidence and polarizations. In particular, the rotational symmetry of the hexagonal honeycomb mesh yields an RF response independent of the incident polarization for a normally incident wave at any azimuthal angle. Further, the goal here is to achieve identical permittivity and permeability close to unity which helps preserve the high RF transmission for wide incident angles (i.e., azimuth and altitude). This is achieved when the glass substrate is sandwiched between two layers of honeycomb-shaped m-DM meshes.

It is worth noting here that the effect of induced normal and tangential components of electric and magnetic polarization moments on the metasurface boundary conditions has been studied extensively [34–37]. It has been established that the normal components of EM properties are redundant to the design of far-field responses of a metasurface structure. Hence, to achieve a high-degree of omnidirectional response independent of the polarization, the design ought to preserve the induced tangential electric and magnetic responses (i.e., $\epsilon_t \approx \mu_t \approx 1$) for different incident angles and polarizations. To demonstrate the meta-glass' wide-angle performance, the induced surface currents on the honeycomb mesh are illustrated for different polarizations and two angles of incidence (0° and 45°) in Figure 4. This figure implies that due to the presence of the electric field tangential to the surface, in-phase currents

Figure 4: Surfacial currents induced on the meta-glass structure due to EM waves at different incident polarizations and angles of incidence. (a) TE and (b) TM polarization at normal incidence. (c) TE and (d) TM polarization at 45° to the normal.

are induced on both sides of the meta-glass structure especially along the direction of the electric field. Moreover, due to the presence of the magnetic field between the two meshes under all incident angles (e.g., 45° and 0°) the magnetic response (i.e., out-of-phase currents) is maintained, which implies that impedance matching is preserved to some extent for all incident angles by virtue of preserving identical tangential permittivity and permeability. Furthermore, the total asymmetrical induced currents in Figure 4 can be interpreted as a superposition of out-of-phase (i.e., magnetic response) and in-phase (i.e., electric response) components. A more detailed analysis of the angular performance of these composite metasurfaces can be found in [33]. Further data for the angular, as well frequency response, of the meta-glass can be found in the Supplementary materials.

The conductivity of the thin m-DM stack is a key parameter in the design. The bulk conductivity of m-DM comprising 30 nm Ag is 1.8×10^{-7} S/m which is only 1/3 of the bulk conductivity of Ag. The relation between the measured conductivity of thin film m-DM stack and the comprising total Ag thickness is discussed in the Supplementary materials. In order to achieve impedance matching, the effective tangential permittivity and permeability of the structure are engineered by precisely tuning the geometrical dimensions of the honeycomb mesh (pitch and the trace width of the m-DM coating). To show this, we first

calculate the total reflection from the meta-glass which is given as [33],

$$r = \frac{r_{12} + r_{21}e^{-i2\phi}}{1 - r_{21}r_{12}e^{-i2\phi}} \quad (2)$$

where the Fresnel reflection coefficient $r_{ij} = \frac{(Z_j - Z_i)}{(Z_j + Z_i)}$ is a function of the intrinsic impedances (Z_i and Z_j) at the interface of media i and j , respectively (Figure 2). The phase $\phi = k_{zz}d$ is the total phase delay along the normal axis (z) inside the glass layer of thickness d , where k_{zz} is the RF wavenumber along the normal. We use 1.1 mm thick glass for the design of the meta-glass structure considering that $d \approx \lambda/10$ at 28 GHz. The effective impedance of the meta-glass is a function of its transmission and reflection coefficients [33]:

$$\frac{Z_{eff}}{Z_0} = \sqrt{\frac{(1+r)^2 - t^2}{(1-r)^2 - t^2}} = \sqrt{\frac{\mu_{eff}}{\epsilon_{eff}}} \quad (3)$$

where ϵ_{eff} and μ_{eff} are the effective tangential permittivity and permeability of the structure under normal incidence, respectively (Figure 5). To match the impedance of the meta-glass, Z_{eff} is equated to the impedance of air and thus Eq. (3) becomes

$$Z_{eff} = Z_0 \sqrt{\frac{\mu_{eff}}{\epsilon_{eff}}} \approx Z_0 = Z_{air} \quad (4)$$

