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High transmittance optical films based on quantum dot doped nanoscale polymer dispersed liquid crystals

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ABSTRACT

We propose a simple way to fabricate highly transparent nanoscale polymer dispersed liquid crystal (nano-PDLC) films between glass substrates and investigate their incident angle dependent optical transmittance properties with both collimated and Lambertian intensity distribution light sources. We also demonstrate that doping nano-PDLC films with 0.1% InP/ZnS core/shell quantum dots (QD) results in a higher optical transmittance. This work lays the foundation for such nanostructured composites to potentially serve as roll-to-roll coatable light extraction or brightness enhancement films in emissive display applications, superior to complex nanocorrugation techniques proposed in the past.

1. Introduction

In the past few decades, significant efforts have been invested in the development of electro-optic materials, methods and manufacturing processes which can enable displays with ultra-slim profiles, enhanced brightness, lower power consumption and customized specifications for various applications [1,2]. In recent years, even flexible, bendable and rollable form-factor displays are emerging due to the advent of self-emissive light sources consisting of flexible electroluminescent organic layers. Such displays are currently being used in new-age applications such as wearable and health-monitoring devices and are poised to usher in a wide range of next-generation devices on several fronts [3–6]. However, the current methods of light extraction, brightness enhancement and light-guiding sometimes are incompatible with the fabrication and application requirements of next-generation emissive displays. A striking example of the incompatibility between proposed methods and fabrication needs is observed in display devices based on self-emissive light sources like OLEDs and LEDs, where the issue of low light out-coupling efficiency persists [7]. This drawback is due to a refractive index mismatch between multi-layer structures, which results in light losses via total internal reflection due to wave-guided modes. Most of the proposed solutions such as nanostructured surface modification, 2D nanocorrugation and photonic crystal fabrication [8–12] involve complex nanofabrication processes which may be difficult or expensive to transfer to actual mass production via roll-to-roll coating, for applications such as flexible displays. Other relatively easier solutions that involve surface roughening and incorporation of diffusive micro-particles may be used for extracting more light from the substrate-to-air interface in self-emissive backlight units [13–15]. However, such methods may cause resolution issues in device applications which require a smooth, defect-free backlight unit surface [16]. A similar incompatibility is encountered in the newly emerging field of ultra-slim liquid crystal displays (LCDs). The thickness limitation in LCDs can be effectively addressed if the overall thickness of the backlight unit is reduced. The three-pronged objective of providing lighter, significantly thinner and more energy-efficient LCDs with fewer light sources can be achieved if the components of the backlight assembly such as the brightness enhancement film and light-guide plate can be mass-produced by roll-to-roll process instead of conventional plastic molding techniques like hot embossing and injection molding which result in a thicker profile [17,18]. Thus, with the emergence of such a large number of emissive displays and their numerous customized applications, the need exists for versatile and adaptable highly transparent optical films that can be used for brightness modulation and light extraction in various types of display devices. With this motivation in mind, it is important to first determine the optimum materials formulation to achieve such high transmittance films with the desired optical properties.

We envisage that a high transmittance optical film that can simply be coated on a light source or backlight component can be a

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practical and cost-effective light extraction or brightness enhancement/modulation method for emissive display applications. We hypothesize that enhanced light extraction can be realized by the use of the aforementioned films in the following manner. Smooth, microdefect-free and high transmittance nanoscale polymer dispersed liquid crystal (nano-PDLC) films can be conveniently coated on glass or plastic surfaces to serve as refractive index matching materials to reduce optical losses. In addition to the use of refractive-index matching media, simply dispersing InP/ZnS photonic nanocrystals or quantum dots (QD) in these films may enable enhanced extraction of wave-guided modes by modifying the angular distribution of wave-guided photons via absorption and emission by quantum dots [16,19]. If permitted by the resolution requirements of the application and fabrication capabilities, the surfaces on which these films are coated may even be micro-patterned with interdigitating microgratings for further enhancement of light extraction by forward surface scattering. In this article, we test the above hypothesis by presenting optical films based on a nano-PDLC material system that can potentially serve as a straightforward and microdefect-free coatable means for enhanced light extraction. For this objective, we demonstrate different types of nanostructured films consisting of nematic LC, InP/ZnS quantum dots and UV-curable polymer. As proof-of-concept, we first build nano-PDLC films in cells consisting of two glass substrates and demonstrate a significant increase in the transmittance of normally and off-axis incident collimated laser light through these cells in comparison to empty cells. We then demonstrate, for the first time, enhancement of light transmittance upon addition of quantum dots to nano-PDLC films. Since most new-age display devices are based on Lambertian intensity distribution light sources such as LEDs and OLEDs, in particular, we demonstrate similar enhancement of transmittance for light from LED arrays. We also show a simple photolithographic technique to prepare an interdigitating ITO micrograting pattern on the glass substrates which further enhances light extraction. It should be noted, however, that this micrograting pattern merely serves to further enhance light extraction and is not used for electrical stimulation of the liquid crystal system. Moreover, since the potential application of these nano-PDLC films is to act as a standalone coatable method for enhanced light extraction, we emphasize at this point that the use of micro-patterned substrates in this study is a mere additional suggestion to improve light transmittance of filled cells if required.

