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Absence of red structural color in photonic glasses, bird feathers, and certain beetles

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Colloidal glasses, bird feathers, and beetle scales can all show structural colors arising from short-ranged spatial correlations between scattering centers. Unlike the structural colors arising from Bragg diffraction in ordered materials like opals, the colors of these photonic glasses are independent of orientation, owing to their disordered, isotropic microstructures. However, there are few examples of photonic glasses with angle-independent red colors in nature, and colloidal glasses with particle sizes chosen to yield structural colors in the red show weak color saturation. Using scattering theory, we show that the absence of angle-independent red color can be explained by the tendency of individual particles to backscatter light more strongly in the blue. We discuss how the backscattering resonances of individual particles arise from cavity-like modes and how they interact with the structural resonances to prevent red. Finally, we use the model to develop design rules for colloidal glasses with red, angle-independent structural colors.

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I. INTRODUCTION

Structural color in materials arises from interference of light scattered from inhomogeneities spaced at scales comparable to optical wavelengths. Opals and most other familiar examples of structurally colored materials are ordered [1,2], and as a result, the color of these photonic crystals [3] depends on their orientation relative to the incident light: they are iridescent. There is another, less well-studied class of materials with angle-independent structural colors. These are called photonic glasses [4–7], because the inhomogeneities form a random, glassy arrangement with short-ranged order but no long-ranged order. As in crystals, the average spacing between neighboring scatterers in a photonic glass is narrowly distributed and determines the resonantly scattered wavelength [8,9]. But unlike crystals, photonic glasses are isotropic, so that the condition for constructive interference is independent of orientation. This coloration mechanism is common in the feathers of birds [9–11], whose colors are visually indistinguishable from those of conventional absorbing dyes. Photonic glasses with structural colors in the visible have also been produced in a variety of synthetic colloidal systems [8,12–20].

However, to our knowledge there are no photonic glasses with saturated yellow, orange, or red color. While systems with angle-independent structural red have been reported [12,15,17,18,21], the color saturation for long-wavelength hues is poor compared to that for blue. Interestingly, red angle-independent structural color also appears to be rare in nature. Birds use structural color only for blue and green; red colors in bird feathers come from absorbing pigments [11]. And while the scales of the longhorn beetle Anoplophora graafi have structural colors that span the visible spectrum, there are no saturated red colors—only a pale purple [22].

The absence of red photonic glasses does not appear to have been acknowledged, let alone explained. Previous work on photonic glasses [8,9,22–25] has focused on structures found in nature and their biomimetic analogues, nearly all of which are blue. Noh and coworkers [26,27] proposed a theoretical model based on single and double scattering to explain the optical properties of these blue samples, and Liew and coworkers [23] and Rojas-Ochoa and coworkers [5] showed that the interscatterer correlations not only give rise to color but also suppress multiple scattering. However, if the color were entirely determined by correlations, one would expect that all colors could be made simply by linearly rescaling the structure. As we show below, this approach does not work (Fig. 1).

Here we present a model that explains the absence of long-wavelength structural colors in photonic glasses. Our model accounts for both interparticle correlations as well as the scattering behavior of individual particles. We show that short-wavelength resonances in the single-particle scattering cross-section near backscattering introduce a blue peak in the spectrum that changes the hue of a red structural color to purple. These resonances are not the traditional Mie resonances, which occur in the total scattering cross-section, but rather are akin to cavity resonances. The model, which agrees with measured spectra from synthetic photonic glasses, provides a framework for understanding the limitations of current photonic glasses and enables the design of new systems without those limitations.

II. EXPERIMENT

To demonstrate that resonant scattering from the interparticle correlations is not sufficient to explain the colors of photonic glasses, we prepare colloidal glasses from poly(methyl methacrylate) (PMMA) spheres of various diameters and study their colors with spectrometry. Figure 1 shows color photographs and reflection spectra of samples prepared in the same way using three different particle diameters $d = 170, 240,$ and $330$ nm. These samples were prepared by mixing one part of an aqueous suspension containing 1% w/w carbon black (Cabot) and 2% w/w Pluronic F108 (BASF) with two parts of a monodisperse suspension of PMMA particles at 20% w/w,
centrifuging the mixture at 5200 g for 30 min, removing the supernatant, and slip-casting on a gypsum substrate. The final samples are amorphous, dense packings of particles in air. The small amount of carbon black suppresses multiple scattering, making it easier to see the color [8].

