Reflective Color Display Using a Photonic Crystal

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Abstract

We report an electrically tunable reflective color display based on a colloidal photonic crystal. The device exhibits a low driving voltage and reasonably fast response time. 3D finite difference time domain (FDTD) method and Bragg formula are used for theoretical investigation and interpretation of the experimental data. Disorder effect and its influences on display performance are analyzed. Other interesting applications discussed include fashion decoration, counterfeit waterproof, and chameleon skin.

Author Keywords

Electronic paper, Reflective display, photonic crystal, FDTD method

1. Introduction

Electronic paper technology has been advancing so rapidly in recent years. Various devices have been developed based on different working principles, such as electrophoretic [1,2], electro-wetting [3] and electrofluidic [4,5]. The major challenge for these displays is direct color generation. Most of them rely on color pigments or dichroic dyes to generate RGB colors, which is inevitable to lose substantial light for display.

Recently, tunable colloidal photonic crystals (PCs) [6-9] are introduced as a novel class of electronic paper display that allows full spectrum tunability in a single pixel. In a photonic crystal display (PCD) device, an ordered array of colloidal particles is embedded in the host material. The electro-responsive PC material would compress or expand under different voltage. Tuning of inter-particle distance would change the reflected color. Besides direct color generation and high light efficiency, PCD also demonstrates other attractive advantages such as low driving voltage and fast response time [6-8]. Another type of quasi-amorphous colloidal structure with angle independent structural color is also recently developed by intentionally poly-dispersing nanoparticles with different particle sizes [9].

In this paper, we report an electrically tunable reflective PCD. The device can be driven at low voltage (a few volts) with a relatively fast response (~130ms). Theoretical investigation and interpretation of the experimental data is then performed based on 3D finite difference time domain (FDTD) method. Various types of disorder and their influences on device performance (contrast ratio, color purity, etc.) are discussed. Finally, we expand the potential applications of PCD to fashionable decoration, counterfeit waterproof, and chameleon skin.

2. Experimental results

In experiment, we used electronic tunable colloidal solutions from NanoBrick [9]. It is an electrophoretic colloidal suspension of $Fe_3O_4@SiO_2$ nanoparticles. Each $Fe_3O_4@SiO_2$ particle has core-shell structure, with diameter of the core and shell around 10nm and 150nm, respectively. The solution was injected into a 50-μm cell with top and bottom transparent electrodes. Different voltages were applied on the cell and the reflection spectra were recorded by the Ocean Optics USB4000 spectrometer.

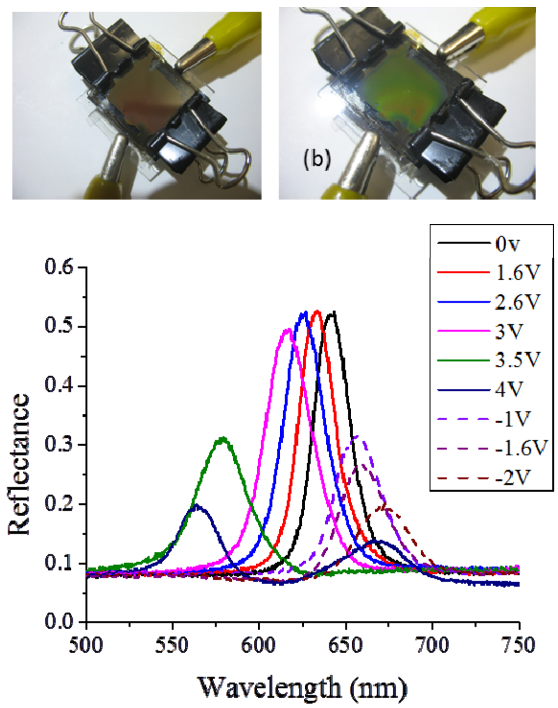

Figure 1. Photos of the reflective PCD at (a) V=0 and (b) V=4V. (c) Measured reflection spectra of our PCD at different voltages.

