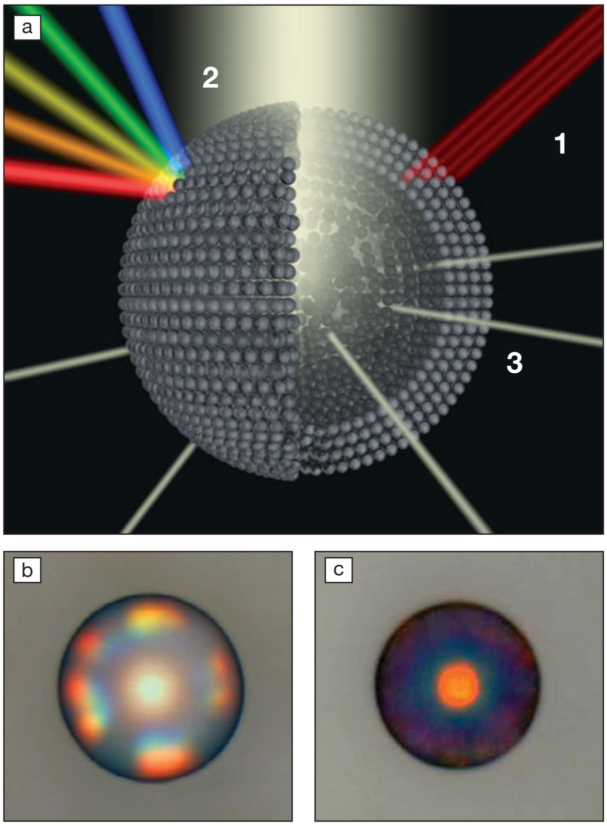
Nano Focus

Structural details elicit color variety in photonic balls

The bright, iridescent hues of a monarch butterfly's wing or a peacock's tail result from their micro- and nanoscale structure. This kind of color that arises from structural periodicities that match the wavelength of visible light is called structural color. Along with pigmentation and bioluminescence, structural color is one of the three main routes by which nature creates color. The ability to fabricate new photoactive materials with the desired color is a highly sought-after goal in materials science. A recent study by Nicolas Vogel of Harvard University and Friedrich Alexander-University, Germany, Joanna Aizenberg of Harvard University, and their colleagues has made a significant step in this direction, as described in *Proceedings of the National Academy of Sciences* (DOI: 10.1073/pnas.1506272112; p. 10845). The researchers identified and controlled three modes of light interaction with "photonic balls" that they were able to precisely tailor in size using microfluidics technology.

Photonic balls are spherical, microscale structures constructed from closely packed colloidal polystyrene nanoparticles. The team was able to control both the size of the colloidal particles as well as the radius of the photonic balls. The light reflected off individual balls was collected by an optical microscope and fed into a spectral analyzer through a fiber-optic cable. The color of the balls changed from blue to green and then red by changing the size of the colloid from 180 nm to 250 nm. Through the microscope, the balls appeared to be colored only at the center, the outer rim being pale and colorless. This pattern undergoes a significant change when the colloids are larger than 400 nm. In addition to the bright spot in the center, multichromatic color patterns appeared at the outer regions with the color traveling from blue near the center to red at the edges. All balls also had a whitish hue that served as a backdrop to their bright spots, diminishing their contrast.

The group analyzed each of these effects and attributed them to different optical phenomena that arise as a consequence of the structure of the photonic ball. The colloids try to pack closely into a sphere, leading to neat crystalline order at the exterior. However, being trapped inside a sphere leaves all of them with frustrated disordered cores that scatter light to create the observed whitish hue. The bright spots at the center of the smaller balls were attributed to Bragg reflections from the ordered outer layers, while the multicolor patches at the exterior were due to grating diffraction.



(a) Schematic illustration of the multiple optical effects from photonic balls: (1) Bragg reflection, (2) grating diffraction, and (3) unselective scattering. Credit: Grant England. (b) Grating colors: 450-nm colloids and (c) uniform red ball: 250-nm colloids. Credit: Nicolas Vogel.

The research team verified this by simulating the reflection spectra of a model ball with ordered crystalline layers. As the colloids exceeded 400 nm in size, the outermost layer acted as a diffraction grating that scattered light at different angles depending on wavelength, leading to the polychromatic appearance of the balls.

Thus nonresonant scattering, Bragg reflection, and grating diffraction are the three main modes of interaction of light with structured matter. All of these have been separately observed in photonic balls before. "Our work is a concise compilation of all the modes," Vogel says in a communication to *MRS Bulletin*. The researchers were able to observe the colloidal structure in great detail using focused ion-beam milling, which allowed the internal layers to be seen in sections. "I do not recall any publication that has looked into the interior of the photonic balls with nanoscale features," Vogel says.

Having established the specific modes of light interaction, the group went a step further by adding gold nanoparticles to the photonic balls. These nanoparticles selectively absorb low wavelength light through plasmon resonance, giving a brighter perceived coloration.

"This work not only provides interesting insights into crystallization processes in confined volumes, but it also allows [us] to obtain a novel class of colored photonic pigments with novel functionalities and striking visual appearance," says Silvia Vignolini of the University of Cambridge.

"This work could lead to the design of all kinds of new optically active microparticles, perhaps for novel biosensing applications, I imagine," says Benjamin Hatton of the University of Toronto. Both Vignolini and Hatton are unaffiliated with the original study.

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