Structural coloring with low-index polymer nanostructures via multipolar decomposition-based design and optimization

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ABSTRACT

Recently, there have been notable advances in nanophotonic structural color generation which enabled various applications in display, anti-counterfeiting, sensors and detectors. However, most advances in this domain have been achieved through the use of high-index materials which require expensive and complex fabrication. In this work, we enable low-index polymer nanostructures to generate structural colors using the multipolar decomposition technique which allows a better understanding and design of the scattering process by identifying the dominant multipole modes from the scattered fields. We set a polymeric (n~1.56) cuboid as the structural color generation platform, examined the contributions of various multipoles from the wave scattered by it, and synthesized the desired color spectrum by adjusting only the height of the cuboid. To validate our findings, we fabricated the designed structural color pixels via light-controlled, low-pressure nanoimprinting and measured the color and spectrum from them. Our experimental results agreed well with the simulation results, providing insights for bringing further advances to structural coloring.

Keywords: Kerker effect, structural color, multipole decomposition, nanotexture, Capillary Force Lithography, Spatial Light Modulation, Meta-surface, Mie theory

1. INTRODUCTION

The color arising from the interaction between an incident lightwave and nanostructures is known as the structural color. Most previous studies relied on high-index dielectric nanostructures for structural color generation. However, fabrication of these high-index subwavelength nanostructures requires costly techniques like electron beam lithography [1], [2] or deep-UV lithography [3], hindering commercialization of structural color. We studied the light-matter interaction of low-index cuboid shaped particles and analyzed their spectral scattering characteristics. We decomposed the scattered fields from the cuboids into four multipoles components, electric dipole (ED), magnetic dipole (MD), electric quadruple (EQ) and magnetic quadruple (MQ). We ignored other higher order terms since they are negligible in the total scattering [4]. We used the exact formula to decompose the scattering of the low-index cuboid which is valid for any size [4]. We then experimentally verify our results by fabricating the height-controlled cuboid structure using the facile and inexpensive method of light-controlled, low-pressure nanoimprinting [5].

2. RESULTS

We start our analysis by finding the transmission of a single NOA73 (n~1.56) cuboid placed on a substrate of the same material in vacuum (Figure 1a). The cuboid height and width are 0.8 and 1.5 μm respectively. We used an x-polarized plane wave as the excitation and performed Finite-difference time-domain (FDTD) simulations to find the scattered fields in the visible wavelength range. We found the peak transmission occurs at λ_o = 0.4 to 0.5 μm. The color generated from this cuboid was observed is shown along with the transmission spectra in Figure 1b. We calculated the contributing multipoles and plotted them in Figure 1c. We found that initially EQ is the dominant mode at $\lambda_o \sim 0.42$ μm while the ED mode remains dominant and contributes most strongly to the total scattering in the vicinity of the peak transmission.

We fabricated our cuboid structure using light controlled low-pressure nanoimprinting. The surface morphology of 2D square lattice cuboid array, obtained through tapping mode atomic force microscopy (AFM) with high aspect ratio Si tips (AR5-NCHR, NanoAndMore), is shown in Figure 2a. The cross-sectional profile of the cuboid is shown in Figure 2b. The

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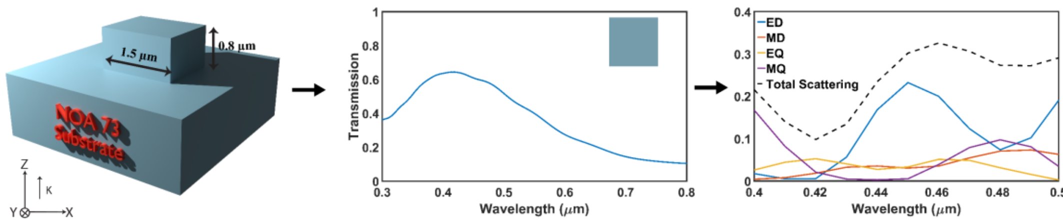
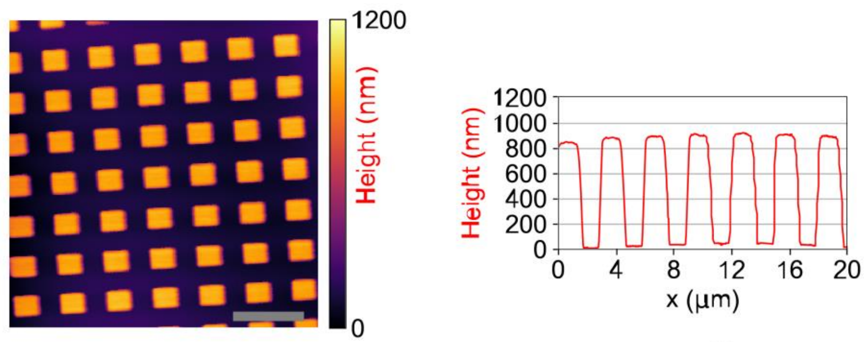
transmission spectra obtained through UV–vis spectroscopy (Cary 5000, Agilent Technologies) is shown in Figure 3a. To validate the color accuracy, the samples were illuminated with white light at a normal incidence angle, and the resulting color was monitored with an optical microscope. The results are shown in Figure 3b.



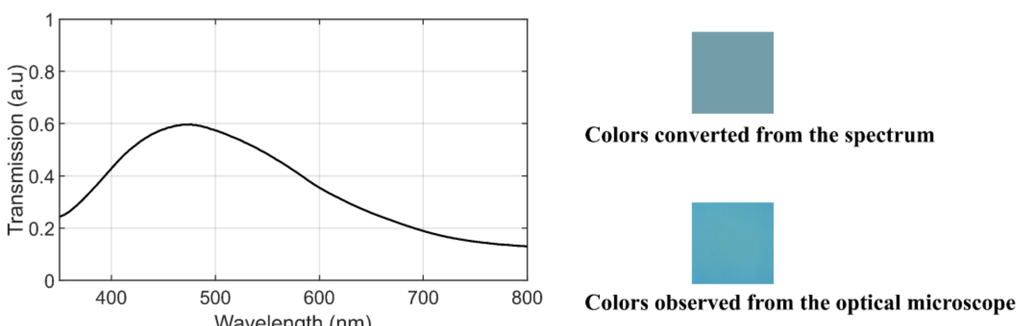
(a) (b) (c)

Figure 1. Multipolar decomposition of single cuboid structure of heights 0.8 μm with its respective transmission spectra (a-c)



(a) (b)

Figure 2. (a) AFM scans of 2D square lattice cubic structure of 0.8 μm height (scale bar: 4 μm) and its (b) cross-sectional profiles with different UV dose.



(a) (b)

Figure 3. (a) AFM scans of 2D square lattice cubic structure of 0.8 μm height (scale bar: 4 μm) and its (b) cross-sectional profiles of with different UV dose.

3. CONCLUSION

In summary, we designed and experimentally demonstrated structural coloring based on low-index, simple cuboid structures by exploiting the multipolar decomposition-based analysis and design. Despite its simple geometry, the cuboid turned out to support several multipole modes that can be utilized to generate structural colors. Our simple structure and inexpensive method of fabrication will offer a new pathway for commercialization of structural coloring.

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