We measure the reflection spectra as a function of wavelength with a fiber-optic spectrometer (OceanOptics HR2000+) mounted on an optical microscope (Nikon LV-100). The samples are illuminated with white light from a halogen lamp that is collimated by minimizing the condenser aperture. The divergence angle of the beam is 0.02 radians. The light scattered by the sample is collected by a 50× objective (Nikon LU Plan Fluor, NA = 0.8) and imaged onto the detection fiber (OceanOptics QP600-2-UV/VIS). Because the objective NA is the limiting numerical aperture in our system, our measurements include light scattered up to a maximum angle $\theta_{\text{max}} = \arcsin(0.80) = 0.93$ radians. We normalize all spectra to the reflected intensity from an aluminum mirror, average the spectra measured over five different locations on the sample, and then smooth the spectra using a 50-nm window.

Two peaks are visible in the spectra, one at 515 nm in the $d = 240$-nm sample and the other at 710 nm in the $d = 330$-nm sample. The ratio of these peak wavelengths is approximately that of the two particle sizes $330/240 \approx 710/515$. The linear scaling is consistent with the hypothesis that the color is due to constructive interference of light scattered from correlated regions of particles. The high reflectivity of the $d = 170$-nm sample at short wavelengths suggests a structural resonance in the ultraviolet (UV), again consistent with this hypothesis. Thus, the peak wavelength does appear to scale linearly with the particle size, and hence with the lengthscale of structural correlations, assuming that the volume fraction and structure of all of our samples are similar.

However, whereas the $d = 170$-nm sample appears blue and the $d = 240$-nm sample appears green, the $d = 330$-nm sample does not appear red. The reason is that its reflectivity rises toward the blue, suggesting a second peak at 430 nm or below. We have observed similar spectra in samples made of polystyrene and silica particles whenever the particle size is 250 nm or larger. Dong and coworkers [22] found a similarly shaped spectrum, with one peak in the red and another apparent one at short wavelengths, for purple longhorn beetle scales. Takeoka and coworkers [20] also observed a short-wavelength peak in the spectrum of their amorphous packings of $d = 360$-nm silica particles. In order to understand the absence of red in all of these photonic glasses, we must understand the origin of this short-wavelength reflectivity peak.

III. THEORY

To explain our observations, we use a single-scattering model where we treat scattering from a particle assembly as the result of two separable processes: scattering from each individual particle, as described by a form factor, and interference between waves scattered from the particles, as described by the structure factor of the glass. This type of single-scattering model has been used to describe the optical properties of similar systems [5,28]. In our analysis, we first use the form and structure factor to calculate the differential scattering cross-section of a glass, and then we derive a formula that relates this cross-section to reflectivity, the quantity that we measure. According to our model, structural color in photonic glasses is primarily determined by the peaks of the structure factor. As we shall show, the form factor can either undermine this color or enhance it, depending on the structure of the system and the particle properties.

The scattering geometry that we model mimics a typical experimental setup, as shown in Fig. 2. A colloidal glass is illuminated by incident light with wavevector $\mathbf{k}_i$ and scatters light with wavevector $\mathbf{k}_s$. The angle between $\mathbf{k}_i$ and $\mathbf{k}_s$ is $\theta$. The vector difference $\mathbf{q} = \mathbf{k}_s - \mathbf{k}_i$ describes the momentum change between the incident and the scattered wave. The source can emit light into a range of angles defined by the source numerical aperture $N_{\text{source}} = \sin(\theta_i)$, and the detector can detect light coming from a range of angles defined by the detector numerical aperture $N_{\text{detector}} = \sin(\theta_s)$.

We assume elastic scattering, so that $|\mathbf{k}_i| = |\mathbf{k}_s| = k = 2\pi n_{\text{eff}} / \lambda$, and

$$q = 2k \sin(\theta/2).$$

Here $n_{\text{eff}}$ is the effective refractive index of the medium and $\lambda$ is the wavelength of light in vacuum. The effective index is a weighted average calculated using the Maxwell-Garnett mean-field approximation [29]:

$$n_{\text{eff}} = n_{\text{med}} \sqrt{\frac{2n_p^2 + 2\phi(n_p^2 - n_{\text{med}}^2)}{2n_p^2 + 2\phi(n_p^2 - n_{\text{med}}^2) - \phi(2n_p^2 - n_{\text{med}}^2)}},$$

