Using Photonic Glasses as Colored Covers for Solar Energy Harvesting

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The increasing demand for renewable energy is promoting technologies that integrate solar energy harvesting materials with the human living environment, such as building-integrated photovoltaics. This places requirements on developing colored covers with a trade-off between efficiency and aesthetics, providing a new stage for the large-scale application of structural color technologies. This study investigates the theoretic feasibility of employing the photonic glass, a random packing of monodisperse dielectric microspheres, as the colored cover for solar energy harvesting. Based on numerous optical simulations, the color and average solar transmissivity of the photonic glasses with varying parameters are evaluated. Results show that using non-absorbing microspheres with relatively high refractive index, about 3 \( \mu \)m thick photonic glasses can enable colors with lightness over 50 while keeping average solar transmissivity over 80%. Due to the short-range structural correlation, it is demonstrated that photonic glasses can generate purple, blue, cyan, light green, and gray colors, but cannot help with yellow and red hues. Finally, the effects of several enhancement methods are clarified, and possible ways for expanding the color range are demonstrated. These results provide a comprehensive guide to the practical implementations of structural color using photonic glasses, particularly in the colorization of solar energy materials.

1. Introduction

Due to the low intensity, using solar energy to power a sustainable future requires large areas of land. But the land is a scarce resource in the human living environment, particularly in cities. This stimulates great interest in technologies that could integrate solar energy harvesting into our daily life on a large scale, for example, building-integrated thermal collector and building-integrated photovoltaics (BIPV).[1–2] For maximizing efficiency, the most typical feature of artificial solar energy harvesting devices like solar thermal (ST) collectors and solar photovoltaics (PV) is their nearly black appearance. However, a black wall or roof is unpopular with most people, therefore in this scenario, attractive aesthetics are just as important as high efficiency.[3–6] This places great demand on developing colorful cover plates for ST and PV, which should promise a decent trade-off between efficiency and aesthetics, and thus should have the following core features: 1) Selective visible light (VIS) reflection; 2) negligible solar radiation absorption; 3) high near-infrared light (NIR) transmission.[7]

Unfortunately, due to their absorption of non-reflected VIS or strong NIR reflection, common colorant materials like pigments and dyes are generally not compliant.[8] In contrast to color by selective absorption, structure color is generated by the scattering, diffraction, and interference of light in micro- and nanostructures.[9–11] This makes it possible to achieve colors covering the entire visible spectrum with solar-transparent materials.[12–14] However, although periodic photonic structures with long-range order could show strong selective reflection and vivid colors, the production process is generally material-consuming and time-consuming, preventing large-scale applications. In this context, the amorphous structural color might be a better candidate, which requires only random structures with short-range correlations.[15–17] Besides, the isotropic structure makes color angle-independent, and appears pretty close to that produced by absorbing pigments and dyes.[18,19] In recent years, the artificial construction of amorphous structural color materials has seen rapid development, especially those made by self-assembled dielectric microspheres, referred to as photonic glasses.[20–22]

Previous studies have demonstrated the feasibility of replacing traditional pigments with photonic glasses or photonic glasses with light-absorbing additives, in which the following advantages are often highlighted: Long-term stability, environmental friendliness, and dynamic tunability.[23–25] While in most cases, another advantage of all-dielectric photonic glasses for colorization is not explored, that is, negligible absorption and high NIR transmission. In this context, we envisioned that photonic glasses and solar energy harvesting materials would be a win–win combination. Recently we reported mass-producible and high-efficiency colored PVs using the photonic glass self-assembled by colloidal ZnS microspheres, preliminarily validating the idea.[26] To guide practical applications in the future, the relationship between structure, color, and solar radiation transmittance needs to be figured out.

As a colored cover for solar energy harvesting materials like solar cells that work outdoor, the photonic glass layer is better to be embedded in a polymer encapsulant (Figure 1A).
Additionally, there should be a glass cover to resist environmental damage. In this context, the matrix of the photonic glass is a polymer with a refractive index from 1.4 to 1.6, rather than the commonly used air. In the analysis of this study, we take both the glass cover and the polymer encapsulant as an optically thick layer with a refractive index of 1.5. Besides, in order to obtain a certain degree of selective reflection with a small quantity of materials, it is preferable to use particles with a high refractive index. The photonic glass in this case has rarely been specifically discussed before. Furthermore, because of the disordered structure and the strong multiple scattering, accurate modeling of the photonic glass remains a critical challenge.