Figs. 1(a) and 1(b) are the photos of our reflective PCD at V=0 and 4V, respectively. The reflective color would turn from dark red to green under a positive voltage. The response time was measured to be 130ms. Fig. 1(c) depicts the measured reflection spectra. When applying a positive voltage, the reflection spectrum shifts to a shorter wavelength, while a negative voltage shifts the reflection spectrum to the longer wavelength side. The tuning range can be further increased by optimizing the particle and suspension system.

As Fig. 1(c) shows, the peak reflectance reaches 52% at λ=637nm when no voltage is applied. The structure also has 8% surface reflection throughout the whole spectrum because the substrates have no antireflection (AR) coating. With AR coating, surface reflections can be reduced and the device can have contrast ratio CR>10:1. This CR is comparable to other electronic display options, such as electrophoretic device (11:1) and reflective cholesteric LC device (10:1) [5]. Moreover, the full width half maximum (FWHM) of the reflection spectrum is quite narrow, so the device has good color purity.

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3. Simulation Method & Results

In this section, we use Bragg formula and FDTD methods to simulate the reflective properties of the PCD. The experimental data are then interpreted based on our simulations results. The PC structure under consideration is face centered cubic (FCC) lattice made of spherical particles. Fig. 2(a) shows a 2D representation of its basic lattice, where r is the particle radius and a is the smallest inter-particle distance, $A = \sqrt{2}a$. Bragg formula can be used to find the Bragg wavelength that has the reflection peak:

$$\lambda_B = \sqrt{2}a*(n_{eff}^{\ 2} - \sin^2(\theta))^{1/2} \qquad (1)$$

The effective refractive index $n_{eff} = f*n_{sph} + (1-f)*n_{medium}$, where f is the filling factor. In our simulation, SiO_2 particles (n_{sph}=1.55) embedded in propylene carbonate (n_{medium}=1.42) are considered.

For display applications, the peak reflectivity of PCD is important since it is directly related to contrast ratio. 3D-FDTD method is used to obtain this information. We perform simulation using commercial software, Lumerical FDTD solutions. Fig. 2(b) shows the basic simulation setting. Simulation domain is represented by the orange area and its size is set as A*A*20μm. For periodic PC structures, the Bloch boundary condition is applied on the x and y directions to save calculation time and computer storage. The boundary condition along z direction is set as perfect match layer condition. The incident plane wave is indicated by the grey area in Fig. 2(b). It is a femtosecond pulse and has spectrum covering the whole visible range. Two frequency-domain planar monitors are represented by yellow rectangles. The monitor on the top is used to record the transmitted power, and the one in the bottom is used to record the reflective power. After recording the time dependent transmitted/ reflected power during simulation, a Fourier transform is performed to obtain the transmission/reflection spectrum

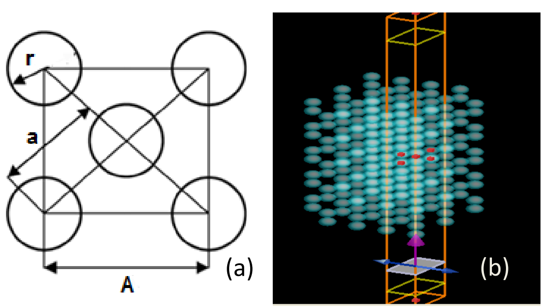

Figure 2. (a) 2D presentation for the basic lattice structure of the FCC structure, and (b) Simulation setting for 3D FDTD

Fig. 3(a) shows the reflection spectrum for a PCD with different inter-particle distance. As the inter-particle distance a is reduced from 350nm to 250nm, the whole spectrum shifts toward a shorter wavelength and the peak wavelength changes from 720nm to 517nm. This means the reflection color would experience blue shift as the PC structure shrinks. With the reduced inter-particle distance, the interaction between particles increases, therefore scattering cross section becomes stronger and the peak reflectivity would increase accordingly. Fig. 3(b) compares the FDTD simulation results with Bragg formula prediction. They show very good agreement. One can also notice that the peak wavelength in Fig. 3(b) is almost linearly dependent on a. This is because in our case the refractive index difference between the particle and medium is quite small, so the variation of peak wavelength is dominated by the tuning of inter-particle distance

Due to the statistical nature of colloidal system, the PC materials used in display won't be perfectly uniform and periodic. Disorder effect must be taken into consideration for addressing real display applications. Although some works have been done for those conventional fixed PC structures [10,11], their results cannot be safely applied to our tunable colloidal PCD devices with low refractive index contrast. Next we investigate the disorder effect by FDTD simulation method. Since the structure is not periodic anymore, the simulation setting we used before is not applicable. We enlarge the simulation domain (7A*7A*20μm), and enforce perfect match layer condition in all directions.