where $n_{\text{med}}$ is the refractive index of the material surrounding the particles (air, in our case), $n_p$ is the refractive index of the particles, and $\phi$ is the volume fraction occupied by the particles. We use the effective index because the particle packings are dense, so that the scattered fields “see” an index intermediate between the particle and medium index.
The structure factor is the Fourier transform of the pair distribution function to that of a hard-sphere liquid. Figure 2 shows the form factor as a function of the scaled particle size $x_0$, where $x_0$ is the center-to-center spacing between nearest neighbors. The peak $q_0$, given by $2\pi/\lambda$, is the dominant peak in the structure factor. The peak at $x_0$ corresponds to the wavevector $q_0 = 2\pi/d_{\text{avg}}$, where $d_{\text{avg}}$ is the average center-to-center spacing between nearest neighbors. The peak wavevector $q_0$ gives rise to constructive interference and color, because it sets the relative phase difference between light waves scattered from neighboring particles. Resonant scattering occurs when this phase difference is an integer multiple of $2\pi$. The wavelengths at which this happens can be determined from Eq. (1):

$$\lambda = (4\pi n_{\text{eff}}d/x_0) \sin(\theta/2).$$

To describe the intensity of scattered light that reaches the detector, we integrate the differential scattering cross-section over the solid angle corresponding to the numerical aperture (NA) of our detector, taking into account transmission and refraction at the air-sample interface:

$$\sigma_{\text{detected}} = 1/k^2 \int_{\theta_{\text{min}}}^{\theta_{\text{max}}} \int_{\phi_{\text{min}}}^{\phi_{\text{max}}} T_{s}\sigma S \sin(\theta)d\theta d\phi,$$

where $T_{s}$ is the Fresnel coefficient for transmission at the sample-air interface, $\theta_{\text{min}} = \pi - \arcsin(\text{NA}/n_0)$ is the minimum scattering angle that we detect, and $\phi$ is the polar angle in the plane perpendicular to the scattering plane. There is no dependence on $\phi$ because the particles are spherical and the structure is isotropic.

The reflectivity for a glass of PMMA spheres at a volume fraction $\phi = 0.55$ as calculated according to Eq. (6), is shown in Fig. 4. We have omitted the Fresnel coefficient for reflection at the air-sample interface to better illustrate the features that arise from scattering from the bulk colloidal glass. The plot is shown as a function of the scaled particle size $kd$, where $k = 2\pi n_0/\lambda$. All terms in Eq. (6)—except for the Fresnel reflection coefficient, which adds an offset in amplitude—scale with $kd$. Thus, this master curve describes reflectivity from a glass made of any particle size (of the same material and
FIG. 4. (Color online) Calculated reflectivity as a function of $kd$ for a photonic glass of spheres at a volume fraction $\phi = 0.55$, as calculated from Eq. (6) with the Fresnel reflection coefficient omitted. The vertical dashed lines denote the $kd$ values that correspond to the range of visible wavelengths we detect, 425 nm (blue line on the right) and 800 nm (red line on the left), when the particle size is $d = 334$ nm.

The calculated reflectivity reproduces the locations of all of the peaks in our data, as shown in Fig. 5. The only free parameters are the volume fraction $\phi = 0.55$ and the thickness $l = 16 \mu m$. The peaks predicted by the theory coincide with the peaks in the data for particle diameters $d = 238$ nm [Fig. 5(a)] and $d = 334$ nm [Fig. 5(b)]; these sizes are in good agreement with the sizes of the particles measured with scanning electron microscopy, 240 and 330 nm. The calculated reflectivity for the $d = 334$-nm system also reproduces the peak in the blue that we observe in the data.

The model underestimates the amount of light scattered off-resonance, especially at short wavelengths. We attribute this discrepancy to multiple scattering. Since the probability of multiple scattering increases with the scattering cross-section of individual particles, its contribution should be more pronounced at short wavelengths, which is consistent with what we see.

With this model and data at hand we can address our original question: why does the glass made of 330-nm spheres scatter so much blue light, when we expect the interparticle correlations to give rise only to a resonance in the red? To identify the source of the reflection peaks in this sample, we compare our data to the reflectivities predicted from the form factor alone and, in another comparison, the structure factor alone [Fig. 5(c)].

From the shapes of these two curves we immediately see that the blue peak comes from the form factor and the red peak from the structure factor, boosted by another peak in the form factor that occurs at a longer wavelength.

