Dynamic Fringe Pattern Generation Using an Electrically Tunable Liquid Crystal Fabry-Perot Cell for a Miniaturized Optical 3-D Surface Scanning Profilometer

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We demonstrated a dynamic fringe pattern generation method by using an electrically tunable liquid crystal (LC) Fabry-Perot (FP) cell. In our LC-FP cell, the multiple interferences within the cavity produce concentric ring-type patterns projected on a flat surface because the resonant mode conditions determined by the optical path lengths are circularly symmetric to the slightly diverging single input beam. The projected fringe patterns can be continuously varied with increasing the diameters of the interference rings since the resonant mode conditions can be electrically controlled by changing the effective refractive index of the LC layer. The resonant mode analysis shows that the real surface profiles can be obtained by comparing the amount of distortions of the projected fringe patterns. Our dynamic fringe pattern generation properties, achieved by using single input beam and single LC-FP cell, can be used for miniaturizing optical 3-D surface scanning profilometers.

Keywords Fabry-Perot; interference pattern; liquid crystal; optical surface profilometer; resonant mode

Introduction

A 3D surface profilometer is a device for extracting an accurate depth profile from an object surface, which is used for an industrial inspection and a medical diagnosis. The surface profile can be obtained by using the direct contact measurement methods such as an atomic force microscopy and a scanning tunneling microscopy.

The contact measurement methods show high precision in depth profile but their measurement speeds are too slow which should scan a surface with a moving tip in a

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point. In addition, the contact methods are not suitable for the bio-medical imaging to living organs or tissues, which can induce damages on the object during measurement.

As for the non-contact method for measuring surface profiles, there are optical 3D surface profilometers which measure 3D shapes of a reflective object by analyzing distortions of the projected fringe patterns. The optical methods can measure the surface profile of a soft material surface in a nondestructive manner with a relatively faster measuring speed by analyzing depth profiles from a whole optical pattern. In constructing optical surface profilometers, an optical instrument for generating and projecting fringe patterns on an object is a key optical component. Analyzing schemes are different depending on generation methods of the fringe patterns and origins of the fringe distortions. In interferometric methods [1], sinusoidal fringe pattern from two-beam coupling is used. In this case, there exists phase ambiguity in analyzing the surface map when depth difference of an object surface in physical length is higher than phase difference of 2π. To reduce the phase ambiguity of the surface map from the distortions of the projected fringes, several sets of fringe patterns are required which can be generated by phase-shifting techniques [2,3] using spatial light modulators. In digital fringe projection methods [4], surface map is reconstructed by analyzing multiple sets of fringe patterns distorted by a surface profile. Therefore, digital projector or a liquid crystal display (LCD) panel [4,5] is also required to get sufficient information from the distorted patterns. However, the conventional fringe pattern generators for optical 3D surface profilometers were too bulky and too expensive to implement a miniaturized 3D surface profilometer for hand-held type medical applications [5].

In this paper, we show that multiple sets of concentric ring-type fringe patterns can be obtained by using single LC Fabry-Perot (FP) cell, where the fringe patterns were generated by multiple interferences from a slightly diverging single input beam. Recently, there have been so many reports on electrically wavelength-tunable LC-FP cells [6–12]. However, the functions and their analysis were only focused on the wavelength tuning properties using normally incident broadband light source, where the applications were limited on tunable filters especially for optical communications. In those cases, the resonant mode analysis and their polarization dependence were fully described. Whereas, there have been no report on the analysis of the resonant mode and the dynamic fringe patterns when the diverging beam is incident on an electrically tunable LC-FP cell. In this paper, we demonstrated the resonant mode analysis in an LC-FP cell depending on the ray directions relative to the optic axis of the active LC layer by modifying the fringe pattern analysis in a conventional FP cell [13]. In our LC-FP cell, the projected fringe patterns can be continuously varied with increasing the diameters of the interference rings since the resonant mode conditions can be electrically controlled by changing the effective refractive index of the LC layer between the cavity mirrors. The resonant mode analysis shows that the real surface profile can be obtained by comparing the amount of distortions of the fringe patterns with the designed fringe patterns from the analytical model. The surface profilometer can be simply miniaturized because the dynamic fringe patterns are constructed only by single beam and single cell structure in our approach. Especially, it is expected that our optical surface profilometer system can be widely applied in environmental and bio-medical areas because it can do fast measurement by using electro-optic effect of LC without any damage on a measuring surface.