Here, we use full-wave electromagnetic simulation in 3D dimensions to study the optical reflection and transmission of thin films made by photonic glasses with relatively large refractive index contrast. Through the simulated spectral reflectance in broad wavelengths from UV to NIR, we have evaluated the generated color and average solar transmissivity, as well as how the particle diameter and layer thickness influence them. Besides, we have examined some potential enhancement methods, such as increasing the fill fraction, improving the structure factor, and using core–shell structures or air for scattering particles. Furthermore, we provide explanations about the physical mechanism behind the inability of photonic glasses to achieve highly saturated colors as well as yellow and red hues. Finally, we demonstrate that by adding absorptive materials or forming long-range structural order, the multiple scattering in photonic glasses could be eliminated, and thus red color could be realized.

2. Simulation

As shown in Figure 1B, the thin film of photonic glass is self-assembled by monodisperse non-absorbing microspheres with diameters of $d$ and refractive indexes of $n_s$. As mentioned above, the matrix is assumed to be a polymer with a refractive index of $n_m$, and $n_m$ is constant at 1.5 in this study. Besides, the fill fraction ($f$) of microspheres in the photonic glass layer and the layer thickness ($t$) would also affect the spectral properties. Totally there are five parameters determining the interaction with light, that is, $d$, $n_m$, $n_m$, $f$, and $t$. In this study we have evaluated how these parameters affect the appeared color and solar transmission.

Existing theories describing the light-matter interaction in photonic glasses are mainly based on the diffusion theory of light-scattering media.\cite{27-29} As illustrated in Figure 1C, the theory treats light scattering of a phonic glass assembly as a superposition of two processes: Mie scattering by a single particle, and interference between the light scattered from short-range correlated particles.\cite{30,31} A major approximation is that the scattering process happens in an effective media with a refractive index of $n_{\text{eff}}$. Although this theory could capture the resonance peaks in a photonic glass, as we will show in the following, it neglects the near-field effect and multiple scattering, especially when dealing with a relatively large refractive index contrast. Recently Aubry et al.\cite{32} used energy-density coherent-potential approximation for calculating $n_{\text{eff}}$, and Hwang et al.\cite{33,34} proposed a Monte-Carlo model accounting for multiple scattering. Nevertheless, these modeling methods are not well suited to the photonic glass studied in this paper.

In this context, for quantitatively modeling a thin film of photonic glass assembled by non-absorbing particles and with a relatively large refractive index contrast, here we adopt full-wave numerical simulation that is first-principle. Since it is a broadband simulation, and the size of the simulation object is about 10 times relative to the light wavelength, we used the finite difference time-domain (FDTD) method with 3D simulation dimensions.\cite{35-38} During the simulation, we first used a force-biased algorithm to generate a random close packing of monodisperse hard spheres, with specific $d$ and $f$.\cite{39} 3D
spatial coordinates of each sphere were then imported into the FDTD simulation region to generate the simulation structure (Figure 2A). Periodic boundary conditions were adopted in the x and y directions, and it should be noted that the imported structure also has periodic boundaries (refer to Section S1 and Figure S1, Supporting Information for details).

But since photonic glasses do not have real periodicity, this approach actually simulates a quasi-periodic photonic glass film with the simulation domain as the basic unit. This is somewhat different from actual situations. Therefore, to reduce simulation errors, it is necessary to have enough large simulation regions and to simulate more randomly generated structures. Accordingly, the length of each simulation structure also has periodic boundaries (marked as 1–8, gray lines), the average result (black line), and the smoothed curve of the average result (red line). Colors generated by these reflectivity curves are also presented, with a small color difference (ΔE) between each of them.

Figure 2. A) Figure illustration of the FDTD simulation region. The boundary conditions at top and bottom x y planes are perfect matched layers (PML), and at four side planes are periodic. A plane wave light source is placed above the photonic glass structure, and the light propagates along the z direction. Frequency domain field profile monitors are placed above the light source and below the structure to measure reflectance and transmittance, respectively. B) Simulated reflectivity curves of a typical thin film of photonic glass, including results of eight randomly generated structures.