with Z_{eff} defined by the preceding relation, the total reflection (Eq. 2) approaches zero and correspondingly the total transmission approaches unity. A more detailed mathematical description of the design of composite coupled metasurfaces for radome applications is given in [33]. Figures 5 and 6 illustrate the effective impedance and tangential permittivity and permeability of the designed structure (pitch = 3.6 mm and trace width = 0.5 mm). Close to unity RF transparency is achieved at 28 GHz where the structure's EM properties match those of the surrounding medium, hence resulting in near zero reflection as the incident wave traverses the meta-glass unabsorbed. In the Supplementary materials we discuss the possibility of tuning the operating bandwidth by changing the pitch (i.e., periodicity) of the honeycomb mesh structures. It is also worth noting that the operating frequency of the structure mainly depends on the thickness of the glass substrate and the pitch of the honeycomb structures, while the trace width mainly affects the losses and therefore the efficiency of the RF transmission at a particular frequency.

Upon closer observation of Figures 4 and 6, it is seen that the structure can operate at different angles and polarizations of the incident wave. A more detailed

Figure 5: Effective tangential permittivity and permeability of the meta-glass structure for normally incident waves.

Figure 6: Normalized effective impedance of the meta-glass (i.e., $Z_{TM} = Z_{TM}^{\text{Meta-glass}} / (Z_{TM}^{\text{Vacuum}})$) for 45° to the normal and normally incident TM waves.

explanation on the derivation and characterization of such homogenized metamaterial slabs is given in [33]. Having established RF transparency in the meta-glass, aided by multiple nano-thin silver films [15], we now turn our attention to realizing optical and RF transparency simultaneously.

2.3 Optical and RF transparency balance

Silver thickness is the primary parameter that has a competing influence on RF and optical transparency; that is, increasing the Ag thickness increases RF transparency but decreases the optical transparency. To illustrate the opposing influence of Ag thickness, we present the RF and optical transmission of meta-glass structures based on a single layer Ag (3-layered DMD) stack and a dual-layer Ag (5-layered DMDMD) stack as a function of total Ag thickness in the composite structure; that is, with identical honeycomb mesh coated symmetrically on both sides of the glass substrate. Figure 7 (a) shows the optical transparency (T_{vis}) and RF transparency (28 GHz) of the meta-

glass as a function of the total Ag thickness in the composite structure. The plots illustrate a drop in optical transmission and conversely an increase in RF transmission with total Ag thickness; and, more specifically we observe that the 5-layered m-DM structure, however, supports higher optical transmission at larger total Ag thicknesses. The relationship between optical and RF transparency for the meta-glass based on the 5-layered m-DM stack is explicitly illustrated in Figure 7b. We note that an increase in total Ag thickness from 20 to 60 nm results in an increase in RF transparency by almost 20%. Moreover, utilizing 140 nm Ag in the design, the RF transmission is increased up to 90% which also enhances the bandwidth (see the Supplementary materials).

3 Results and discussion

The honeycomb meta-glass is a versatile metamaterial design for wideband and wide-angle optical, and RF transparency applications. Hereunder, we present experimental data on the optical and RF performance of the meta-glass structure. The results pertain to the honeycomb-shaped m-DM coating comprising the 5-layered spectrally selective coating (DMDMD) based on AlN and Ag.

3.1 Optical transparency

The measured optical performance of the meta-glass compared to the low-emissivity glass and bare glass in the visible and near-infrared regions is presented in Figure 9. The dual Ag layer optical coating comprises a total Ag thickness of 30 nm. Peak optical transmission in the visible (at ~550 nm) of the bare glass substrate, meta-glass, and low-emissivity glass are 92, 78, 82%, respectively, while in the

Figure 7: (a) RF transmission at 28 GHz and corresponding T_{vis} profile for the meta-glass structure composed of honeycomb meshes made of optimal spectrally selective coatings (single metal layer (DMD) and dual metal layer (DMDMD)) shown as a function of the total Ag thickness on each side of the glass substrate. (b) Change in the T_{vis} profile with increasing RF transmission in meta-glass structures comprising of optimal DMD and DMDMD spectrally selective stacks.

infrared region the IR reflection is approximately uniform with wavelength at 8, 28, and 88%, respectively. Examining more closely the transmission of the meta-glass (78%) and low-emissivity glass (82%), we note that in the former case each side of the glass substrate is coated with the spectrally selective m-DM coating with an area coverage of 25%, while in the latter case the entire surface of only one side is coated. Further, since each spectrally selective coating has a total Ag film thickness of 30 nm, the two honeycomb meshes have a cumulative Ag thickness of 60 nm which is twice that of the low-emissivity glass. Moreover, both sides of the metasurface are encapsulated with 20 nm thin AlN to prevent oxidation of the Ag. The net effect of these factors is the basis for the 4% reduction in transmission.