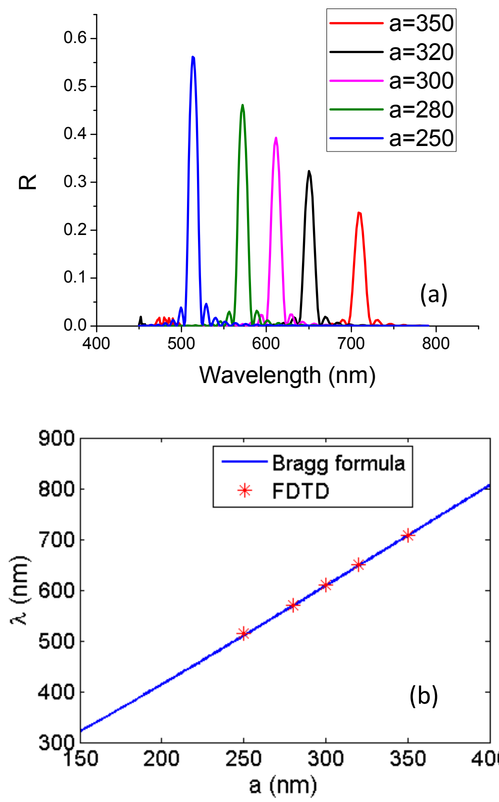

Figure 3. (a) 2D presentation for the basic lattice structure of the FCC structure, and (b) Simulation setting for 3D FDTD.

First we would discuss the disorder effect caused by particle size/position randomization. Simulation results prove both polydispersity in particle size and randomness of particle position could affect the reflection spectrum. As shown in Figs. 4(a) and 4(b), the peak reflection would decrease with the increasing degree of disorder. Position disorder has a larger influence on reflection peak than size disorder. Some vacancies (missing sphere) could also occur, and its effect is simulated in Fig. 4(c), a clear decrease of reflection peak is observed. In real application, the polydispersity in particle size and missing sphere could all lead to variation of particle position. Thus, those disorder effects would be combined, and the measured reflectivity would be much lower than that of perfect PC structure.

Other type of disorder could also occur during PC lattice tuning. One is anisotropic compression/relaxing of lattice. Let us assume the top and bottom electrodes are in the *xy* plane and the voltage is applied along *z* direction. When applying a DC voltage to the PC device, the lattice could uniformly shrink/expand in all directions, or mainly vary along the *z* direction. This phenomenon is shown in Fig. 5(a). The original PC that has interparticle distance a=320 nm is indicated by the black curve. If the PC structure uniformly shrinks in all directions, its reflection spectrum would blue shift significantly, and peak reflectivity increases greatly (red curve in Fig. 5(a)). If PC structure is only compressed along the *z* direction, then the reflection spectrum would shift less and the peak reflectivity would only increase slightly (blue curve in Fig. 5(a)). On the other hand, the gravity effect and particle repulsive interaction may also lead to randomization in lattice constant during lattice tuning. Its effect is shown in Fig. 5(b). If the lattice constant along *z* is randomized, then the peak reflectivity would decrease greatly. For another extreme case that the structure has lattice constant linearly varying from top to bottom, the peak reflectivity is lowered significantly, and the reflection spectrum is much broader.