3. Results and Discussions
3.1. Comparison between Air Matrix and Polymer Matrix

At first, we investigated the effects when changing from an air matrix to the polymer matrix (Figure 3). In the air matrix, we use particles with \( n_s = 1.5 \), close to that of commonly used colloidal microspheres like SiO\(_2\), polymethyl methacrylate, and polystyrene. As shown in Figure 3A, by varying particle diameters (\( d \)), the reflection peaks move over the VIS wavelength range (\( \lambda_0 \) from 400 to 700 nm), that is, \( \lambda_0 = 424 \text{ nm} @ d = 200 \text{ nm} \), \( \lambda_0 = 529 \text{ nm} @ d = 250 \text{ nm} \), and \( \lambda_0 = 636 \text{ nm} @ d = 300 \text{ nm} \). This fully demonstrates the structural resonance in the photonic glass. Since the reflection peaks locate at wavelengths corresponding to blue, green, and red spectrums, respectively, the standard sRGB colors generated by these reflectivity curves are greatly varied (displayed by the color rectangles in Figure 3A). However, due to the strong reflection at short wavelengths, the color generated by the photonic glass with \( d = 300 \text{ nm} \) appears closer to purple rather than the expected red.

In order to make the photonic glass in a polymer with scattering intensity similar to that in air, \( n_s \) must also be increased accordingly (see Figure S7, Supporting Information, for the effects of \( n_s \)). Therefore, here we assume that the particles have an \( n_s = 2.0 \) when they are in the polymer matrix, and by doing so we obtain very similar results (Figure 3B) to those presented in Figure 3A. Nevertheless, it should be noted that the particle diameters are notably reduced. The reflection peaks appear at: \( \lambda_0 = 439 \text{ nm} @ d = 150 \text{ nm} \), \( \lambda_0 = 525 \text{ nm} @ d = 180 \text{ nm} \), and \( \lambda_0 = 613 \text{ nm} @ d = 210 \text{ nm} \). This phenomenon could be explained by the diffusion theory for light-scattering media, which points out that the structure-correlated resonance peak is determined by:

\[
\lambda_{\text{resonance}} = \frac{4 \pi n_{\text{eff}} d_{\text{avg}} \sin \theta}{x_0} \tag{1}
\]

where \( n_{\text{eff}} \) is the effective refractive index of the medium, \( d_{\text{avg}} \) is the average center-to-center spacing between nearest particles, proportional to \( d \). For backward scattering, the scattering angle \( \theta \) is \( \pi \) and \( \sin(\theta/2) \) equals 1. Besides, \( x_0 \) is the location of the first peak in the structure factor. Therefore, for photonic glasses with the same structure factor, the reflection peak positions are determined by \( n_{\text{eff}}d \). With \( n_{\text{eff}} \) increasing from the air matrix to the polymer matrix, \( d \) should thus be reduced to keep \( \lambda_{\text{resonance}} \) unchanged.
3.2. Effect of Thickness on Reflectance, Color, and Solar Transmissivity

Based on the results presented in Figure 3B, we extend the thickness of photonic films to investigate how it affects spectral reflectance, color appearance, and solar transmittance. We have studied the thicknesses of 1, 3, 5, and 7 µm, with other parameters unchanged. The results when \( d = 150, 180, \) and 210 nm are all presented in Figure 4A, which clearly show that the reflectance increases with thickness, while the increase rate is gradually slowed. Since increasing thickness would lead to a significant increase in computational effort, we did not simulate the photonic films with higher thickness. Besides, the photonic glass with much higher thickness is also not suitable for colorizing solar energy materials.

In some early work about photonic glasses, it is pointed out that for a thick slab of photonic glass in the absence of absorption, the function \( 1/T \) is directly proportional to the slab thickness, where \( T \) is transmissivity. Based on the FDTD simulation results, we validate that this law also applies for a thin film of photonic glass that is a few micrometers thick and colored, as demonstrated by Figure 4B (see also Figure S4 and Figure S3, Supporting Information). This means that by simulating a photonic glass with only two to three different thicknesses, we may directly deduce the reflection spectrum of the photonic glass at other thicknesses, through the relationship \( 1/(1-R) = t \).

