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OPTICAL METASURFACES

Metasurfaces provide the extra bling

Structuring surfaces coated with nanoparticles in the subwavelength range allows almost complete control over the optical appearance of an object.

Frank Scheffold

The visual appearance of flat surfaces and curved objects is paramount in life and technology. It determines perceived attractiveness and allows for signalling in nature, beautifully illustrated by colourful birds, insects and flowers. Since time immemorial, people have been fascinated by shiny metallic jewellery, gilded clothing, tableware, weapons, and goblets. Gemstones draw part of their appeal from a combination of reflectivity and colour effects. More recently, effect coatings for cars have gained in popularity. Attributes like glossy, matte or diffuse often describe the visual appearance, thus encompassing more than simply colour, colour purity and brightness.

Recent progress in materials science has led to many new structurally coloured materials. These are materials where colour emerges from nanostructured scattering interference instead of selective absorption provided by common dyes. Structural colours are non-fading and can be a sustainable alternative to traditional colouring methods. Researchers designed dye-free pigments [1], explored coloured living bacteria,[2] and adaptive chameleon-inspired structural colour,[3] often mimicking colour formation in nature. However, those earlier studies primarily focused on colour and neglected other critical aspects of visual appearances, such as glossy reflectivity or a diffuse scattering background.[4] Now, writing in Nature Materials, Vynck et al. show how one can engineer surfaces on a subwavelength length scale to control an object's entire visual appearance almost at will.[5] The authors employ the concept of metasurfaces, which are artificial optical materials obtained by patterning a surface on subwavelength length scales using metallic and dielectric nanostructures.

Vynck et al. use the bidirectional reflectance distribution function (BRDF) to characterise a surface's visual appearance.[6] Computer graphics gaming applications also rely heavily on the BRDF and other domains such as the remote sensing or photometry of celestial objects.[7] Spectrally resolved BRDF measures the ratio of reflected radiant flux in a given direction to incident radiant flux in another direction. In contrast to simple wavelength scans of reflectivity, which are sufficient to determine colour, the BRDF comprehensively quantifies phenomena such as diffuse and specular reflections. It enables a prediction of an object's colour and appearance in different and varying environments.

Equipped with this powerful tool, Vynck et al. can design and optimise the visual appearance of metasurfaces on the computer. To this end, they employed a combination of subwavelength surface patterning with resonant nanoparticles and thin layered substrates in their simulation. The interplay between diffuse and specular reflectance is vital for setting the visual appearance—interferences and scattering can tailor the relative contribution.

The modelled metasurfaces consist of a monolayer of dielectric nanoparticles, either metallic silver (Ag) or high index dielectric silicon (Si). The nanoparticles have diameters between 100 and 200 nm to match the resonant scattering conditions for visible light. In addition, spatial structuring of nanoparticles over the surface provides additional control over the visual appearance. To this end, structural correlations affect the collective optical response of nanoparticle assemblies in two and three dimensions. As shown previously, liquid-like disordered structures and hyperuniformity can inhibit diffuse scattering or promote backscattering depending on the degree of correlations and the characteristic length scale of short-range order. [8-10] The degree of structural correlations can easily be set and used to dial in and out certain spectral features while retaining the same material composition. By controlling the nanoparticles' spatial correlations, they can manage, quasi-independently, the colour of the specular and diffuse components of reflectance, leading to stunning visual effects (Figure 1a). Beyond purely planar structures, adding high-index layered substrates with a substantial specular reflectivity can boost the interaction of light with resonant nanoparticles. Here photons, similar to a ball between a bumper and the wall of a pinball, bounce back and forth between the substrate and the nanoparticle monolayer, thereby enhancing the interaction between both.

Impressive visual appearances emerge from this interplay between specular reflections and diffuse scattering. This effect becomes evident when looking at a spherical metasurface visualising the appearance of the surface at many scattering angles (Figure 1). Vynck et al. conclude their study with an experimental demonstration of their concepts. To this aim, they patterned a centimetre-scale silica (SiO_2) substrate with silicon nanodiscs using standard silicon lithography technology. The nanodiscs act as scattering particles. Their experimental findings demonstrate the 'diffuse-halo' effect predicted by the numerical calculations, Fig. 1b. Strong structural correlation ($p=0.5$) of nanodiscs suppresses diffuse light intensity near the specular reflection, which is surrounded by sharp angular lobes of diffuse intensity.

The work of Vynck et al. realises a whole range of essential tasks. First, it establishes a platform for multi-scale modelling of the optical properties of complex surfaces. In addition, it shows how colour, coherent and diffuse reflection can be controlled with a minimal set of independent variables using a reasonably simple design. Moreover, they show how in-plane structural correlations in a multilayer geometry can be exploited to control the perpendicular reflection.

