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Polarization switchable two-color plasmonic nano-pixels for creating optical surfaces encoded with dual information states

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ABSTRACT

We demonstrate tunable, polarization-dependent, dual-color plasmonic filters based upon arrays of asymmetric cross-shaped nano-apertures. Acting as individual color emitting nano-pixels, each aperture can selectively transmit one of 2 colors, switched by controlling the polarization of white-light incident on the rear of each pixel. By tuning the dimensions of the pixels we build a polarization sensitive color palette at resolutions far beyond the diffraction limit. Using this switchable color palette we are able to generate complex optical surfaces encoded with dual color and information states; allowing us to embed two color images within the same unit area, using the same set of nano-apertures.

Keywords: nano-pixels, cavity-apertures, plasmonics, metasurfaces, color filter, color printing, nano holes, optical surfaces

1. INTRODUCTION

Color filters are a vital elements of modern digital imaging and display systems, allowing white-light to be broken into component parts for the purpose of recording or projecting information. Although conventionally constructed from polymers embedded with organic dyes, there has been increased interest as of late towards the development of filters which rely on the plasmonic resonances of engineered metallic nanostructures to provide more environmentally robust color filtering solutions[1-5] (whereas filters based on organic dyes are susceptible to degradation over time, plasmonic filters offer long-term stability). Furthermore, plasmonic filters can perform over length scales of >100 nm, making them ideal for miniaturized, compact optical imaging solutions where space is at a premium. Effective color filtering has been demonstrated using both positive nanostructures [6-12] and 'negative' nanostructures (apertures through a metallic thin-film). [13-14] These filtering solutions have thus far been shown applicable to color separation in CMOS image sensors, [15, 16] to full-color image reproduction ('printing') with pixel sizes beyond the diffraction limit [3, 4, 17], and to ultra-high resolution optical data storage. [18] As a result, this technology has the potential to compete with conventional color filtering techniques (which employ dyes, liquid crystals and quantum dots) in the near future.[19, 20]

Typically, color filters, whether they be conventional or plasmonic, are tuned to operate efficiently at a single wavelength. We have recently demonstrated that by using cross-shaped nano-apertures in an aluminum thin-film it is possible to encode a single aperture with dual color selectivity.[21] Each aperture in this case acts as a plasmonic nano-pixel capable of emitting one of two colors chosen by controlling the polarization of white-light incident on the rear of the pixel. By altering the length of the 'arms' of each cross, as well as the spacing between individual crosses in an array, it is possible to tune the plasmon band of the structures across the visible spectrum and create a polarization sensitive color palette. We now demonstrate that by careful arrangement of differently colored nanopixels in an array format we can generate full-color micro-scale images. Significantly, the ability to embed two colors within each pixel allows us to generate image arrays encoded with dual information states (i.e. the polarization sensitive array can display two distinct images using the same set of pixels). These new pixel technology holds the potential to improve upon current plasmonic pixel examples by enabling smaller, more versatile filter sets for imaging applications (where a single array can function at two selectable filtering regimes within the same unit area, rather than building two separate arrays), while also having potential applications in display technologies, image 'printing', storage, anti-counterfeiting, and biosensing.