In Figure 4A, the sRGB color for each spectral reflectance curve is presented by the rectangle filled with the corresponding color. With increasing thickness, the appeared colors remain similar hues while being brighter and less saturated. Quantifying the colors that photonic glasses can exhibit and clarify their variation with structural parameters like \( d \) and \( t \), we further calculate the CIE \( L^*a^*b^* \) color coordinates for each reflectance curve (see the introduction about \( L^*a^*b^* \) color space in Section S2, Supporting Information). As shown in Figure 4C, the color lightness rises with increasing film thicknesses, keeping a similar pace with reflectivity. However, the color hues are not greatly influenced by the thickness, especially when the film thickness is larger than 3 µm, as demonstrated in Figure 4D (see also Figure S8, Supporting Information), further increasing the thickness does not significantly affect the positions on the chromaticity chart. Thus, the relative saturation \( C^* = \sqrt{a^*^2 + b^*^2} \) will only be slightly changed from a thickness of 3 to 7 µm. But because color lightness is improved, the appeared colors are more unsaturated. Besides, the results demonstrate that photonic glasses could enable blue colors to be relatively saturated, but the relative saturation for green colors is only half, which is 15. As mentioned above, for large particles that make reflection peaks at over 600 nm, the generated color is purplish red instead of red, and color saturation is also very low.
To be applied for colorizing PVs and STs, the transmittance of solar energy is a critical judgment criterion. Here we calculate the average solar transmissivity (AST) in wavelengths from 300 to 1200 nm, and both solar photon flux and energy flux are used to calculate the AST values, denoted as AST_P and AST_E, respectively (see Section S5, Supporting Information for details). Figure 4E presents the AST_P of the photonic glasses with different particle sizes and film thicknesses (see also Table S1, Supporting Information). As can be seen, when using small particles to obtain blue color hues, the resultant AST_P is higher, about 87.6% at lightness of 50. Even for a thickness of 7 µm, over 81% of solar radiation could be transmitted. Increasing particle diameters leads to the reduction of solar transmissivity. For example, at a thickness of 3 µm, the AST_P is 87.6% for 150 nm, 84.2% for 180 nm, and 81.2% for 210 nm. In brief, we suggest that photonic glasses are suitable for achieving blue hues and can achieve appealing colors, close to the sky blue, and also maintain high transmittance. For unsaturated green color hues, using photonic glasses is also a viable choice, which could transmit about 84%/81% of solar photons/energy when generating a green color with a lightness of ~62. However, it seems that red color hues cannot be achieved with photonic glasses, and using large particles could not bring satisfactory results.

3.3. The Effects of Potential Improvement Methods

In this section, we have studied the effect of several parameters, including structure factor, fill fraction, and scattering particle types, and have checked if there are possible methods to increase color purity and AST. First, based on the random close packing of spheres that are generated by the numerical algorithm, we used a Monte-Carlo method and a modified Weeks–Chandler–Anderson potential to lower the energy of the packing (see details in Section S6, Supporting Information). With the simulation, the hard sphere packing could be in a more thermodynamically stable state, and thus exhibits a higher and narrower peak in its structure factor (calculated by Equation (S22), Supporting Information), demonstrating an improvement in the short-range order. This results in a slightly more concentrated reflectance curve (Figure 5A), with the peak a little bit higher and the valley lower. Thus, the generated color has slightly higher saturation and increased solar transmissivity, but the degree of improvement is extremely limited (Table 1). In this case, it is suggested that a photonic glass structure with higher short-range order is preferred in practice, but meanwhile, such an improvement would not lead to a significant change so as to achieve red hue.

Another way to change the structure factor is by varying the fill fraction of particles. Compared to a fill fraction of 55% used previously, here we generate the photonic glass with a fill fraction of 64%, which is the maximum value for a random close packing of hard spheres. As shown in Figure 5B, when the structure has a higher fill fraction, the first peak of the structure factor gets higher and narrower. Besides, the peak position is shifted slightly to the right. Therefore, to promise the peak positions of spectral reflectance curves almost unchanged, the particle diameter is increased from 210 to 212 nm (Figure 5B). In addition, the spectral reflectivity...
Table 1. The details about the generated color and AST corresponding to those spectral reflectivity curves presented in Figure 5.

| Methods            | Structure parameters | Lightness, L* | Relative saturation, C* | sRGB   | AST_P/AST_E |
|---------------------|----------------------|---------------|-------------------------|--------|-------------|
| Improving structure factor | d = 210 nm, f = 55%, t = 3 μm | 59.4          | 12.4                    |        | 0.812/0.779 |
|                     | after improvement    | 58.8          | 13.8                    |        | 0.821/0.788 |
|                     | d = 212 nm, f = 64%, t = 3 μm | 56.8          | 13.2                    |        | 0.836/0.805 |
|                     | d = 212 nm, f = 64%, t = 3.3 μm | 58.8          | 12.7                    |        | 0.825/0.792 |
| Core–shell particles | d = 150 nm (shell = 0 nm) | 50.0          | 28.6                    |        | 0.876/0.846 |
|                     | shell = 15 nm        | 54.1          | 28.0                    |        | 0.872/0.837 |
|                     | shell = 35 nm        | 59.6          | 16.3                    |        | 0.868/0.835 |
|                     | shell = 50 nm        | 55.5          | 3.3                     |        | 0.876/0.851 |
| Inverse structures  | d = 200 nm           | 54.8          | 30.7                    |        | 0.840/0.798 |
|                     | d = 250 nm           | 70.7          | 15.6                    |        | 0.768/0.716 |
|                     | d = 300 nm           | 74.5          | 4.2                     |        | 0.709/0.660 |