Large-scale applications of surfaces of this kind based on the lithography process used here are still unrealistic. However, nanoparticle self-assembly combined with roll-to-roll deposition could open up possibilities for such applications in the near future.[1]

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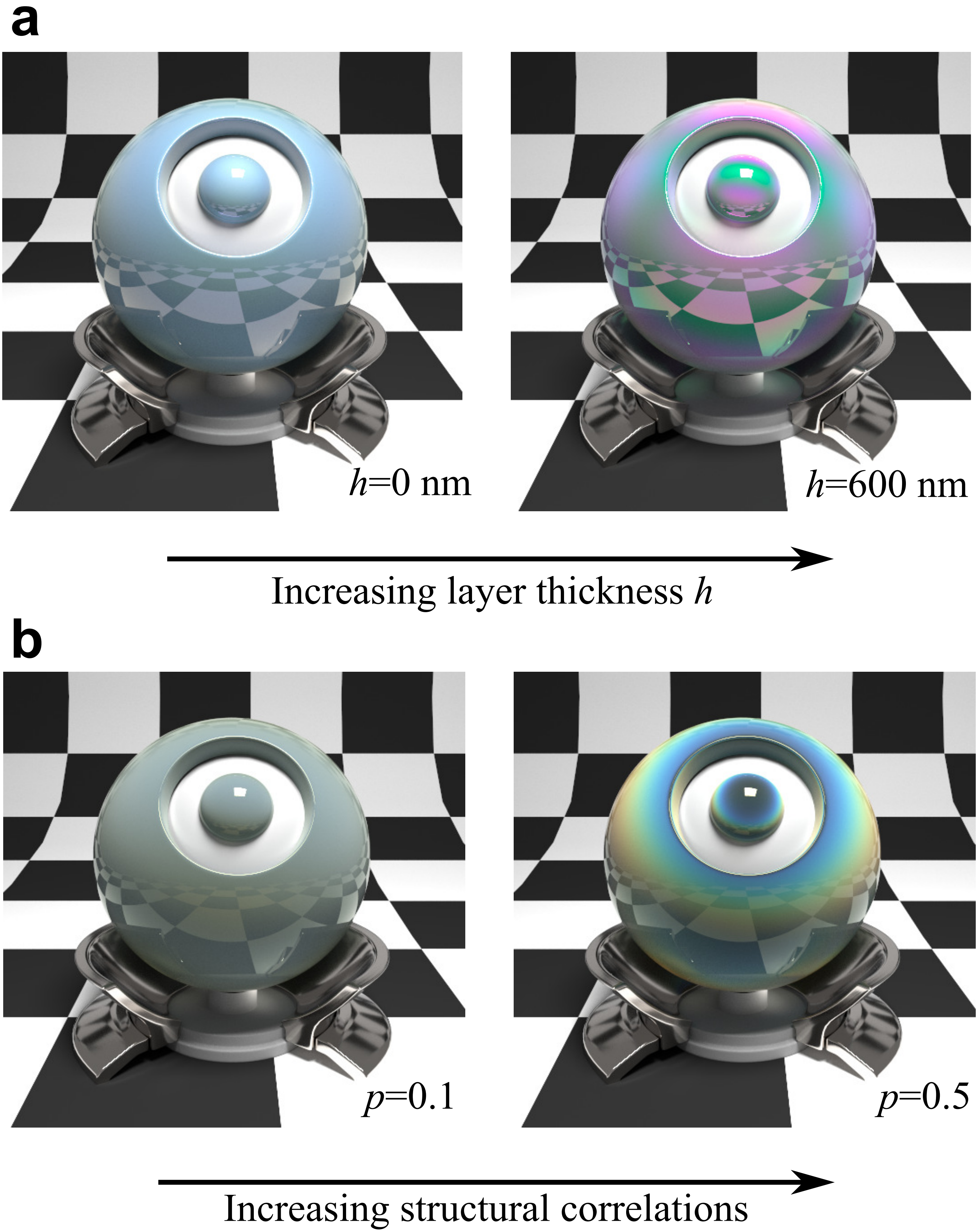
Competing interests

The author declares no competing interests.

Figure 1 | Rendered images of a macroscopic spherical probe covered by metasurfaces. **a**. silver nanoparticles, radius r = 90 nm, distributed randomly on a SiO_2/Si substrate. Without and with an additional thin SiO_2 layer of thickness h=600nm. **b**. spherical probe for a metasurface composed of the identical silver particles now at a density $\rho = 5\ \mu m^{-2}$ on a glass substrate for different degrees of structural correlation (p). Panels reproduced with permission from **a, b,** ref 5, Springer Nature Ltd.

[Note to the art editor: Figure 1a taken from Figure 3e of reference 5. Figure 1b taken from Figure 4d of reference 5.]



a
h=0 nm
h=600 nm
Increasing layer thickness h
b
p=0.1
p=0.5
Increasing structural correlations