Roughness dependence of optical coefficient polarization on pixels’ diffractive elements by stretching technique

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Abstract

In this research work, two polydimethylsiloxane diffractive elements (DEs) of 3 mm thickness under the same conditions are fabricated using molding technique and one DEs rough surface is modified by plasma O₂ treatment in a vacuum chamber. The effects of both rough surface DEs on the structure and optical properties are investigated by atomic force microscope, white light interferometer and FDTD simulated, which indicates that the plasma O₂ treatment induces the formation of nanostructures and decreases the surface roughness up to some roughness level. The optical transmittance, reflectance, absorption, Raman scattering spectra and optical coefficient measurement provides better results to polymer DEs, to be used as replica, efficient and cost effective. Furthermore, the stretchable technology is applied on both DEs, which provides results towards diffraction grating and thus, have widespread applications in optical transmission and reflection domain such as measuring, imaging, coding and solar energy.

1. Introduction

The dielectric silicone polymer PDMS is widespread optical material which is used to fabricate various optical systems, elements and devices. Provided its chemical material properties; its inert, non-toxic and surface is hydrophobic [1]. With other multipurpose properties such as viscoelastic with excellent optical and rheologic attributes [2], they are used as a structural material in microfluidic systems and biosensors often [3, 4], narrow-line feedback elements [5], tunable optical filters [6], polarization beam splitters [7], dispersion engineering [8], microwave frequency selective elements [9, 10], and color filters [11–13]. By nature, the surface of PDMS is hydrophobic which presents a challenge in micro-channels. Numerous treatments such as O₂, C₂F₂, S̄F₆, C̄F₄, SiC₄, CCl₄ or mixture of the gases have been practical on PDMS surface to improve its hydrophobic properties. Besides, PDMS as a substrate or a structural material also growing according to the variety of design choices by post processing methods such as etching, coating, polishing, deposition and surface modification [1–12]. These efforts have merely been made specifically for PDMS enhancement and treatment, yet not any attempt is available on purely PDMS based properties as a substrate.

Recently, the polymers [2] and semiconductors [3] applications are growing in numerous fields by a variety of deposition techniques, commonly on glass substrates and plastics. In these applications, guided mode resonant (GMR) tunable phenomena have attracted significant interest. The GMR properties inventing in quasi-guided waveguide modes [14]. The quasi-guided waveguide modes made up on a decorated substrate with subwavelength periods are well known [15, 16]. The resonant wavelength of such DEs can be easily adjusted for reflectors, polarizers, band-pass and band-stop, by changing the structural and material properties. As a consequence of their frequent usage in parametric spaces, variety of new models are being developed [17–20]. In such models, GMR color DEs in reflection or transmission domain receives great attention [21, 22]. The main applications of GMR color DEs are multimedia projectors, computers, mobile and cameras [23, 24], pulse shaping [25, 26], encoding and decoding [27], and optical imaging [28]. Hereinafter, the polymer-based reflective color DEs with experimental efficiency of 30%–85% are also available in the literature [29, 30] and in

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transmission mode, Ellen bogen et al [31] proposed polarization dependent transmission color filters using a 2D metal (Al) grating along with a Si$_3$N$_4$ core. Another attempt based on localized surface Plasmon’s on metallic nano-antennas, focused on shifting colors by changing the polarization [32]. These DEs mostly improved by diffraction of gratings phenomena.

Hence, a method is demonstrated that is the PDMS DEs’ substrates replicated from the rough glass substrate. Within the wavelength range of 190 – 900 nm the optical coefficient $N$ and $K$ values are changed by the illumination wavelength of light on the DEs’ substrates, as a result disperse color pixels disappear with high transmittance and low reflectance.

2. Fabrication process of PDMS DEs

Figure 1 (a) illustrates a fabrication route to net-shape the replicated rough PDMS DEs, used a fused rough silica glass slide with the following dimensions ($7 \times 5 \times 1.2$ mm$^3$) and PMMA frame ($6 \times 4 \times 5$ mm$^3$). Firstly, the fused silica glass and the PMMA frame installed into Petri dish. Later on, the silicone elastomer kit Dow Corning Corporation by weight 10 ratio 1 base-curing agent mixed, stirred 5 – 8 min at ambient temperature and dispensed on the master glass. After being bubbles removed, followed by curing at 65 °C for 4 h. The 3 mm PDMS substrates are achieved after peeling from rough glass. Hereby, we get two PDMS DEs substrates under same condition and each DEs has $\sim$0.2 mm roughness thickness, tested by the XP-1 Stylus Profilometer (Ambios technology). At last, one PDMS DEs was treated by O$_2$ plasma (15 W, 3 min) while the other one was not treated by O$_2$ plasma as shown in figures 1(b), (c).