We conclude that the structural colors of our photonic glasses are determined not only by interference between waves scattered from correlated particles, but also by resonances in the single-particle scattering cross-section. This can also be seen by rescaling the measured reflectivities by $\sigma_F,\text{detected}$ and plotting them as a function of the dimensionless wavevector.
FIG. 6. (Color online) (a) Reflection spectra from Fig. 1 plotted against the dimensionless lengthscale $kd$. Note the increased scattering at high $kd$ values (short wavelengths) for the $d = 330$-nm sample. (b) Same as (a) but normalized to the single-particle form factor integrated over the detected scattering angles, $\sigma_{F,\text{detected}}$, as defined in Eq. (7). The increased scattering at high $kd$ values disappears, indicating that it is due to the form factor. Differences in amplitude of the peaks are likely due to differences in the sample thickness.

$kd$ (Fig. 6). Here $\sigma_{F,\text{detected}}$ is the single-particle differential scattering cross-section, integrated over the angle subtended by the detector:

$$\sigma_{F,\text{detected}} = \frac{1}{k^2} \int_{\phi=0}^{2\pi} \int_{\theta=0}^{\pi} T_{r=\alpha} F(\theta) \, d\theta \, d\phi. \quad (7)$$

We see that after rescaling, the long-wavelength reflectivity peak of the $d = 330$-nm sample coincides with the reflectivity peak of the $d = 240$-nm sample at the same value of $kd$, showing that these peaks arise from structural resonances, while the short-wavelength (high $kd$) peak in the $d = 330$-nm sample disappears, showing that it arises from single-particle scattering.

We note that the single-particle resonances responsible for the high reflectivity at small wavelengths are not the so-called “Mie resonances.” Mie resonances are observed in the total single-particle scattering cross-section, obtained by integrating the differential scattering cross-section over all angles. The closest Mie resonance for a 334-nm PMMA particle in our effective medium occurs at 310 nm. Instead, as we shall show, the resonances that contribute to the high reflectivity at small wavelengths occur for scattering angles near backscattering.

We first consider the single-particle scattering cross-section for pure backscattering. This is proportional to the differential scattering cross-section for $\theta = \pi$. As shown in Fig. 7, the backscattering cross-section can have one or more resonances, and the wavelengths at which these occur increase linearly with the particle “optical diameter,” $n_p d$, following the relation

$$\lambda_{\text{resonant}} = 2n_p d/z, \quad (8)$$

where $z$ is an integer that corresponds to the order of the resonance. This suggests that these resonances are akin to those of a Fabry-Pérot cavity, where constructive interference occurs for wavelengths that fit an integer number of times within the round-trip optical pathlength enclosed by the cavity [35]. Similar resonances occur in the differential scattering cross-section for all angles, as shown in Fig. 8. Our calculations show that the resonant wavelength shifts toward the blue as the angle decreases. This blue-shift is consistent with the decrease in the round-trip optical pathlength inside the sphere with decreasing angle (see inset). When the differential scattering cross-section is integrated over the detected solid angle ($\theta = 150^\circ$–$180^\circ$ for our detection numerical aperture of 0.8, after refraction), these resonances, though broadened, persist [Fig. 5(c)]. We therefore conclude that constructive interference of light inside the particles contributes to enhanced reflection at short wavelengths.

Our results show that the absence of red structural color in photonic glasses can be attributed to the blue scattering resonances within the component particles. These resonances occur in addition to the resonances from interparticle correlations, meaning that structural color in photonic glasses arises from the combination of resonant scattering from the structure and from the individual particles. For blue and green
structural colors, these single-particle scattering resonances do not affect our perception of color because they occur in the UV. While these observations are based on glasses of PMMA spheres, the same principles apply to most typical colloidal materials, such as polystyrene and silica, whose refractive indices are not significantly different from that of PMMA. The chitin particles in beetle scales have similar optical properties [22].

Although the single-particle resonances we observe should also occur in photonic crystals, the structure factor in crystals is much more sharply peaked than in glasses, so that structural resonances can dominate the single-particle resonances, and photonic crystals can have structural red color. The price to be paid for this red color is strong angular dependence: changing the angle between source and detector changes the resonant wavelength, leading to iridescence. Photonic glasses have a lower and broader peak in the structure factor as a consequence of their disorder. The breadth of the peak allows the glass to maintain nearly the same structural color over a range of angles between the source and the detector. At the same time, the low peak amplitude (relative to a crystal) makes the color of the glass susceptible to contamination from the single-particle resonances. Thus, we see that there is an inherent tradeoff between angular independence and structural red color.

