Abstract

Novel photo-aligned optical thin-films, based on Rolic’s monomer corrugation (MC)-technology [1] are presented. The MC-technology enables nano- and micro-topologies on polymer thin-films, including photo-patterning of topologies. The new MC-films enhance brightness, contrast and viewing cone of reflective LCDs and markedly improve anti-reflection and glare of displays.

1. Introduction

Functional optical films such as anti-reflective and reflective coatings are crucial for improving the performance of reflective LCDs. Parameters to improve are: brightness, angle of view of maximum brightness and poor contrast hampered by glare. Conventional reflective LCDs use metallic reflectors which are brightest at the glare angle. However, to avoid serious image degradation due to specular reflection from the reflector as well as from the display surface forces the viewer to read the display at an offset from the angle for maximum reflection. As a consequence contrast and brightness degrade and colors desaturate. To remedy these problems, holographic reflectors have been developed which improve brightness and contrast by deflecting the display image from the glare angle [3-6]. The same holds for diffuse directive reflectors with asymmetric, mechanically machined topologies, such as blazed [7], or micro slanted reflectors [8-9]. However, existing solutions still exhibit limitations, such as: restricted angle of view, insufficient brightness over the visible spectral range, complexity of fabrication, difficulty to apply to large areas, costs, or non in-situ applicability of the reflectors. Beyond efficient diffuse reflectors, the visibility of LCDs can be further improved using anti-reflective coated LCD-polarisers. This yields lower diffuse reflectors, the visibility of LCDs can be further improved using anti-reflective coated LCD-polarisers. This yields lower brightness and contrast and light transmittance and improves contrast and brightness of the displays. However, so far there exists no single antireflection technology meeting the requirements of all applications such as : diverse size, shapes and materials, simple fabrication process and low costs.

Recently we presented a new technology to photo-generate high-resolution thin-film polymer topologies [1]. Compared with conventional techniques, our novel monomer-corrugation (MC)-technology is basically simple, low cost and applicable to virtually any planar- or non-planar substrate and material. Isotropic as well as anisotropic topologies ranging from nano- to micro-meters were demonstrated to be feasible, enabling a broad range of optical thin-film elements. Examples are broadband antireflective and antiglare coatings which markedly improve the visibility of pictures, text, displays, or other optical information behind glass or plastic substrates [1]. Moreover, the surface topologies of MC-films were shown to be photopatternable and MC-topologies can be combined with numerous LPP/LCP optical thin-film elements [10-14]. This opens up such diverse applications as topological aligning layers for LCDs - including hybrid topology/photo-alignment-, optically strongly anisotropic retarders made of low birefringent materials, uni- and multi-directional diffusers and reflectors, optical security elements, reflective and transmissive polarizers, as well as diffractive optical thin-films [1-2]. Here we report on the optical performance of isotropic MC-nano-topologies and anisotropic MC-micro-topologies for reflective LCDs. Highly efficient anti-reflective and ultra-thin diffuse and directional MC-reflectors which can be integrated into displays are shown to be feasible.

2. Processing of MC-thin-films

The MC-technology is based on the coating of blends of miscible monomers - such as blends of liquid-crystalline pre-polymers and monomeric liquid crystals (LCs) - where only the pre-polymers are photo-crosslinkable. After coating an MC-film on a substrate, phase separation is induced by crosslinking the pre-polymer component(s) via exposure to ultraviolet radiation. Depending on MC-material design and film preparation, subsequent removal of LC-component(s) leaves nano- or micro-pores in the cross-linked, solid polymer thin-film [1]. In addition to topologically isotropic pores, we have shown that anisotropic MC-topologies are generated on surfaces exhibiting anisotropic aligning forces, such as on linearly photo-polymerized (LPP)-substrates [1-2,10-12]. Upon uv-light exposure anisotropic phase-separation occurs in the MC-thin-film [1]. Amplitude and periodicity of the polymer topologies are tuneable by adjusting film thickness, LC-prepolymer content, aligning direction, strength of alignment and cross-linking conditions. This enables control of the pore- or groove-period, height of the vertical MC-profile as well as control of the distribution and volume fraction of MC-pores or grooves.