3.2 RF transparency

Here, we show that the RF transmission of the designed metasurface outperforms that of bare glass and low-emissivity materials for a wide range of incident angles (Figure 10). Furthermore, Figure 11 shows that the designed meta-glass possesses 80% RF transparency at 28 GHz with 6 GHz operating bandwidth under normal incidence for both TE and TM polarizations. It is worth noting that the wideband performance is due to the off-resonance design of the structure which also helps to lessen RF losses.

Figure 8: Photographs of (a) the fabricated optically and RF transparent meta-glass, and (b) the RF measurement apparatus.

The RF reflection and transmission of the meta-glass in comparison to that of the low-emissivity and bare glasses, measured using the quasi-optical measurement apparatus (Figure 8b and Method section), are shown in Figure 11. We observe an increase by as much as 10 and 80% in RF transmission for the meta-glass compared to that of bare glass and low-emissivity glass, respectively. The much

Figure 9: Measured spectral optical transmission and reflection for the bare glass substrate, meta-glass, and low-emissivity glass under normal incidence.

Figure 10: Modelled data showing the angular dependence of RF transmission for incident TE (a) and TM (b) polarization along with the measured RF transmission for TE (c) and TM (d) incidences.

Figure 11: Measured and Modelled RF transmission and reflection of the bare glass substrate, low-emissivity glass and the designed meta-glass comprising of optimized m-DM spectrally selective (DMDMD) coating with a total of 30 nm Ag on each side under normal incident.

greater increase in RF transmission when compared to low-emissivity glass is due to its RF shielding property. Further, examining the angular RF performance measurements (Figure 10) we see that the meta-glass maintains high RF transmission for angles of incidence up to 60° for TE polarization and even higher angles under TM polarization, where the latter is due to the presence of Brewster's angle.

Moreover, comparing the transmission of the meta-glass structure with that of the bare glass (see the Supplementary materials sup-Figures 2–4) we see that the meta-glass outperforms the glass for angles up to 40° and for all angles of the TE incident wave. However, due to the presence of the Brewster angle at 66° , glass has a higher transmission for TM waves. At the same time, the meta-glass structure does not possess a Brewster angle and hence preserves constant transmission over a wider range of angles. Although the higher transmission of glass beyond 40° for TM polarization might seem like a disadvantage, preserving constant transmission over a wide range of incident angles (see the Supplementary materials) is highly advantageous in radar applications, where a

scanning radar beam would not be affected nor deformed. Moreover, the differences in the transmission magnitudes between the two polarizations are smaller in the meta-glass. Finally, a small difference between the magnitude of transmission for TE and TM polarizations is important for maintaining polarization fidelity, i.e., one would want to avoid turning a circularly polarized wave into an elliptically polarized wave.

Overall, the modelled and experimental results are in good agreement, indicative of accurate optical and EM modelling on the one hand and fine control over the fabrication processes in realizing the meta-glass structure on the other.

4 Conclusion

In summary, we have theoretically analysed and experimentally demonstrated the first optical and RF transparent meta-glass structure based on ultrathin Ag films. The structure is a composite metasurface comprising identical honeycomb mesh-based metasurfaces on both faces of the glass substrate wherein the mesh avails a multilayered metal-dielectric spectrally selective coating. The combination of the metasurface design and the spectrally selective coating effectively yields high electrical conductance and high optical transmission simultaneously. We report 78% peak optical transmission along with 82% RF transmission at 28 GHz with a 6 GHz bandwidth in 3.6 mm pitch and 0.5 mm trace-width honeycomb mesh. Moreover, the conductivity of the honeycomb meshes in the transverse direction makes the meta-glass structure a viable candidate for transparent sensors while not possessing conductivity in the normal direction. In addition, the work provides a superior alternative to standard transparent but conductive material structures such as ITO, which are becoming scarce. This study paves the way for the design of new transparent metamaterials using multilayered metal-dielectric spectrally selective coatings wherein a multitude of functionalities can be incorporated including infrared reflection and active electrical modulation of optical and microwave properties.