Figure 5. A) The spectral reflectance for the photonic glass with improved structure factor. The insert figure compares the structure factor with/without improvement, as functions of qd, with q = 2ksin(θ/2) and k = 2meff/λ0. All the other parameters for these two structures are the same. B) The effects of increasing fill fraction. With the fill fraction increasing from 55% to 64%, the particle size and film thickness need to be increased to guarantee the same reflection peak position and reflection peak height. C) Simulated spectral reflectance for photonic glasses made of core–shell particles with different shell thicknesses. The core has a diameter of 150 nm and a refractive index of 2.0. The shell has a refractive index of 1.46. D) Simulated spectral reflectance for inverse photonic glasses with varying particle diameters, using air as the material of scattering particles.
makes is responsible for scattering light. But higher shell thickness close to that of silica. Since the refractive index difference originate from the scattering of individual particles. Thus, a higher scattering cross section of a single particle will make the multiple scattering stronger. Unfortunately, when intending to produce structural peaks in wavelengths corresponding to red (600–650 nm), the particle diameter should generally be from 190 to 310 nm, considering that \( n_{\text{eff}} \) is generally in the range of (1.2–1.8). For these scattering particles or particles with even smaller sizes serving as the scattering core, the scattering strength is always higher at short wavelengths. Therefore, it is not feasible to eliminate this multiple scattering by modifying the scattering microspheres, unless using absorptive materials to absorb the light that is multiple scattered. This has been widely used in previous studies to enhance color saturation.\[^{[37,45,46]}\]

Intuitively, it is the high reflectivity at short wavelengths that makes the generated color not pure. As pointed out by Hwang et al.,\[^{[46]}\] the increase in scattering intensity toward shorter wavelengths is because of multiple scattering, which originates from the scattering of individual particles. Thus, a higher scattering cross section of a single particle will make the multiple scattering stronger. Unfortunately, when intending to produce structural peaks in wavelengths corresponding to red (600–650 nm), the particle diameter should generally be from 190 to 310 nm, considering that \( n_{\text{eff}} \) is generally in the range of (1.2–1.8). For these scattering particles or particles with even smaller sizes serving as the scattering core, the scattering strength is always higher at short wavelengths. Therefore, it is not feasible to eliminate this multiple scattering by modifying the scattering microspheres, unless using absorptive materials to absorb the light that is multiple scattered. This has been widely used in previous studies to enhance color saturation.\[^{[37,45,46]}\]

To prove this idea, here we simulate the photonic glasses that are partially absorptive for visible light. To realize it, we have modified the imaginary refractive index of the matrix material, and we assume it is 1/10 of the measured imaginary refractive index of melanin (see details in Section S7 and Figure S5, Supporting Information). The real refractive index remains at 1.5. In practice, this could be achieved by homogeneously mixing a small quantity of melanin nanoparticles in the polymer matrix. Compared with the results for the non-absorbing photonic glass presented in Figure 3B, the addition of absorbing material causes a significant change in spectral reflectivity. As shown in Figure 6A, the strong reflection at short wavelengths is greatly suppressed, making the reflection peak at the long wavelength prominent. Thus, the color produced is no longer purplish and is closer to a dark red hue. What’s more, based on the inverse photonic glass presented in Figure 5D, with absorptive matrix its appeared color changes from gray to brownish yellow (Figure 6B). As demonstrated in Figure 6C, the colors produced by non-absorbing photonic glasses are mainly limited in the blue-green-purple region of the chromaticity diagram, and such range could be extended to produce yellow and red when using a light-absorbing matrix. But meanwhile, since the absorptive matrix absorbs over 20% of solar photons, the color lightness is smaller and AST_\(P \) is reduced to 67.2% (Figure 6D, Supporting Information). Considering that the non-absorbing photonic glass with the same structure has an AST_\(P \) of 81.2%, it is suggested that using absorptive matrix is not a sound method when applied
for colorizing solar materials. However, it is suggested that the photonic glass could be directly mixed with solar absorbing materials in the upper layer, such as in a solar thermal collector. In this case, the photonic glass can not only generate colors close to traditional pigments but also facilitates a high absorption efficiency thanks to the strong light scattering effect.