3. Anti-reflective MC-coatings

We succeeded to achieve MC nano-porous topologies exhibiting a reduced effective refractive index n̄ in polymer film such that the antireflection criterion [15] n̄ = (n_a n_s)^(1/2) is meet, where the respective indices n_a and n_s are those of air and substrate at a given wavelength [1]. Low indices (n_a ≅ 1.22) required for glass and transparent plastic substrates (n_s ≅ 1.5) were achieved (see Fig. 1a) by adjusting the volume fraction of the MC-pores. Isotropic MC-nano-topologies act as efficient antireflection coatings for glass and plastic substrates. This is illustrated in Fig. 1b, which shows the wavelength dependence of the reflectance from a PMMA panel which is MC-coated on both sides. Compared with uncoated PMMA a drastic reduction of surface reflectance results. The photopic reflectance over the entire visible spectral range
which takes the visual response of the human eye into account, amounts to only 0.1 % per MC-coating. Fig. 1b shows the performance of a single MC-antireflection layer which we applied to a plastic LCD-polarizer (from Nitto Denko corporation) and laminated onto a glass substrate. The resulting surface reflectance over the entire visible spectral range of the MC-coated polarizer decreases by a factor of two from 6% to 3.5% (Fig. 1b). In parallel, the transmission of the MC-coated polarizer increased by remarkably 1.5%.

![Graph](image1.png)

**Figure 1 a)** variation of the effective refractive index, $n_f$, of the nano-corrugated polymer film as a function of the wavelength (closed circles) compared to the intrinsic index of the corresponding smooth polymer film (open circles). **b)** dependence of the reflection of a two- side coated PMMA (squares) and one-side coated polarizer (circles) versus wavelength of $10^\circ$ incident light. The solid lines are the corresponding photopic reflectance.

4. Diffusive and reflective MC-coatings

Anisotropic MC-micro-topologies with micro-pores instead of nano-pores act as diffusional layers. By depositing a metal layer on top of such a diffuser, we have shown that ultra-thin directional MC-diffuse reflectors can be realized with an overall thickness of only about 0.5 $\mu$m [2]. Due to their groove alignment, MC-coatings combine both, light-scattering and light diffraction effects. As a consequence incident light can be redirected into a desired off-specular viewing cone whose shape depends on the MC-groove geometry. By tailoring the geometry of the grooves, the amount of specular- versus scattered-light can be synergetically controlled such, that strong brightness enhancement results in MC-reflectors. Fig. 2 illustrates this effect for the two different MC-reflectors R1 and R2. For comparison also included in Fig. 2 is a white, commercial holographic reflector from Polaroid. The MC-diffuse reflector R1 is made to redirect incident light into a cone of $-10^\circ$ to $20^\circ$, with maximum reflectance around $8^\circ$ close to the normal of the display surface. From Fig. 2 it follows that the gain in brightness of R1 is two- to six-fold larger than the brightness of a standard-white BaSO4 diffuser. The MC-R2 reflector is designed for maximum reflectance at $15^\circ$ off-axis from vertical light incidence. Fig. 2 shows that the gain of R2 reaches 12 and that the gain of brightness of both MC-reflectors exceeds the gain of the holographic reference reflector by up to a factor of five over virtually the entire off-specular angular range. Moreover, the glare peak, which seriously degrades contrast and color saturation, is drastically reduced in of our MC-reflectors (Fig. 2). Compared with the holographic reflector and its strong specular peak, the glare peak of the MC-reflector R1 is 50% smaller, whereas the glare of MC-reflector R2 is virtually suppressed (Fig. 2). This illustrates that glare can be re-distributed in MC-reflectors such that it does no longer hamper performance but enhances brightness within the preferred viewing cone of the reflector. As a consequence high brightness over a broad viewing range result while simultaneously improving contrast and maintaining the white appearance of MC-reflectors. As follows from the calorimetric data $(Y,x,y) = (1.33,0.31, 0.33)$ of the BaSO4 and $(8.99,0.31, 0.34)$ of the MC-reflector R1, determined at $10^\circ$ using a D65 illuminant, and those of the holographic reflector $(4.08,0.27, 0.30)$, the MC-reflector R1 is indeed whiter than the holographic reflector.

