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Colouring at the nanoscale

Nicky Dean

The increasing miniaturization and resolution of consumer electronics poses quandaries for generating colour in imaging devices, which plasmonic nanostructures may be able to overcome.

Digital cameras are getting smaller and producing better quality images all the time. A large part of this success is down to advances in the technology behind the image sensor, which now have pixels that are just a few micrometres in size. But the current technology uses colour filters based on dyes and this approach may not withstand further shrinking because of the way the sensor handles colour information. The drive towards ever higher resolution displays is hampered by similar concerns, as pixel sizes shrink and screen sizes grow. Fortunately, plasmonic colour pixels could offer a solution for both of these technologies.

Typical digital cameras use either CCD (charge-coupled device) or CMOS (complementary metal–oxide–semiconductor) imager arrays to turn the incoming light into electrical signals. CMOS arrays are an example of active-pixel arrays, in which each pixel contains a photodetector with an active amplifier. They are more common than CCDs for regular consumer electronics, as they tend to be cheaper and consume less electricity. But regardless of which system is employed, the pixel array can only record intensity information — any knowledge of the wavelength or polarization of the light is lost once it is absorbed by the imager. To produce colour images, an array of colour filters is placed over the imager. Each colour filter in the array records intensity information within a given wavelength range, covering red, green and blue (RGB), and assigns a specific colour to each pixel. Finally, computational algorithms process the light intensity information for each colour channel into a full-colour image.

Figure 1 | An image captured using a commercial CMOS camera but with a plasmonic colour filter array instead of the standard dye-based one, after full computational reconstruction and signal processing. Reproduced with permission from ref. 12, © 2013 American Chemical Society.

Ordinarily these colour-filter arrays are fabricated using dye-doped polymers, with each dye individually tailored for each colour channel. But as the size of the pixel shrinks, this approach becomes increasingly plagued by problems. First, the spacing between the colour array and the imager (which lies at the bottom of the structure) becomes smaller, meaning that the filters become less efficient at collecting and guiding light down to the photodetector. Second, crosstalk between adjacent pixels caused by scattering becomes a bigger proportion of the total signal, causing colour information to be muddied and lost in the final image. Moreover, the fabrication of the dye filter requires numerous processing steps and becomes more prone to imperfections and inefficiencies as the dimensions of the pixels shrink, especially with pixels now at the wavelength scale.

A plasmon has a resonant frequency that depends on the metal used and on the particulars of the nanostructured features on the surface. Early attempts at exploiting plasmonics for colour pixels came in 2001 and used subwavelength grid nanostructures fabricated on top of CMOS active-pixel sensors (with lateral dimension of 0.18 μm) for imaging in

the visible[1,2]. High responsivities and transmissivities were shown at red, green and blue wavelengths by tuning the grid periodicity and spacing. This approach was later used to demonstrate plasmonic colour filtering on the scale of tens of micrometres for pixels of fixed colour[3].

Of course, for practical image-capture applications, any structure must be properly integrated as part of a full camera set-up. This requires the patterning of multiple filters into an RGB array over the top of the CMOS imager array. By utilizing metal–dielectric–metal stacks, it has been possible to capture full-colour images with such a filter array[4]. At a thickness of 400 nm, this structure was half the thickness of a conventional dye-based filter, clearly illustrating its advantages for miniaturization.

As promising as these approaches seem, however, they still require multiple fabrication steps and numerous different layers. To overcome this difficulty, researchers have recently found a simpler route to plasmonic filters in the form of subwavelength hole arrays[5–7]. Tuning the size of the holes and their mutual distance alters the resonant frequency of the array and hence the colour that they transmit. In this configuration, most of the light is transmitted and relatively narrowband colour filters can be produced from thin (~150 μm) metal sheets[8,9]. A specific arrangement of holes forms a pixel of a desired colour and these separate pixels can then be combined into an RGB array, just like the regular dyes or the metal–dielectric–metal stacks — except that there is now only a single layer to worry about. Such an array can then be combined with commercial CMOS image sensors[10,11] and after some appropriate computation and processing a full-colour image can be obtained (Fig. 1)[12]. Furthermore, only a few holes are needed to create a desired colour, enabling pixel sizes of just a few micrometres[9].

Filters such as these are fundamentally transmissive. Yet there are no intrinsic reasons that prevent plasmonic nanostructures from being used in reflection. Indeed, a wealth of applications opens up when considering light bouncing off nanostructured plasmonic surfaces. Complementary to nanohole arrays, reflective structures tend to rely on nanopillars or similar raised assemblies, with the geometry of the pillar — rather than the hole — responsible for tuning the plasmonic resonance.

Exploiting this approach with silver and gold nanodiscs raised over a backreflector has allowed images of just a few tens of micrometres across to be made with a resolution down to the optical diffraction limit, but also with a rich and varied colour palette (Fig. 2)[13,14]. By further considering the geometry of the pillar and elongating the shapes, the polarization of the interrogating light can also be used as a degree of freedom[15]. In this way, stereoscopic images can be encoded in the nanostructure array and potentially used as elements for data storage, although the resolution of the read-out equipment would ultimately limit their storage capacity. At the same time, encoding multiple images within the same space that are apparent only to separate polarizations could provide security assurance much like a hologram currently does, but on a significantly smaller scale that is harder to counterfeit. This approach could be exploited for plasmonic steganography, in which information, in the form of a micrometre-sized image, for example, is concealed within another image.

Figure 2 | Optical micrograph of the Lena image created using silver nanodiscs of varying size on a backreflector. The discs are arranged in an array with a period of 125 nm. Most pixels are formed from a 2 × 2 array of discs and code for one colour. Scale bar, 10 μm. Reproduced from ref. 13, 2012 Nature Publishing Group.

Another natural potential application for plasmonic colour pixels is to replace the pixels used in current displays. Here, the small footprint of the plasmonic pixel could offer enhancements in resolution. Although some initial colour image displays have been constructed using plasmonic arrays[3,11,13–15], there are issues with the vividness of the colour that can be obtained. Another problem arises when dynamic images are desired, as plasmonic colour is defined by the geometry of the nanostructure, which is fixed at the outset. For dynamic displays, therefore, methods for addressing or altering individual pixels across a whole display need to be developed.

One approach to the issue of colour vividness is to pay more attention to the diffractive effects arising from scattering between individual nanostructures. In the case of reflective structures, the geometry of an individual nanorod mostly contributes to the colour, while in the far-field, coupling between the scatterers leads to a narrowing of the ensuing spectrum but also an increase in its intensity[16]. Thus, careful arrangement of the individual elements can enhance the colour intensity of the image. As an added advantage, the use of nanorods as the scattering element makes this approach compatible with liquid-crystal technology, thus also providing a possible solution to the dynamic colour switching problem.

The results obtained so far make a compelling case for using plasmonic nanostructures as colour pixels, especially as alternatives to the current dye-based filters used in cameras. While the dye route is still cheap and efficient, the continued push towards miniaturization will require the development of a completely new technology. For plasmonics to become that new technology there are still hurdles to overcome, especially in terms of fabrication costs for industrial manufacturing. However, the flexibility of plasmonic nanostructures and their intrinsic ability to manipulate light at the nanoscale positions them as a prime candidate. ❐

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