Electronic Supplementary Material (ESI) for Nanoscale.

Supporting Information

Three-Dimensional Cavity-Nanoantennas with Resonant-Enhanced Surface Plasmons as Dynamic Color-Tuning Reflectors

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1. Nanocross-Film Cavity as Fabry-Pérot Plasmonic Resonator

The proposed metasurface structure is designed to consist of metal-coated cross-capped-nanopillars standing in arrays on a metal nanofilm. In the structure, nanocavities are formed between the nanocross array and nanofilm, which serve as front and back reflectors. Each nanocavity provides a way to efficiently arouse resonant coupling and electromagnetic-energy concentrating of surface plasmons, whose features are investigated by means of the numerical finite-difference time-domain (FDTD) simulation. The resonant behavior of the electromagnetic field inside the cavity (Movie 1) clearly proves that such a plasmonic cavity could indeed operate as a Fabry-Pérot (FP) nanoresonator. The localized highly-enhanced electric field energy indicates the existence of a standing-wave resonance in the cavity. As a result, the plasmon cavity nanoresonators exhibit efficiently far-field propagation and high reflection.

2. Subtle color tunability

In order to highlight the widely tunable potential, we present a cornucopia of colors from plamsonic color reflector exposured under white light with varied incident angles. The colors are anchored in a 3D RGB coordinate system to form a bright-colored cube. The full-color and fine-tuned palette is revealed. Figure S1a exhibits some superior color generation by the mushroom plasmonic reflectors, owing to surface-plasmon-coupling induced standing-wave and FP resonance features in the plasmonic nanopillar-nanocavity coupling system. The characteristic resonances and the corresponding color generation can be controlled by tuning light incident direction as well as polarization angle. We also present four representative groups of the palette colors, including spectral colors (three primary colors: red, green and blue), non-spectral colors (their complementary colors: cyan, magenta and yellow), and achromaticity colors (white and black), as shown in Figure S1b. Thus, it was experimentally proved that the reflectors have the capability to define bright color with a high contrast over a broad color-gamut. This characteristic is highly desirable for ultrahigh resolution multicolor dynamic display and imaging.

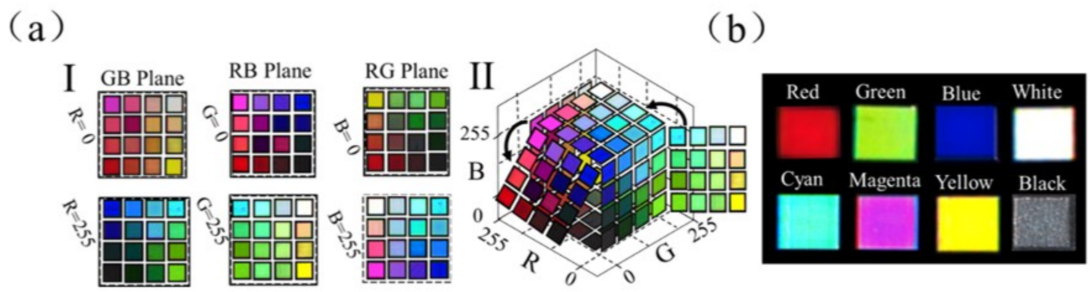

Figure S1. (a) Optical micrograph of structural colors for the fabricated plasmonic nanostructures. (b) Representative colors displayed by the plasmonic palette, highlighting its coloration capabilities of hue blending.

The coupled resonances affect the reflection of specific wavelengths in the visible region and thus the associated color appearance. We have observed sophisticated variations in color tone (Figure S2). Therefore, the 3D cavity-nanoantennas display a noticeably broader range of effective incident-light-sensitive colors. In general, when incident light is adjusted carefully, subtler color changes are obtained in the bright-colored cube of RGB coordinate system.

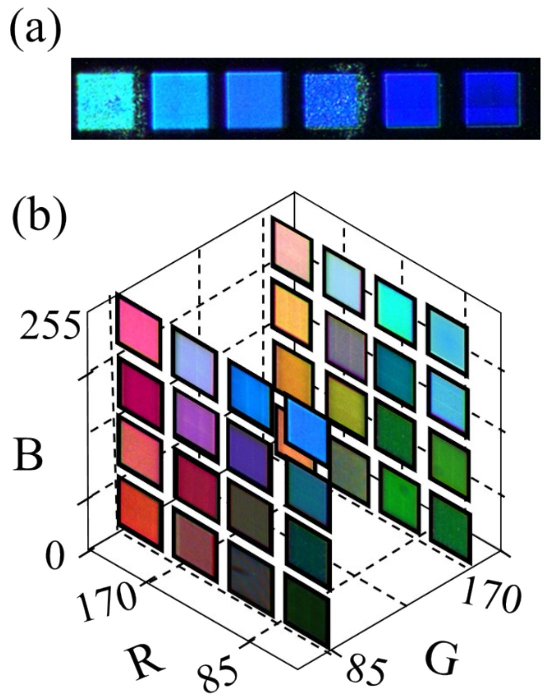

Figure S2. Experimental demonstrations of the metasurface palette for sophisticated color scheme. (a) The finely appeared colors of the palette, obtained by subtly varying the incidence-light angle Φ from 68° to 80° with 2° interval and keep its polarization angle at θ=30°. (b) Experimental subtler color images with incident-field variations.