2. Experimental

The proposed nano-PDLC films are prepared via polymerization induced phase separation (PIPS) by UV-curing a mixture of nematic liquid crystal 4-Cyano-4′-Cyanobiphenyl (5CB) (Merck, $n_o = 1.5357$) and Norland Optical Adhesive 81 (NOA81) ($n = 1.56$) in a cell consisting of two flat glass substrates ($n = \sim 1.5$) separated by 25 μm spacers. The weight percentages of LC and NOA81 are 25% and 75% respectively. Films containing 25% LC, 74.9% NOA81 and doped with 0.1% InP/ZnS core/shell nanocrystals or quantum dots coated with Oleylamine ligands (NNCrystal US Corporation, Emission Peak ∼560 nm) are similarly prepared via PIPS between flat glass substrates. Quantum dots are dispersed in the LC/polymer mixture by sonication for one hour. An FEI Quanta 450 scanning electron microscope (SEM) is used for observing the morphology of these films. The aforementioned quantum dot doped and undoped films are also similarly prepared in a cell, one of whose glass substrates is patterned with interdigitating ITO microgratings and the other is flat. Such micrograting patterns are fabricated via a photolithographic process described in Fig. 1(a)–(g), with an SEM (Hitachi S-2600) image of the micrograting pattern shown in Fig. 1(h). The micrograting spacing as well as the width of each individual micrograting element is 5 μm. It should be noted that ITO is chosen to fabricate the micrograting pattern due to ease of fabrication and abundant availability and does not serve the purpose of electro-optical studies. Optical transmittance of blue (460 nm), green (514 nm) and red (632.8 nm) light from collimated laser and LED array light sources (100 W Cree XLamp XT-E) through empty and film-containing cells is measured using the setup shown in Fig. 2. For films built on microgratings, light is incident on the cell from the flat glass side. Optical transmittance at various incident angles from 0 to 60° is measured by placing the cell on a rotating stage. The transmittance values of different cells are calculated by normalizing the photodetector voltage observed when light is incident on the photodetector after passing through a cell to the voltage when light is directly incident on the photodetector. The standard error for all transmittance values reported henceforth is no more than 0.45%.

3. Results

The SEM image of an undoped nano-PDLC film is shown in Fig. 3. The films consist of a polymer matrix with relatively mono-dispersed LC droplets (represented by cavities) smaller than 100 nm in size. An empty cell consisting of two flat glass substrates with an air gap of 25 μm between them would be expected to have the lowest transmittance values due to the glass-air-glass refractive index mismatch and losses due to substrate modes at the glass-air interfaces. Hence, comparing the transmittance values of cells containing nano-PDLC films with those of an empty cell would be ideal for demonstrating their potential for light extraction or brightness enhancement.

As proof-of-concept, we first test the brightness enhancement potential of nano-PDLC films by performing optical transmittance measurements with collimated lasers. As a representative example, Fig. 4 shows the incident angle-dependent collimated blue laser light transmittance values of various kinds of cells. As conjectured previously, an empty flat glass cell has the lowest transmittance values. As the cell is filled with an undoped nano-PDLC film, the transmittance of light incident at 0° and 60° increases by ∼5% and ∼7% respectively. Flat glass cells with InP/ZnS quantum dot doped films show an even further increase in transmittance, with the transmittance at 0°, 20°, 30° and 60° incident angles being higher by ∼7%, ∼8%, ∼17% and ∼12% respectively compared to an empty cell. Quantum dot doped nano-PDLC films built on interdigitating microgratings of optimum width and spacing (both 5 μm) show an even higher transmittance than those built on flat glass, particularly at high angles of incidence. This optimum micrograting width and spacing of 5 μm was determined after performing transmittance measurements with microgratings of various sizes such as 5 μm, 7.5 μm and 10 μm. The latter two types of microgratings did not show an enhancement in optical transmittance and hence, 5 μm was chosen as the optimum grating dimension. Compared to empty flat glass cells, the transmittance increase of ∼15% at both normal incidence and 60° incidence in quantum dot doped films on microgratings is noteworthy. Similar enhancement of optical transmittance is also observed when the same cells are subjected to green laser light. However, when the same experiments are attempted with red laser light, doping nano-PDLC films with InP/ZnS quantum dots does not result in enhancement of optical transmittance.

We also use Lambertian output light sources, namely, LED arrays for quantifying the optical transmittance of quantum dot doped and undoped nano-PDLC films. We believe that testing these films with LED light sources enables a more practical approach toward gauging their potential for use as brightness enhancers in new-age display devices based on OLEDs and LEDs. Figs. 5–7 show