5 Method

5.1 Simulations

All the RF simulations were modelled in Ansys HFSS software using thin film boundary condition for the honeycomb metallic meshes. The well established transfer matrix

method was used for the analysis and optimization of the optical m-DM coating [30, 31].

5.2 Fabrication

The meta-glass structure was fabricated using photolithography, sputter deposition of Ag-AlN spectrally selective multilayer thin films, and lift-off techniques. The sputtering deposition technique for Ag-AlN stacks is comprehensively explained in the literature [15]. To fabricate the pattern on the glass substrate, we used metal lift-off and photolithography processes. The sequential fabrication steps were as follows: We used 10×10 cm bare glass (1.1 mm thick Corning Eagle XG glass) as the glass substrate. The S1818 photoresist and UV-expose mask aligner were used to expose the patterns on both sides of the glass. Optimal Ag-AlN spectrally selective m-DM thin films were deposited on the photoresist. The m-DM stack (DMDMD) contains a total Ag thickness of 30 nm; this film stack is coated on both sides of the glass substrate. Lastly, we used the lift-off technique to develop the honeycomb-shaped pattern on each side of the glass substrate to attain the composite metasurface based meta-glass. The metasurfaces were then encapsulated with 20 nm of AlN in order to prevent oxidation of the film stacks and in particular the exposed Ag on the edges of the honeycomb mesh pattern.

5.3 RF measurements

The quasi-optical microwave apparatus consisted of a Vector Network Analyzer (VNA), two k-band antennas, and confocal lenses optimized to operate at (25–38) GHz (Figure 8b). The Gaussian beam-waist (beam width of 4 cm) is located at the centre, where the sample is positioned, and is designed to cover 10 hexagonal unit cells and is small enough so as to avoid any spillover of the incident wave on the 10×10 cm sample [38] (Figure 8b).

5.4 Optical measurements

Optical transmission and reflection measurements in the UV, visible, and IR regions (200–2,500 nm) were carried out using the PerkinElmer Lambda 1050 UV/VIS/NIR spectrometer.

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References

- [1] L. Liu, H. Chang, T. Xu, et al., “Achieving low-emissivity materials with high transmission for broadband radio-frequency signals,” *Sci. Rep.*, vol. 7, no. 1, pp. 1–7, 2017.
- [2] M. Lämmle, T. Kroyer, S. Fortuin, M. Wiese, and M. Hermann, “Development and modelling of highly-efficient PVT collectors with low-emissivity coatings,” *Sol. Energy*, vol. 130, pp. 161–173, 2016.
- [3] D. Alonso-Álvarez, L. Ferre, L. Lin, N. J. Ekins-Daukes, and D. J. Paul, “ITO and AZO films for low emissivity coatings in hybrid photovoltaic-thermal applications,” *Sol. Energy*, vol. 155, pp. 82–92, 2017.
- [4] K. Nomura, H. Ohta, A. Takagi, T. Kamiya, M. Hirano, and H. Hosono, “Room-temperature fabrication of transparent flexible thin-film transistors using amorphous oxide semiconductors,” *Nature*, vol. 432, p. 488, 2004, November.
- [5] A. Katsounaros, Y. Hao, N. Collings, and W. A. Crossland, “Optically transparent ultra-wideband antenna,” *Electron. Lett.*, vol. 45, no. 14, pp. 722–723, 2009.
- [6] J. Zhao, C. Zhang, Q. Cheng, J. Yang, and T. J. Cui, “An optically transparent metasurface for broadband microwave antireflection,” *Appl. Phys. Lett.*, vol. 112, no. 7, 2018, <https://doi.org/10.1063/1.5018017>.
- [7] D. Hu, J. Cao, W. Li, et al., “Optically transparent broadband microwave absorption metamaterial by standing-up closed-ring resonators,” *Adv. Opt. Mater.*, vol. 5, no. 13, pp. 1–8, 2017, Art no. 073504.
- [8] C. Ji, K. T. Lee, T. Xu, J. Zhou, H. J. Park, and L. J. Guo, “Engineering light at the nanoscale: structural color filters and broadband perfect absorbers,” *Adv. Opt. Mater.*, vol. 5, no. 20, pp. 15–34, 2017.
- [9] K. Chen, L. Cui, Y. Feng, J. Zhao, T. Jiang, and B. Zhu, “Coding metasurface for broadband microwave scattering reduction with optical transparency,” *Opt Express*, vol. 25, no. 5, p. 5571, 2017.
- [10] T. Jang, H. Youn, Y. J. Shin, and L. J. Guo, “Transparent and flexible polarization-independent microwave broadband absorber,” *ACS Photonics*, vol. 1, no. 3, pp. 279–284, 2014.