Table S1. Calculated and measured chromaticity coordinates of color responses shown in Figure 3a and d

Incident angle (θ=45°, φ=15°-75°)	Chromaticity coordinates	
	Simulated	Measured
15°	(0.53, 0.39)	(0.51, 0.39)
30°	(0.47, 0.37)	(0.46, 0.37)
45°	(0.41, 0.35)	(0.40, 0.34)
60°	(0.39, 0.34)	(0.38, 0.33)
75°	(0.37, 0.31)	(0.36, 0.30)

Incident angle (θ=10°-50°, φ=45°)	Chromaticity coordinates	
	Simulated	Measured
10°	(0.45, 0.38)	(0.46, 0.38)
20°	(0.44, 0.37)	(0.44, 0.38)
30°	(0.46, 0.37)	(0.44, 0.36)
40°	(0.40, 0.33)	(0.39, 0.32)
50°	(0.34, 0.29)	(0.33, 0.28)

Figure s3 shows the calculated reflection spectra maps of plasmonic cavity-nanoantennas as a function of the polarization angle. Benefiting by cavity design of nanoresonator reflector, the structure will interfere propagating fields of different light-incidences with the waves reflected in such cavity to achieve narrow-band reflection under visible light. The multiple resonances in cavity-coupling structures results in the overlaying of spectral colors and the corresponding surface coloration with low saturation.

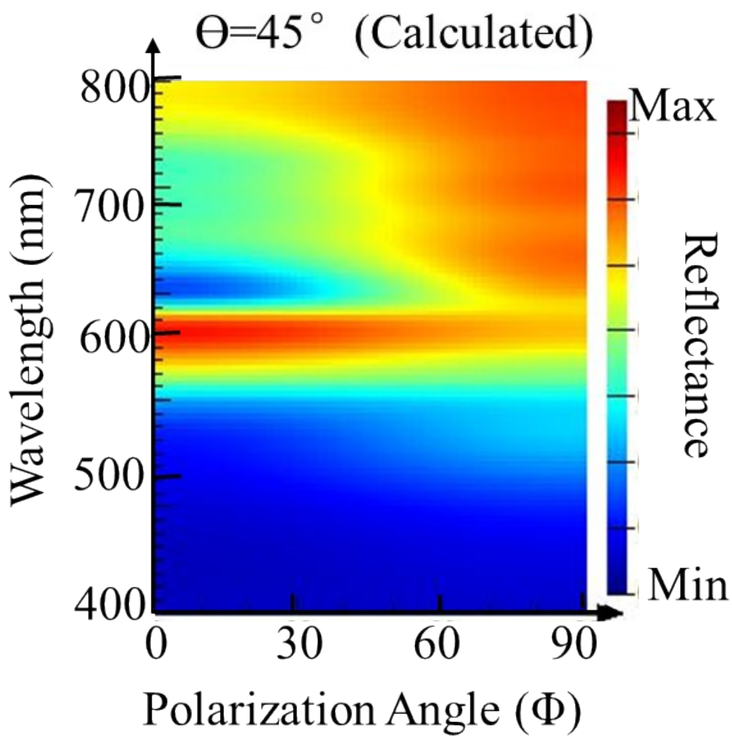

Figure s3 Contour maps of the calculated reflection through the cavity-antenna array as a function of both the wavelength and the polarization. The single red-orange band in the map indicates the strong peak reflection. Such cavity coupling can give rise to a single spectral peak in reflection leading to the generation of saturated colors.

Here we use the clover-nanoantenna arrays to form incidence-dependent checkerboard pattern color, illustrating that such plasmonic cavity-based reflector can realize structural color at the diffraction limit. Figure 4 shows the reflection spectra of the incidence-dependence colors of the proposed structure. We observed that there is a slight discrepancy for(θ =0, ϕ =0) and (θ =0, ϕ =30), which is consistent with microscopic image observations. The colors of the pixels observed under an optical microscope were also included alongside the reflection spectra, illustrating that resonant cavity mode of plasmonic nanostructures indeed produce the alternating colorful stripes at high magnification and the resulting new colors through overlaying and toning strategies.

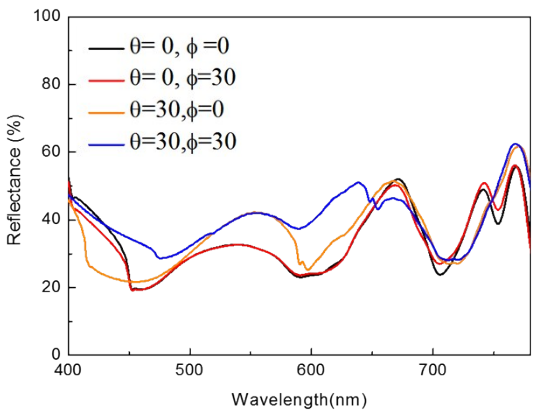

Figure s4 Angle-resolved reflectance spectra of clover-nanoantenna arrays.

Movie S1 Plasmonic standing-wave resonances property in FP nanocavity