Device Schemes

Figures 1(a) and (b) show the structure of the fabricated LC-FP device and the generated fringe patterns on a flat surface at a normal incident condition by using the proposed LC-FP cell, respectively. The one substrate of the LC-FP cell had stacked layers with ITO glass, dielectric mirror layer, and homeotropic LC alignment layer. The other substrate was stacked with homeotropic LC layer, ITO glass, and dielectric mirror layer. The LC alignment layers were mechanically rubbed with anti-parallel directions. Between the LC alignment layers, a nematic LC (NLC) with a negative dielectric anisotropy was filled to the NLC-FP cell, where the refractive indexes were $n_0 = 1.4747$ and $n_e = 1.5571$.

Thus, the NLC-FP cavity was formed by the electrically tunable NLC layer (d_{lc}) and the thick glass layer (d_g) between the dielectric mirrors. The total thickness of the FP cavity gives as follows: $d = d_{lc} + d_g$. When the gap within the cavity is too small, the resolution of surface profilometer is very poor due to the wide distance between fringe patterns. However, we cannot increase the cavity gap sufficiently with only the NLC layer considering the stability of the LC alignment and the response time of the NLC layer. Therefore, the cavity gap was increased by the glass layer in our structure. We fabricated the two types of the NLC-FP cells with different LC layer thickness of 6 μm and 15 μm. In both samples, the thickness of the glass layer within the FP cavity was 700 μm. The reflectance of the dielectric mirrors were 50% and

(a)

(b)
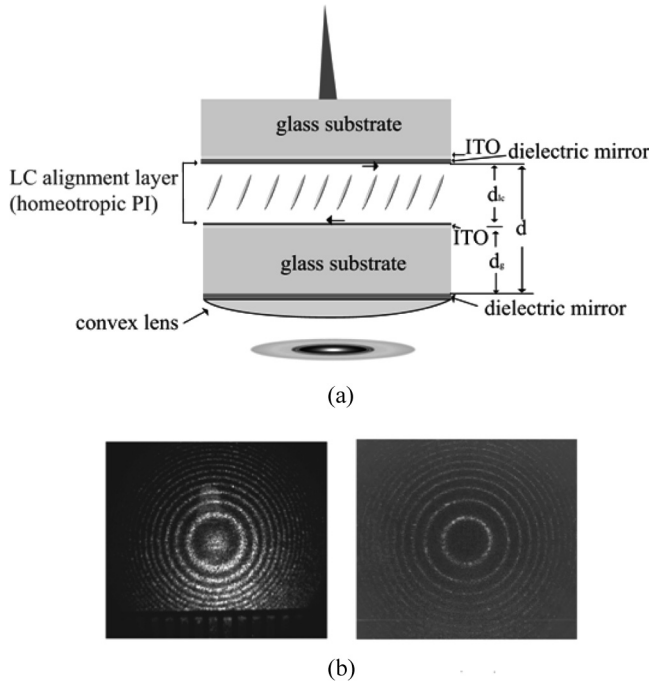
Figure 1. (a) The schematic diagram of the proposed NLC-FP cell, and (b) the projected fringe patterns on a flat surface at a normal incident condition, which is observed without an applied voltage to the LC-FP cell. The left and right images are the projected fringe patterns obtained with the cell conditions of the lower mirror reflectance (50%) and the lower LC cell gap ($d_{lc} = 6$ μm), and the higher mirror reflectance (95%) and the higher LC cell gap ($d_{lc} = 15$ μm), respectively.