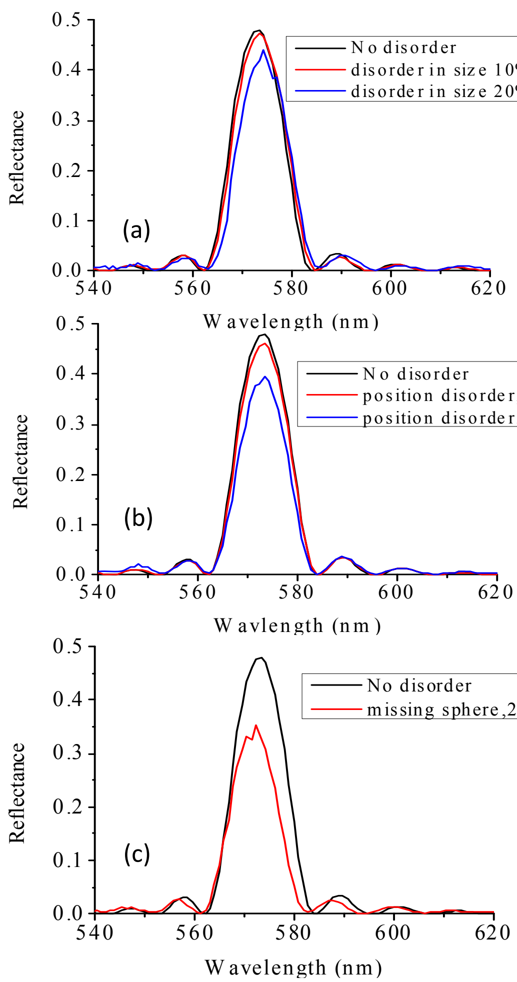

Figure 4. Simulated reflection spectrum of PC structure with: (a) Particle size disorder, (b) Particle position disorder, and (c) Missing sphere disorder. The original structure (without disorder) has particle radius r=75nm, interparticle distance a=280nm, and period number is 25.

The measured reflection phenomena in Fig. 1(c) can be explained based on simulation data. When applying a positive voltage on the device, the charged particle would move to the top surface which is closer to the viewer's side. The interparticle distance near the top surface becomes smaller. From simulation results in Fig. 3(a) the reflection is expected to shift to a shorter wavelength. This is consistent with the measured results in Fig. 1(c). On the other hand, applying a negative voltage would push particles to the bottom surface so that the reflection spectrum would shift to a longer wavelength.

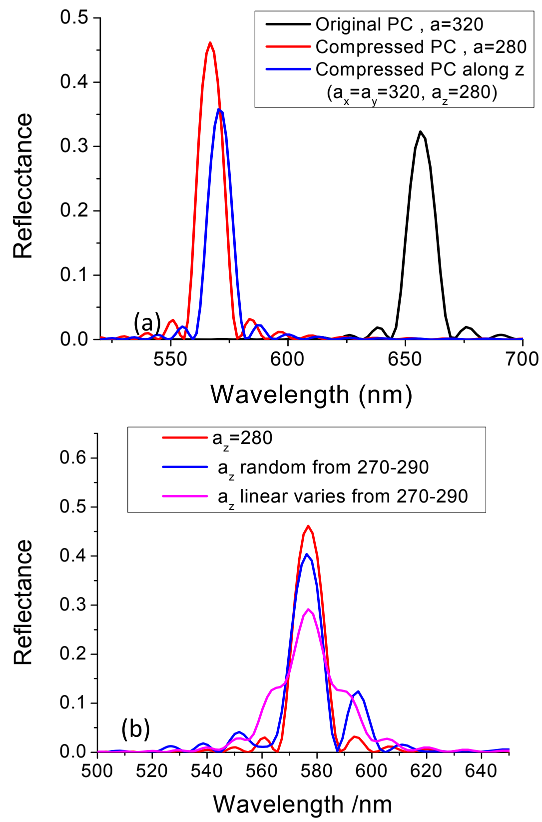

Figure 5. Simulation of the disorder effect during lattice tuning: (a) Uniform/anisotropic shrinking of the PC lattice, and (b) Random/gradual variation of lattice constant.

The measured reflection phenomena in Fig. 1(c) can be explained based on simulation data. When applying a positive voltage on the device, the charged particle would move to the top surface which is closer to the viewer's side. The interparticle distance near the top surface becomes smaller. From simulation results in Fig. 3(a) the reflection is expected to shift to a shorter wavelength. This is consistent with the measured results in Fig. 1(c). On the other hand, applying a negative voltage would push particles to the bottom surface so that the reflection spectrum would shift to a longer wavelength.