3. Characterization of DEs substrate

The DEs are characterized by different tests. Firstly, both DEs roughness are examined by atomic force microscopy (AFM) as illustrated in figures 2(a), (b).

The DEs surface roughness is attained hardly and the castoff DEs are based on scattering theory. In scattering, the incident light signal is amplified through localized surface. The root mean square surface roughness ($R_q$) values and 3D view of both DEs with and without plasma treatment are illustrated in figures 2(a), (b). The plasma treatment DEs condensed the surface roughness. Since the surface roughness of the film has
same variation tendency as that of original substrate [19]. Absolutely, the roughness condensed with plasma treatment up to some maximum value and then again induces with further increasing (i.e. post processing or treatment). For more clarifications, DEs structure is also observed by white light interferometer. The $R_q$ values are illustrated in figures 2(c), (d). The same variation tendency by AFM measurement also observed in figures 2(a), (b).

Furthermore, by changing the illumination wavelength of light on DEs its resonance wavelength is tuned, causes a shift in electric field density on roughened DEs surface. This leads to frequency change in DEs, because of the PDMS Si–O backbone and generates different cross-sections for optical properties including absorption and scattering. In this attempt, the resonance wavelength was tuned for transmission and reflection on both physical DEs. By altering the illuminated input light wavelength on DEs surface, the output differs. Figures 3(a)–(c) shows the calculated spectral response of transmittance, reflectance and absorption. Firstly, the transmittance comparison of master rough and plain glass with replica DEs as a reference is shown in figure 3(a). The graph shows that the master rough glass has better transmittance than the plain glass. Besides, both PDMS DEs have glowing transmittance about 85%–95%. This comparison enables PDMS to be chosen as a substrate for DEs. Furthermore, due to the roughness, both DEs refractive index differs and the resonances dips occur at different wavelengths.

Secondly, the reflectance comparison of master rough and plain glass with replica DEs as a reference is shown in figure 3(b). Both master glasses have better reflectance than PDMS DEs. Besides, PDMS DEs have high
and low resonance dips in color spectrum range, which means reflective index and material properties changed and have much influence in color spectrum range, the DE without treatment has more impact on these properties. These characteristics lead us to consider both DEs substrate in practice. Thirdly, the absorption of both DEs with master rough glass substrate are shown in figure 3(c). On the plain and rough glass substrate, a tiny peak was observed at 840 nm range. On the contrary, the PDMS DEs 300–1800 nm have shown high and low peaks. Moreover, the Raman spectra before and after plasma are observed by JPK as shown in figure 3(d), the DEs have peaks on same range with and without treatment. The first and highest peak observed at 450 nm, second at 650 nm, third at 600 nm and two small peaks also observed at 1250 nm and 1410 nm. In comparison, after plasma treatment notable reduction in peaks are observed, significantly the signal intensities are improved without plasma treatment, caused by dielectric plasma enhancement and PDMS Si–O backbone.

Finally, the DEs electronic field distribution properties, evaluated by the commercial FDTD software, are illustrated in figures 4(a), (b). In design, 480 nm laser vertically used along the y-axis polarization direction to the xy-plane of the DEs. Due to the decrement in electric field intensity, both DEs electric field distribution shifted and after plasma treatment the DEs roughness had minor reduction. Consequently, the dispersal homogeneity of the Si–O ions density immersed towards degradation. The enhancement electromagnetic theory reveals that the surface roughness increment induces because of the occurrence of high-density hot spots. The simulation has good match towards experimentation results. Moreover, the substrates roughness and reflective index (K and N) values changed, which leads to the proposed dielectric roughness dependence of optical DEs.