Can this tradeoff be broken? One obvious way is to introduce a dye that absorbs blue light. However, this is how traditional colors are produced; red paint, for example, consists of strongly scattering particles mixed with pigment particles that absorb the incident and scattered blue light. In contrast, structural color must arise from resonances that allow scattering at certain wavelengths to dominate scattering at all other wavelengths. The absence of wavelength-dependent absorbers makes structural color appealing for applications such as coatings, because all colors can be produced from the same materials. Therefore, we pursue a different way to break the tradeoff between angular independence and long-wavelength structural color.

To create a red structural color, we would need to manipulate the resonances from two independent processes: single-particle scattering and coherent scattering from the particle assembly. The characteristic scale for the single-particle scattering resonances is the particle optical diameter \(d_{\text{opt}}\) [Eq. (8)], and for the structural resonances it is the effective interparticle spacing \(n_{\text{eff}}d_{\text{avg}}\) [Eq. (4)]. Our control parameters are therefore the particle diameter \(d\), its refractive index \(n_p\), the interparticle spacing \(d_{\text{avg}}\), and the index of the medium \(n_{\text{med}}\), which determines the effective index \(n_{\text{eff}}\).

Red photonic glasses could be made by tuning these control parameters to blue-shift the second resonance of the form factor into the UV while keeping the peak of the structure factor at long wavelengths. This can be achieved with particles that have a small optical diameter, as shown in Fig. 7. The simplest way to reduce the optical diameter is to use particles with a refractive index smaller than that of the medium. In these inverse glasses, the diameter of the particles is about the same as the spacing between their centers \(d_{\text{avg}} \sim \sqrt{6d_0}/3\), but their lower refractive index makes the optical pathlength inside each particle shorter than the optical pathlength between two particles. As a result, the form factor resonances are blue-shifted compared to those of our PMMA colloids of similar size, while the structure factor resonances remain at about the same wavelength.

Another effective way to blue-shift the form factor resonance while not shifting the structural resonance is to decouple the particle size from the interparticle spacing and to use smaller particles as the scatterers. This can be done by packing core-shell particles with a strongly scattering core and a transparent shell. We have already demonstrated that this approach enables the creation of full-spectrum, angle-independent structural pigments [21]. Such pigments still suffer from poor color saturation in the red compared to the blue, but the short-wavelength reflectivity is substantially reduced relative to colloidal glasses made of homogeneous (that is, not core-shell) particles.

One can combine the core-shell and inverse-structure approaches to design a system with a single visible resonance at long wavelengths. In particular, the shell diameter could be chosen such that the interparticle spacing gives rise to a resonance in the red, and the core diameter chosen such that the first-order peak in the form factor boosts the peak from the structure factor, while the second-order form-factor peak is fully in the ultraviolet. Our calculations show that such a structure could be made from core-shell particles with air cores and silica shells, embedded in a silica matrix, as shown in Fig. 9.

Curiously, the photonic structures found in bird feathers resemble these inverse glasses: they often consist of air pockets in a matrix of \(\beta\)-keratin [9,11] that has a refractive index close to that of silica [36]. However, birds do not seem to have taken advantage of their inverse structures for colors other than blue. They rely instead on pigments to acquire yellow, orange, and red colors [11,37]. Whether this is due to a physical effect not accounted for in our model or is the result of evolution or chance remains to be seen.
are not sufficient to understand the reflectivity of photonic glasses. The scattering behavior of their constituent particles plays an equally important—and previously unrecognized—role. In particular, interference of light inside the particles can lead to enhanced scattering at wavelengths other than those related to the interparticle correlations. Our model describes our experimental observations well, and it can be used to guide the design of new photonic glasses with purely red structural color.

To this end, we have shown that it is possible to control the locations of both the single-particle scattering resonances and the structural resonances by tuning the refractive indices, particle sizes, and interparticle distances. Our model predicts that inverse glasses made of core-shell particles with a low-index core and a high-index shell that is index-matched to the medium might produce angle-independent structural red color. If future experiments show that such structures show poor color saturation in the red, these results would suggest that another mechanism, such as multiple scattering, should be accounted for. If successful, these structures would complete the palette of visible colors achievable with photonic glasses, opening the path to their use in practical applications such as long-lasting dyes or reflective displays.

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