95% in two samples of the LC layer thickness of 6 μm and 15 μm, respectively. The line width of fringe patterns should be sharp to obtain precise 3D surface map in measuring surface profiles with optical scanning methods. As shown in Figure 1(b), a higher reflectance mirror is suitable in our system.

When we irradiate a polarized diverging beam to the NLC-FP cell without an applied voltage, the LC-FP cell with vertically aligned NLC geometry produces nonperiodic concentric circular interference patterns because the resonant mode conditions determined by the optical path lengths are circularly symmetric to the slightly diverging single input beam as shown in Figure 1(b). When we apply voltages to the NLC-FP cell, optical paths of extraordinary rays are changed due to dielectric anisotropy of the NLC, whereas optical paths of ordinary rays are not changed. Thus, the incident beam should be linearly polarized parallel to the rubbing direction of the LC alignment layer to control the resonant conditions. The phase delay, δ of the LC-FP cavity is expressed as follows in our NLC-FP cell [13,14].

$$\delta = 4\pi d_{lc} n_{eff} \cos \phi_{lc} + 4\pi d_g n_g \cos \phi_g \tag{1}$$

$$\left(\frac{1}{n_{eff}}\right)^2 = \frac{\cos^2(\theta_{lc} - \phi_{lc})}{n_0^2} + \frac{\sin^2(\theta_{lc} - \phi_{lc})}{n_e^2} \tag{2}$$

where n_{eff} and n_g are the effective refractive index of the LC layer and the refractive index of the ITO glass layer, respectively. ϕ_{lc} is the incident angle to the normal direction on the reflective mirror surface adjacent to the LC layer. ϕ_g is the incident angle to the normal direction on the reflective mirror surface adjacent to the glass layer in the bottom substrate as shown in Figure 1(a). θ_{lc} is the tilting angle of the LC director to the substrate. Here, θ_{lc} and n_{eff} are the voltage-dependent parameters.

Figure 2 shows the dynamic fringe patterns observed by varying applied voltages where the image plane was flat and parallel to the LC-FP cell as shown in Figure 1(a). Figure 2(a) was obtained at the NLC-FP cell which was made by the lower reflectance mirror (50% reflectance) and lower LC cell gap of ($d_{lc} = 6$ μm). Figure 2(b) was the projected image of the cell using 95% reflectance mirror and the 15 μm LC cell gap. In the field-on state, the LC is tilted along the rubbing direction.

Therefore, there is small difference in both ϕ_{lc} and ϕ_g depending on the propagation direction of the incident light. However, the diverging angle of the incident beam is so small ($<0.2°$) that the projected fringe patterns show circularly ring patterns in the whole driving voltages. Actually, the fringe patterns shown in Figure 2 were obtained by the rays within the diverging angle of $0.001°$ among the incident diverging beam in our experimental condition, which was obtained by the ray tracing method. The multiple reflections of the rays within the cavity are another reason for the circularly symmetric fringe pattern in our NLC-FP system.