- [11] M. Suche, S. Christoulakis, K. Moschovis, N. Katsarakis, and G. Kiriakidis, "ZnO transparent thin films for gas sensor applications," *Thin Solid Films*, vol. 515, no. 2 Spec. Iss., pp. 551–554, 2006.
- [12] S. Lee, A. Reuveny, J. Reeder, et al., "A transparent bending-insensitive pressure sensor," *Nat. Nanotechnol.*, vol. 11, no. 5, pp. 472–478, 2016.
- [13] D. Ebert and B. Bhushan, "Transparent, superhydrophobic, and wear-resistant coatings on glass and polymer substrates using SiO₂, ZnO, and ITO nanoparticles," *Langmuir*, vol. 28, no. 31, pp. 11391–11399, 2012.
- [14] A. Kim, Y. Won, K. Woo, C. H. Kim, and J. Moon, "Highly transparent low resistance ZnO/Ag Nanowire/ZnO composite electrode for thin film solar cells," *ACS Nano*, vol. 7, no. 2, pp. 1081–1091, 2013.
- [15] R. H. H. Ko, A. Khalatpour, J. K. D. Clark, and N. P. Kherani, "Ultraspeed ultrathin Ag films by AlN seeding and Ar/N₂ sputtering for transparent conductive and heating applications," *APL Mater.*, vol. 6, no. 12, 2018, Art no. 121112, <https://doi.org/10.1063/1.5052261>.
- [16] B. P. Jelle, S. E. Kalnæs, and T. Gao, "Low-emissivity materials for building applications: a state-of-the-art review and future research perspectives," *Energy Build.*, vol. 96, no. 7491, pp. 329–356, 2015.
- [17] H. B. Jing, Q. Ma, G. D. Bai, L. Bao, J. Luo, and T. J. Cui, "Optically transparent coding metasurfaces based on indium tin oxide films," *J. Appl. Phys.*, vol. 124, no. 2, 2018, Art no. 023102, <https://doi.org/10.1063/1.5027589>.
- [18] C. Zhang, X. Wu, C. Huang, et al., "Flexible and transparent microwave-infrared bisealth structure," *Adv. Mater. Technol.*, vol. 4, no. 8, 2019, Art no. 1900063, <https://doi.org/10.1002/admt.201900063>.
- [19] Y. Ruan, Q. F. Nie, L. Chen, and H. Y. Cui, "Optical transparent and reconfigurable metasurface with autonomous energy supply," *J. Phys. D: Appl. Phys.*, vol. 53, no. 6, 2019, Art no. 065301, <https://doi.org/10.1088/1361-6463/ab548c>.
- [20] C. Xu, B. Wang, M. Yan, et al., "An optical-transparent metamaterial for high-efficiency microwave absorption and low infrared emission," *J. Phys. D: Appl. Phys.*, vol. 53, no. 13, 2020, Art no. 135109, <https://doi.org/10.1088/1361-6463/ab651a>.
- [21] D. Hu, J. Cao, W. Li, et al., "Optically transparent broadband microwave absorption metamaterial by standing-up closed-ring resonators," *Adv. Opt. Mater.*, vol. 5, no. 13, pp. 1–8, 2017.
- [22] Q. Cheng, G. Song, C. Zhang, Y. Jing, C. Qiu, and T. Cui, "Transparent coupled membrane metamaterials with simultaneous microwave absorption and sound reduction," *Optics Express*, vol. 26, no. 18, pp. 22916–22925, 2018.
- [23] Y. Ye, J. Y. Y. Loh, A. Flood, et al., "Plasmonics of diffused silver nanoparticles in silver/nitride optical thin films," *Sci. Rep.*, vol. 9, no. 1, p. 20227, 2019.
- [24] R. B. Green, M. Guzman, N. Izyumskaya, et al., "Optically transparent antennas and filters: a smart city concept to alleviate infrastructure and network capacity challenges," *IEEE Antenn. Propag. Mag.*, vol. 61, no. 3, pp. 37–47, 2019.