To compare the light distribution from MC-reflectors in space, conoscopic measurements were made under different lighting conditions. The light distribution of MC-reflector R2 illuminated under $-30^\circ$ with bright, collimated daylight (D65 white illuminant) is shown in Fig. 3a. Fig. 3b shows the cross section of the reflection profile versus the polar angle. Apart from the specular peak at $30^\circ$, which is markedly reduced in R2, there are two strong and diffuse off-specular peaks corresponding to the positive (right) and negative (left) diffracted orders of the MC-topology. The diffuse peak in the left is between 0 and $25^\circ$, with a maximum at $17^\circ$. This distribution agrees well with the results in
Fig. 2. The same holds for the right diffuse peak in Fig. 3b between 35 and 70°, with its maximum at 45°.

We will show that synergetic MC-topologies which are coated with silver (instead of aluminium) enable white MC-reflectors with very high gain and a broad range of polarization-independent reflectance. Moreover, MC-reflector topologies which act as polarizers for incident light can be realised too.

5. Photo-patterning of MC-Coatings

Based on photo-patterned alignment, we have realised MC-layers with anti-reflective or reflective properties that differ in different areas [1]. This is demonstrated by Fig. 5a which shows two photographs of a photo-patterned diffuse MC-reflector on a flexible plastic substrate. The two different photo-aligning directions of adjacent pixels in Fig. 5 differ by 90°. To illustrate the directional dependence of MC light-scattering, the photographs in Fig. 5 are taken at illumination- and viewing-angles under which adjacent pixels scatter light such, that either the positive or the negative scattering image appears. Fig. 5 demonstrates that MC-photo-patterning can be employed such, scattering range and uniformity of scattered intensity are strongly affected. By properly combining photo-patterning and MC-topological effects, pixellated MC-reflectors can be achieved whose pixels scatter light into the same azimuthal direction, but which exhibit different scattering peak angles along the polar direction. Furthermore, pixellated MC-reflectors whose pixels scatter light into different azimuthal directions can be realised too. Such multidirectional MC-reflectors redirect incident light from different directions towards the viewer, thereby further increasing brightness.
6. Application of MC-reflectors in reflective LCDs

Directional diffuse MC-reflectors which can either be laminated to the outer bottom substrate of a reflective LCD or directly coated onto one of the internal display substrates (in-situ) redirect incident light into a cone close to the display normal. This leads to a display with increased brightness within an optimal cone of view. Fig. 6 shows a photograph of a normally white two-polariser TN-LCD with an MC-reflector attached to the outer surface of the bottom substrate. The right half of Figure 5 shows that directional MC-reflectors significantly improve the brightness of a display compared with a conventional diffuse reflector on the left. Because MC-films are ultra thin, they can effectively be integrated into displays (in-situ reflectors). Unlike rough internal scattering reflectors which disturb the alignment uniformity of LC molecules [16], MC-reflectors do not require planarisation layers to prevent alignment degradation. Single-polarizer as well as two-polarizer TN-LCDs with bright, high contrast internal and external MC-reflectors will be demonstrated.

7. Summary

Novel and efficient anti-reflective and paper-white reflective coatings, which are based on our recently introduced monomer corrugation (MC)-technology are demonstrated [1]. MC-reflectors strongly reduce the glare of diffuse reflectors and re-distribute reflected light into optimal viewing cones, yielding increased brightness over a broader field of view. Because MC-reflectors are ultra-thin they can be integrated into reflective LCDs. Moreover, photo-patterning of MC-diffusers and reflectors and their combination with other optical elements, such as with LCP-thin-films [10,13], markedly broadens the range of functional optical thin-films for LCDs. Our MC-technology enables integration of optical, electrical and aligning functions in hybrid thin-films.

8. References