Due to variation of the effective refractive index of the LC layer, the projected fringe patterns are dynamically moving outward from the center of the projection by increasing applied voltages to the NLC-FP cell. In our vertically aligned LC geometry, the radius, R_p, of the fringe ring at each resonant order is increased due to the increased optical path within the cavity. Here, p denotes the order of the bright fringe rings from the center of the projected patterns [13]. When we compare the projected images from two NLC-FP cells, the variations of the ring diameters in
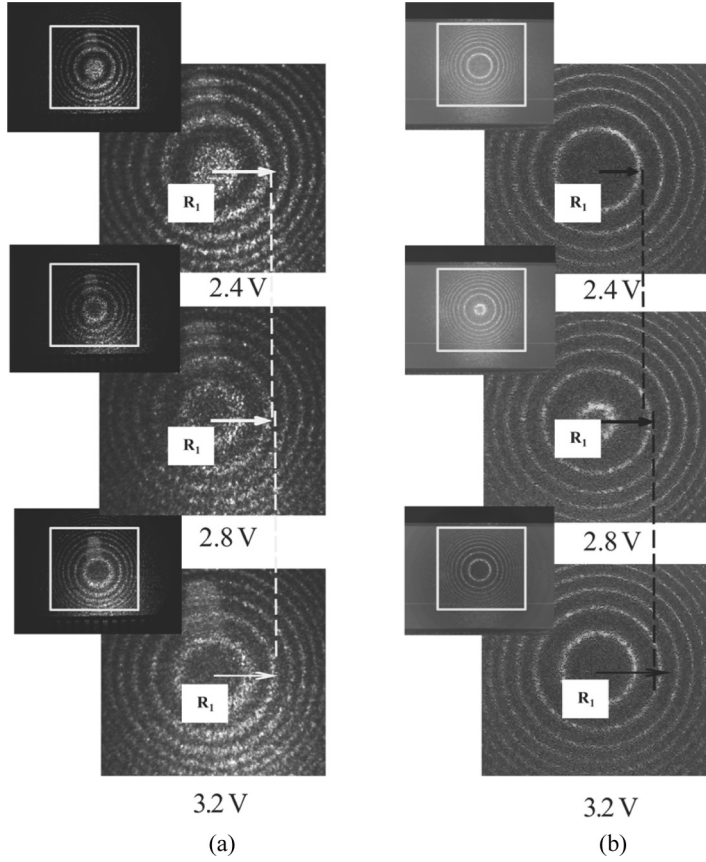
Figure 2. The dynamic fringe patterns measured by varying applied voltages where the image plane was flat and parallel to the LC-FP cell as shown in Figure 1(a). The images of (a) and (b) are obtained by using the LC-FP cells with the same cell conditions used in obtaining the left and right images of Figure 1(b), respectively.

the same variation of an applied voltage were larger in the cell with $d_{lc} = 15\,\mu m$ because we can obtain larger variation of the effective refractive index of the LC layer at the same voltage condition as the thickness of the LC layer becomes larger. The fact that the field-induced tilting angle of the LC layer can be sufficiently small in the whole driving voltages for scanning is an another merit suitable for getting circularly symmetric ring patterns irrespective of applied voltages. Hereafter, the experimental results were ones obtained with the NLC-FP cell made by the thicker cavity ($d_{lc} = 15\,\mu m$) and the higher reflective mirror (95%).

Measurement Principle and Experimental Results

In our surface scanning method, the real surface map is obtained by analyzing the distortions from the ideal ring fringe patterns which can be obtained in a flat surface as shown in Figure 2. The derived ideal ring fringe patterns are used as the reference fringe patterns in analyzing the surface profile and we should know the reference fringe patterns from the resonant mode analysis.

In our NLC-FP cell, the resonant mode equation at the center can be expressed as

$$2d_{lc}n_{eff}(v) + 2d_g n_g \pm \frac{\lambda}{2} = (m_1 + e)\lambda + 2d_{lc}\Delta n_{eff} \tag{3}$$

where m_1, e $(0 < e < 1)$, and λ are the resonant mode number of the innermost bright fringe ring, the fractional order at the center, and the wavelength of the incident light $(\lambda = 632.8\,\text{nm})$ [13].