- [25] I. Faniayeu, S. Khakhomov, I. Semchenko, and V. Mizeikis, "Highly transparent twist polarizer metasurface," *Appl. Phys. Lett.*, vol. 111, no. 11, 2017, Art no. 111108, <https://doi.org/10.1063/1.4994777>.
- [26] M. Safari, M. Albooyeh, C. R. Simovski, and S. A. Tretyakov, "Shadow-free multimers as extreme-performance meta-atoms," *Phys. Rev. B*, vol. 97, no. 8, pp. 1–10, 2018.
- [27] A. Momeni, M. Safari, A. Abdolali, and N. P. Kherani, "Tunable and dynamic polarizability tensor for asymmetric metal-dielectric meta-cylinders," pp. 1–12, 1904, <https://arxiv.org/abs/1904.04102>.
- [28] M. A. Miri and A. Alù, "Exceptional points in optics and photonics," *Science*, vol. 363, no. 6422, 2019, <https://doi.org/10.1126/science.aar7709>.
- [29] S. J. Palmer, X. Xiao, N. Pazos-Perez, et al., "Extraordinarily transparent compact metallic metamaterials," *Nat. Commun.*, vol. 10, no. 1, pp. 1–7, 2019.
- [30] C. C. Katsidis and D. I. Siapkas, "General transfer-matrix method for optical multilayer systems with coherent, partially coherent, and incoherent interference," *Appl. Opt.*, vol. 41, no. 19, p. 3978, 2002.
- [31] R. M. Wood, "Thin-film optical filters: 3rd edition," *Opt. Lasers Eng.*, vol. 37, no. 6, pp. 673–674, 2002.
- [32] M. N. Polyanskiy. Refractive index database, <https://refractiveindex.info>. [Accessed on 2020-04-10].
- [33] Y. He and G. V. Eleftheriades, "A thin double-mesh metamaterial radome for wide-angle and broadband applications at millimeter-wave frequencies," *IEEE Trans. Antenn. Propag.*, vol. 68, no. 3, pp. 2176–2185, 2019.
- [34] S. A. Tretyakov, D. H. Kwon, M. Albooyeh, and F. Capolino, "Functional metasurfaces: do we need normal polarizations?" *32nd Gen. Assem. Sci. Symp. Int. Union Radio Sci. URSI GASS*, vol. 1–3, 2017, <https://doi.org/10.23919/URSIGASS.2017.8105076>.
- [35] M. Safari, H. Kazemi, A. Abdolali, M. Albooyeh, and F. Capolino, "Illusion mechanisms with cylindrical metasurfaces: a general synthesis approach," *Phys. Rev. B*, vol. 100, no. 16, Art no. 165418, 2019, <https://doi.org/10.1103/PhysRevB.100.165418>.
- [36] M. Safari, A. Abdolali, H. Kazemi, M. Albooyeh, M. Veysi, and F. Capolino, "Cylindrical metasurfaces for exotic electromagnetic wave manipulations," *IEEE Antenn. Propag. Soc. Int. Symp. Proc.*, pp. 1499–1500, 2017, <https://doi.org/10.1109/APUSNCURSINRSM.2017.8072792>.
- [37] D. H. Kwon, M. Albooyeh, F. Capolino, and S. A. Tretyakov, "Equivalent realizations of reciprocal metasurfaces: role of tangential and normal polarization," *Phys. Rev. B*, vol. 95, no. 11, pp. 1–9, 2017.
- [38] Y. He and G. V. Eleftheriades, "Matched, low-loss, and wideband graded-index flat lenses for millimeter-wave applications," *IEEE Trans. Antenn. Propag.*, vol. 66, no. 3, pp. 1114–1123, 2018.

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