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2. METHODS

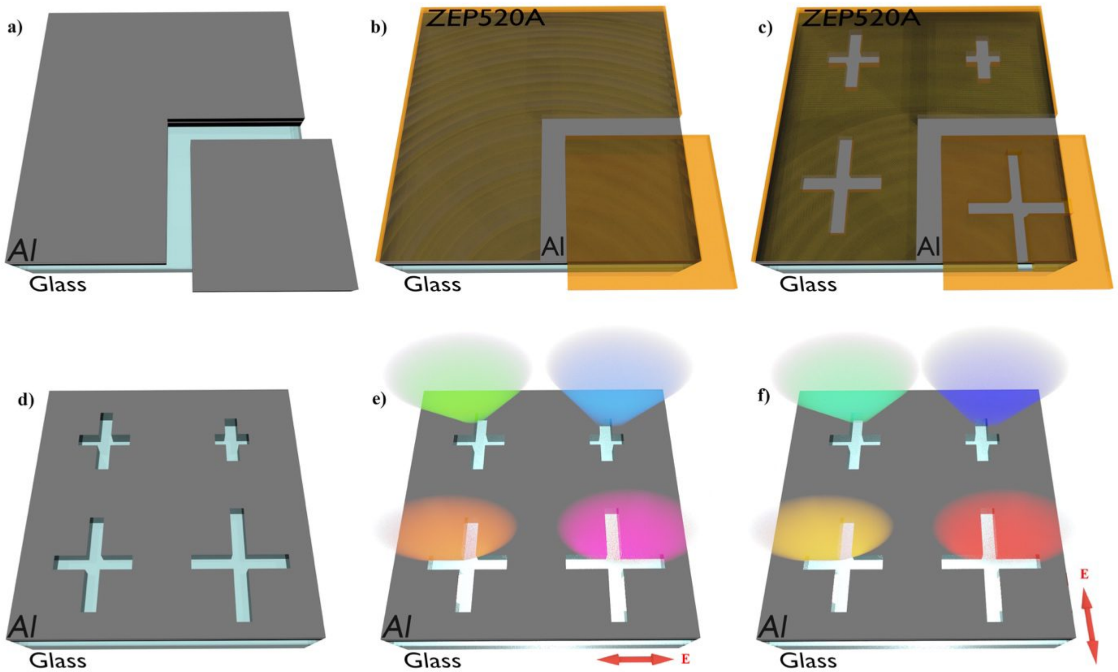

Figure 1. Schematic of the fabrication process a) Deposition of a 100nm Al layer onto a glass substrate b) Deposition of a 220nm ZEP520A ebeam resist layer c) Patterning of the cross-shaped pixels via Ebeam lithography, followed by development d) SiCl4 dry-etching of the exposed Al areas, followed by removal of the ZEP520A mask e) & f) White light excitation of the sample at different polarizations showing single pixels can transmit 2 different colors.

Figure 1 shows a schematic of the fabrication steps taken to produce the dual color nano-pixels using nano-scale cavity apertures defined in a thin-film of aluminum. Al was chosen as our filter metal due to the flexibility of its plasmon resonance band (which can be tuned over a wide spectral range from deep UV to NIR), its low-cost, and its compatibility with current CMOS manufacturing processes. Initially, a 100nm Al layer was deposited onto a 500 µm Pyrex glass substrate. Spun onto the Al layer was a 220nm layer of ZEP520A, a positive electron-beam resist. A Vistec VB6 UHR EWF electron-beam lithography tool was used to pattern the pixel geometries into the resist. After development of the exposed resist, an Oxford instruments System 100 RIE tool was used to etch the electron-beam-defined pattern through the Al layer using SiCl4. After excess resist removal a 150nm SiO_2 layer was deposited onto the sample using an Oxford instruments Plasmalab 80+ PECVD tool. The SiO_2 layer prevents excess oxidation of the Al taking place and also acts to increase transmission through the apertures.

3. RESULTS AND DISCUSSION

Figure 2 shows bright-field images of a selection of color nano-pixel arrays when illuminated from the rear using light polarized along the x-axis (Figure 2a) and the y-axis (Figure 2b). The color displayed by each pixel array is dictated by the length of the aperture's 'arms', as well as the spacing between each aperture in the array. [21] As is the case for nano-scale slit apertures, the selection rules for light transmission through these cross-shaped apertures dictates that the electric-field of the exciting light must be perpendicular to the arm through which light propagates. As a result, the color transmitted through the x-axis arm of the cross is dictated by the length of the x-axis arm, and the period of the y-axis arm (and vice-versa). To demonstrate color tuning possible using these selection rules, a polarization dependent color palette was created (Figure 2). The x-axis arm length was held steady at 140 nm while the length of the y-axis arm was varied from 140 – 200 nm in 20 nm increments (rows moving from top to bottom in Figure 2). The period of the arrays (in both the x and y-axes) was varied from 250 – 340 nm in 30 nm increments (columns moving left to right in Figure 2).