In Fig. 1(c), a clearly visible decrease of peak reflectivity and broadening of reflection spectrum can be observed under high voltages. Two possible reasons could attribute to this phenomenon: Some particles could possibly stick together and result in missing sphere disorders. Also, particles concentration would gradually vary from top to bottom surface. Our previous simulation results in Figs. 4(c) and 5(b) prove both cases would lead to decreased reflection peak. One can also observe from Fig. 5 that peak reflectivity decreases less under a positive voltage than under the same value of a negative voltage. This is because the PC structures inherently have higher reflection when moving toward short wavelength, as Fig. 3(b) shows. This effect would particularly compensate for reflection peak decreasing under a high voltage.

4. Potential applications

Besides tunable reflective color display, our device also demonstrates great potential in other application areas. First it can be used in fashionable decoration and counterfeit waterproof to generate irremovable color pattern. Structural color is favored in these applications since it can display some metallic and iridescent color that cannot mimic by the chemical pigment, also it is eco-friendly and free from chemical bleaching. Some other techniques, like M-ink[8], have been developed to display irremovable colorful pattern. Our PCD can do the same.

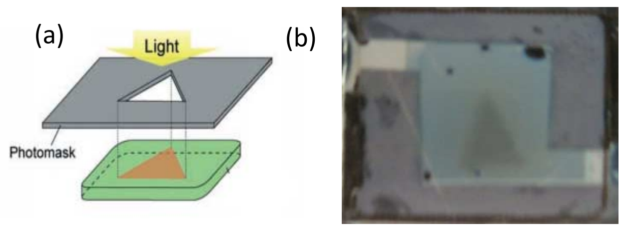

Figure 6. (a) Schematics UV curing with a photomask. (b) Generated color pattern upon removing the bias voltage.

The photonic crystalline colloidal solution was mixed with Norland Optical Adhesive NOA76 by 80 wt% and 20 wt% and then filled into a 50-µm glass cell. The PC material would change its original color under 5V of biased voltage. The cell was then cured by UV light through a photomask, as shown in Fig. 6(a). After removing the bias voltage, the exposed area would preserve its color, while the unexposed area would return to its original color appearance. Fig. 6(b) shows the generated color and it can be preserved for several days. A multi-color pattern can also be realized by repeating the UV exposure process several times with different bias voltages.

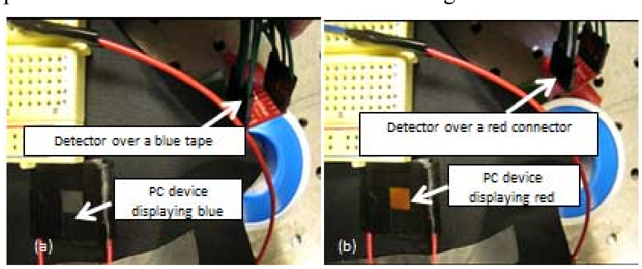

Figure 7. Chameleon skin when displaying (a) blue and (b) red.

Another interesting application of our device is chameleon skin, which means an object would change color according to the environmental condition. We constructed a chameleon skin device by connecting the PCD part with RGB color sensors. Each colorsensor was used to detect the environmental color and this information was sent to a programmable micro controller. The controller then generated an appropriate voltage based on previously recorded voltage/color datasheet. Under this voltage, the PCD would quickly change its color to 'mimic' the environmental color. Such an example is shown in Fig. 7. The PCD would appear blue when the detector attach to a blue tape and display red color when the detector is attach to a red object. Our chameleon skin can respond to the environmental color change in a relatively short time (< 200 ms), and it could find useful military applications.

5. Conclusion

We have demonstrated an electronically tunable reflective color display based on colloidal photonic crystal material. The operation voltage is about 4V. We also used 3D FDTD method to optimize the device design. Other possible applications, such as fashion decoration, counterfeit waterproof, and chameleon skin are also discussed.

6. Acknowledgement

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