For microspheres that are randomly assembled, it is the impenetrability of hard spheres that imposes a short-range correlation. In reciprocal space, this leads to the structure factor exhibiting a primary peak, as shown in Figure 7A. Due to the modification of light scattering by this structural correlation, we can observe the spectral reflection peak at the same location. For the left side of this structural peak, the fast drop of structure factor to nearly 0 leads to a reduction of scattering strength. This is beneficial for the high transparency at long wavelengths (Figure 7A) and is desired for solar energy harvesting. However, since particles are randomly packed, for an arbitrary particle there is always a certain probability that finding other particles at a distance beyond its diameter. As a result, the structure factor oscillates up and down around 1 and would not be close to 0 at the right side where wavelengths get shorter. Besides, if the first peak of the structure factor locates at red wavelengths, the second peak must locate at UV wavelengths. This means that light scattering in the wavelengths between UV and red spectra cannot be eliminated by the interference effect. Unless the structure factor between the primary and second peak could be down to nearly 0.

Certainly, this requirement could be met by photonic crystals that have long-range order. As demonstrated in Figure 7B, the structure factor of an ideal photonic crystal structure is characterized by a series of Dirac peaks in certain positions. This leads to sharp reflection peaks and thus saturated colors. By using particles with $d$ of 200 nm and $n_s$ of 2.0, we show that the photonic crystal structure could generate pretty saturated red hues, even exceeding the domain of sRGB color gamut (Figure 7B). Although in practice such a structure with perfect periodicity is nearly unattainable, it is expected that a polycrystalline structure could also provide the realizability of highly saturated colors, which are demonstrated in some recent studies.[25,47,48]

Figure 7. The structure factor and spectral reflectivity as a function $4m_{\text{eff}}/\lambda_0$. A) The case of the photonic glasses with $d$ of 150, 180, and 210 nm, as also presented in Figure 3B. B) The case of a photonic crystal with $d$ of 200 nm and $t$ of 3.1 $\mu$m, enabling pretty saturated red color.
4. Conclusions

In summary, this study demonstrates that a thin film made by a random packing of monodisperse dielectric microspheres, that is, photonic glass, could be a promising candidate for colorizing solar energy harvesting materials. In addition to its advantage of being able to be produced on a large scale and at a low cost, we show that the short-range structural correlation enables selective reflection of VIS light with little NIR reflection. Thus, by using non-absorbing microspheres with relatively high refractive index, we show that a 3 µm thick photonic glass film is capable of producing colors with lightness over 50 yet keeping average solar transmissivity over 80%. Various color hues can be obtained by changing the microsphere size, while photonic glasses are more recommended to produce hues for only purple, blue, cyan, and light green. Based on both simulation results and theoretical analysis, we validate that the multiple scattering at short wavelengths is unavoidable in a photonic glass structure, resulting in yellow and red color hues unavailable. This limitation could be overcome by either adding light-absorbing materials or using long-range ordered structures to eliminate multiple scattering. Nevertheless, it should be noted by so doing the structure is no longer a photonic glass, and there might be a significant reduction in solar transmittance and an increase in fabrication cost.

We have also studied the effects of some possible improvement methods for photonic glasses. Results suggest that structures with higher short-range order are preferred. This is because the higher and narrower structure factor peak can lead to a narrower reflection peak. Thus, it is essential to optimize the particle assembly conditions in practice. Coating small-size scattering particles with a relatively thin shell may increase the scattering intensity of the photonic glass. Taking advantage of this could be helpful when the core particles are not easily obtainable. When using air as the material of scattering particles, we find that inverse photonic glasses are unexpectedly free of distinguishable reflection peaks, which is greatly different from the results of 2D simulations. Nevertheless, this characteristic makes it feasible for realizing color close to metallic silver or white yet with still over 60% transmissivity of solar energy.

5. Experimental Section

Detailed descriptions of all the methods used in this study are provided in the Supporting Information.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Z.L. and T.M. designed the research; Z.L. investigated the simulation method and performed simulations, Z.L. and S.L. analyzed data; Z.L. wrote the original manuscript, and S.L. and T.M. revised the manuscript.

Data Availability Statement

The data that support the findings of this study are openly available in Harvard Dataverse at https://doi.org/10.7910/DVN/Q3SV7A, reference number 47.

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