Figure 2a was illuminated with light polarized along the y-axis. As a result, the colors we see transmitted by the arrays in this case are a result of light propagation through the x-axis arm of each cross-shaped pixel. Since the x-axis arm is being held steady at 140 nm, we see that each column transmits a different color. The color variation from column to column is due to the change in array period alone. As the inter-aperture distance increases we see a distinct red-shift in the light transmitted by those arrays (moving from blue at a period of 250 nm to green at 340 nm.)

In the case of Figure 2b, the light incident on the rear of the palette was polarized along the x-axis. As a result, Figure 2b shows the transmission of color through the y-axis arms of the cross-shaped pixels. Since we are altering both the y-axis arm length and the period of the apertures, each of the 16 arrays exhibit a different color. As was the case for the transmission of light through the shorter, x-axis arm, the colors transmitted through the y-axis arm red-shifts with increasing period. Furthermore, since we are altering the length of the transmission arm in this case, we also see a red shift, at constant period, as the arm length is increased from 140 – 200 nm. Using a combination of these parameters it is possible to tune these pixels across the entire visible spectrum.

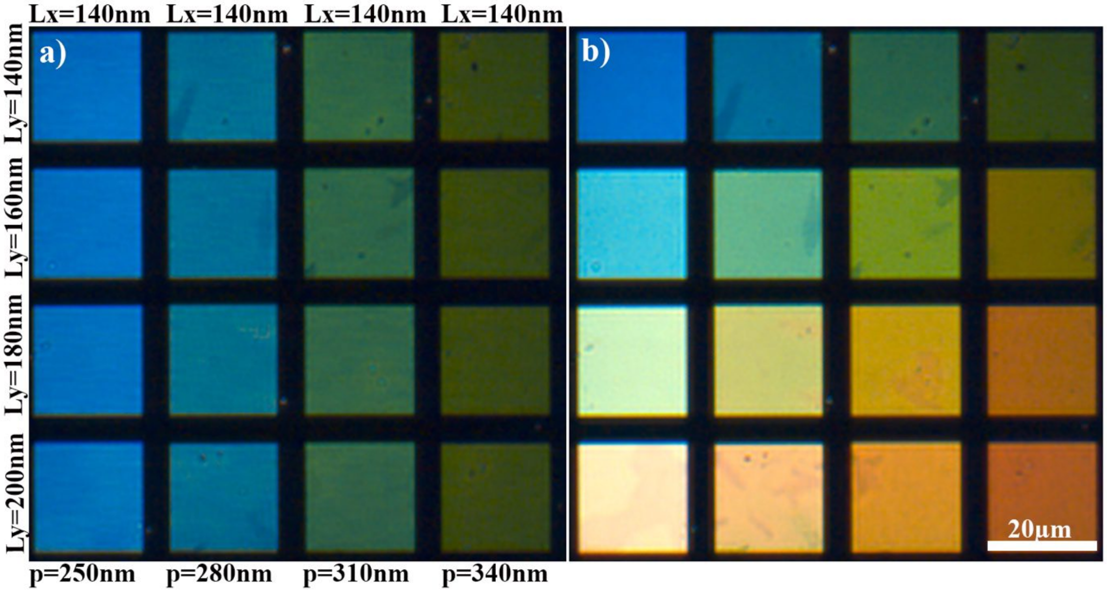

Figure 2. Nano-pixel color palette based on Al nano-apertures a) it shows the situation when the sample excited with a x-polarized white light b) the arm length and period of each nano-pixel array in x and y direction has been shown. c) it shows the situation when the sample is excited with a y-polarized white light.

Figure 3 illustrates an application of these new, polarization selective dual-color nano-pixels; a nanopatterned surface encoded with two different micro-scale images. In this case, a polarization dependent, color micro-display has been created that displays a different image at each illumination state. The pixels have been arranged such that their color output contributes to these different images at each polarization. Note that we are not using different pixels to each of the 2 images seen in Figure 3; the same pixels are used in each image and engineered to perform a different color function at each polarization. Significantly, this allows us to encode 2 information states into the same unit area using the same nano-pixels. As a result, in addition to high-resolution color image reproduction, this technology may prove useful for applications in high-density optical storage, and color filtering for image recording in miniaturized consumer devices (where a single pixel could function at two wavelengths, thus reducing the number and size of filtering elements required).