4. DEs fabrication concept

The major part of our DEs depends on optical constant as renowned as N and K values. The N is the reflective index of the material and K is the material roughness. The optical properties such as the resonance wavelength, peak reflection efficiency and resonant linewidth among rough surface DEs are deeply depend on the typical refractive index of materials which is a function of the wavelength. Hereby, we use it to fabricate the dielectric roughness dependence of optical DEs, based on nano-roughness arrays of dielectric PDMS, giving to polysiloxanes or silicones are commonly known as semi-inorganic polymers, composed of a siloxane (Si–O) backbone and carry two organic hydrocarbon substituents. The well-known and important polysiloxane is
polydimethylsiloxane (PDMS), in which organic substituents are methyl groups [12]. The arrays of PDMS are tailored to interact with light at visible range of frequencies through excitation of the localized rough surface scattering. This phenomenon records the polarization state of illuminated light for visible spectrum. Likewise, it also changes unpolarized light (white light) to chromatically polarized light. Based on this colored physics, we fabricate the DEs.

4.1. Characterization of \( N \) and \( K \) values

The ellipsometer is used to calculate the \( N \) and \( K \) values of the DEs as illustrated in figure 5. The color pixels with wavelength range of 190–900 nm are considered and measured. The 190–212 nm device exhibits dark blue color and light blue color, 213–249 nm device exhibits dark green color and light green color, 250–290 nm device exhibits yellow color, 291–400 nm device exhibits brown color, and 400–900 nm device generates red color. Moreover, on plasma treated DE, small variation is observed through \( n \) and \( k \) values as shown in figures 5(a), (b). The pixels’ spectral bandwidth is approximately 10 nm and have \( \sim 94\% \) transmission efficiencies and \( 10\% \) reflectance polarization efficiencies.
4.2. Optical setup for transmission and reflection by stretching technique

For centuries, the nanoparticles of metal had been used for color pattern on a glass and viewed in both reflection and transmission mode,[33], in which the color effect results come from absorption and strong scattering of light through metal nanoparticles by reason of a resonant collaboration of EM light field at visible frequencies. In contrast, the practice rough surface promotes enhancement in EM field due to the existence of Si–O ions. The practice DEs strong scattering effect of light are easily judged from figure 3. Furthermore, the DEs are operated under the normal white light illumination with a linear polarization are illustrated in figure 6. The input white light is passed through glowing PDMS DEs and detected on the CCD (AKITA Digital color CCD Camera, Model: AK-311C). The photos of the transmission domain on several wavelengths are shown in figure 5(c). The differences between both DEs on CCD are hard to realize, almost same results are obtained, though N and K values. Although, negligible difference is observed as shown in figures 5(a), (b).

At last, the DEs transmission and reflection are characterized by stretching the PDMS along the natural lines direction, which inspected before stretching via AFM. Next, the handmade device is used for stretching. After the stretching, the groove period appears on 10% stretching afterwards no any grooves appear due to the same material roughness. Further stretching leads to PDMS roughness to non-periodic stretches. The reasonable stretching takes the rough surface PDMS DEs towards periodic diffraction grating. The optical scattering test tools, involving tunable laser, beam splitter, receiving screen and CCD camera. All mentioned tools set vertically and the elements had same distance (3 cm) from each other. The 400 nm white light was vertically incident to the BS, figure 6(a) shows the reflection scattering pattern of DE without plasma treatment and the figure 6(c) is the reflection photograph, figure 6(d) is the transmission photographs after 10% stretching and figure 6(e) is the AFM grating image and its periodic structure. The figure 6(b) shows the reflection scattering pattern of DEs with plasma treatment and the figure 6(f) is the reflection photograph, figure 6(g) is the transmission photographs after 10% stretching, figure 6(h) is the AFM grating image and its periodic structure. The stretching percentage with respect to original length is a good grounding to categorize the Pixels of DEs.
5. Conclusion

The DEs AFM and white light profiling tests show reduction onto the plasma treated DEs surface, which proves the phenomena of enhancement. The transmittance, reflectance, absorption and Raman spectra give favorable practical result towards DEs which is further proved through the FDTD simulation. This comparison enables PDMS to be chosen as a substrate for DEs. The ellipsometer results enable the DEs to be used in practical applications as a color pixel DEs within the range of 190–900 nm with glowing transmittance. Furthermore, when the stretchable technology is applied on DEs it takes them toward the diffraction grating, which have potential applications in optical measurement devices, imaging, encoding/decoding, glowing color displays and energy storage applications.

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