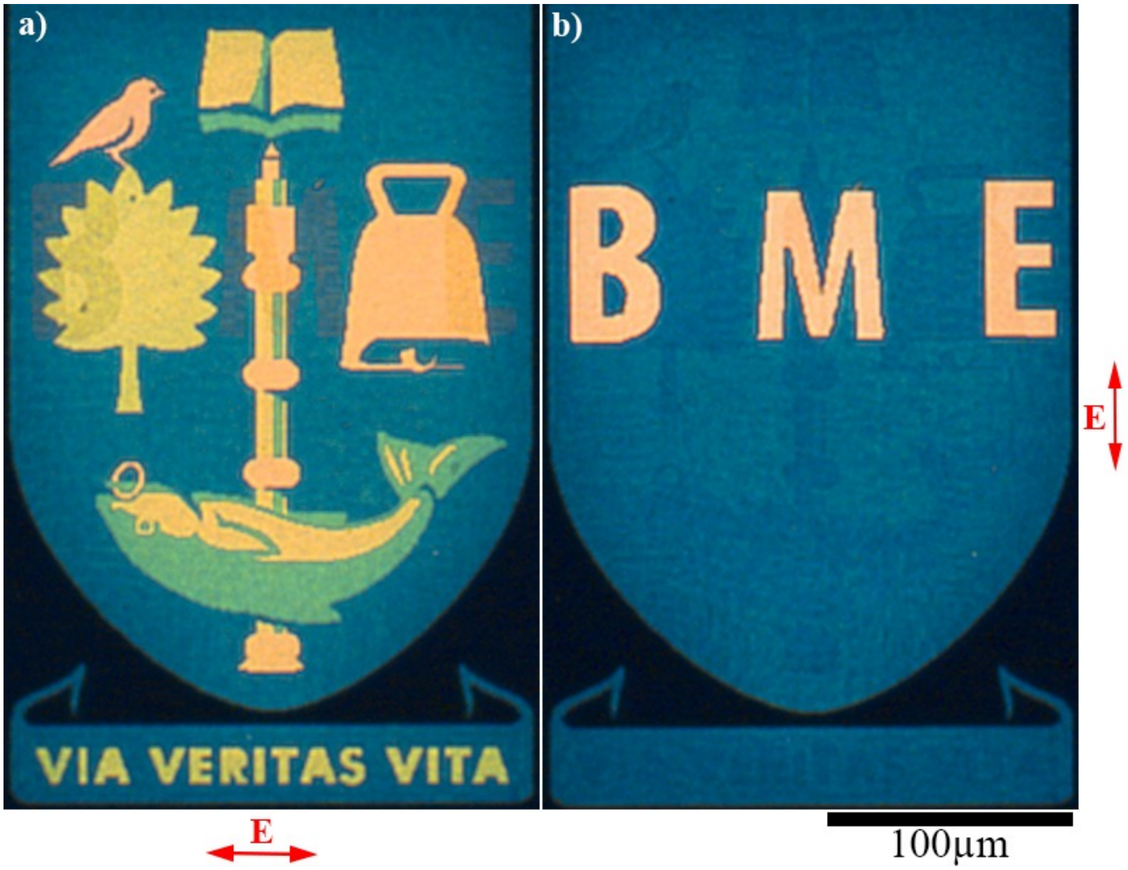

Figure 3. A polarization-dependent micro-display consisting of sub-wavelength plasmonic nano-pixels. a) An image of the University of Glasgow coat of arms, displayed when the array is illuminated with white-light polarized along the x-axis. b) When the illuminating white-light is polarized along the y-axis, the same pixels display the letters BME (to represent Glasgow's Bio Medical Engineering Research Division).

4. CONCLUSION

We have demonstrated a new dual-color plasmonic nano-pixel that can be used to create micro-scale image displays with polarization sensitive outputs. Using these sub-wavelength nano-pixels it is possible to create optical metasurfaces encoded with dual information states.

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