For the pth bright fringe ring by the slightly diverging rays, the resonant mode condition of Eq. (3) can be modified as follows,

$$2d_{lc}(n_{eff}(v)\cos\phi_{lc}) + 2d_g n_g \cos\phi_g \pm \frac{\lambda}{2}$$
$$= m_p\lambda = [m_1 - (p-1)]\lambda, \;\; (p\!:\! 1, 2, 3, \ldots) \tag{4}$$

where m_p is the resonant mode order of the pth bright fringe ring. Hence, we can express the resonant condition of the pth bright fringe ring in a form that the resonant mode number is removed from Eqs. (3) and (4) as follows,

$$2d_{lc}n_{eff}(v)\frac{\phi_{lc}^2}{2} + 2d_g n_g \frac{\phi_g^2}{2} = (p - 1 + e)\lambda + 2d_{lc}\Delta n_{eff} \tag{5}$$

By using the Snell's law and the lens equation, ϕ_p and D_p of the pth bright fringe ring is obtained as follows,

$$\phi_p^2 = \frac{n_{eff}(v)n_g[(p - 1 + e)\lambda + (2d_{lc}\Delta n_{eff})]}{(n_g d_{lc} + n_{eff}(v)d_g)} \tag{6}$$

$$D_p^2 = (2f\phi_p)^2 = 4f^2 \frac{n_{eff}(v)n_g[(p - 1 + e)\lambda + (2d_{lc}\Delta n_{eff})]}{(n_g d_{lc} + n_{eff}(v)d_g)} \tag{7}$$

where ϕ_p is the angle between the normal incident ray and the ray constructing the pth bright fringe ring as shown in Figure 3. D_p is the diameter of the pth bright fringe ring. f is the focal length of the lens. As a result, the real surface profile can be obtained as follows,

$$h = \Delta R_p \times \cot\left(\frac{R_{p,reference}}{f}\right) \tag{8}$$

$$\Delta R_p = (R_{p,reference} - R_{p,measure}) \tag{9}$$

where $R_{p,reference}$ and $R_{p,\text{measure}}$ are the radius of the pth bright fringe ring of the reference fringe patterns and the measured fringe patterns, respectively. h is the calculated surface depth measured at the pth bright fringe ring from the difference of $R_{p,reference}$ and $R_{p,\text{measure}}$.

Figure 4 shows R_p as a function of the effective refractive index of the NLC layer where the filled circle and the line denote the measured results and the simulation
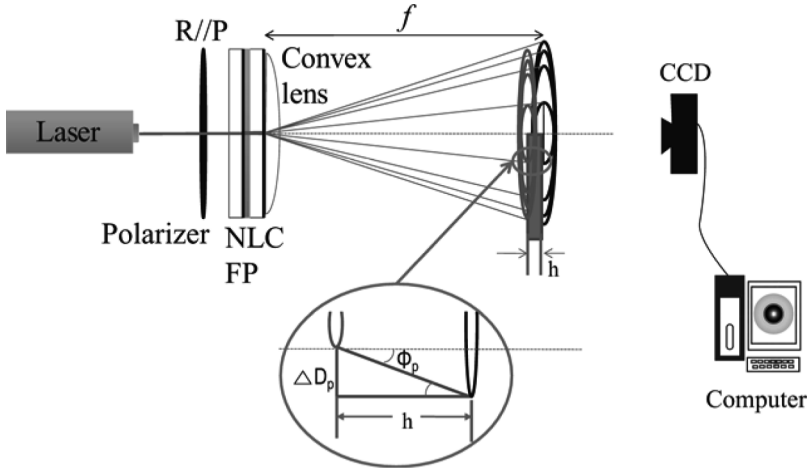
Figure 3. Schematic diagram showing the real surface profile measurement from the projected dynamic fringe patterns using our NLC-FP cell.

results from Eq. (7), respectively. In our measurement of R_p's from the projected images, the average values from the radius values with the half-maximum intensity at each fringe peak were used. In the experimental results of Figures 4 and 5, the bar and the dot symbols represent the radius values with the half-maximum intensity at each peak and R_p's from the average value, respectively.

Because the effective refractive index increases as an applied voltage increases, D_p also continuously increases as derived in Eq. (7) until a new innermost bright

Figure 4. Plot of R_p as a function of the effective refractive index of the NLC layer where the dot and the line denote the measured results and the simulation results from Eq. (7), respectively.
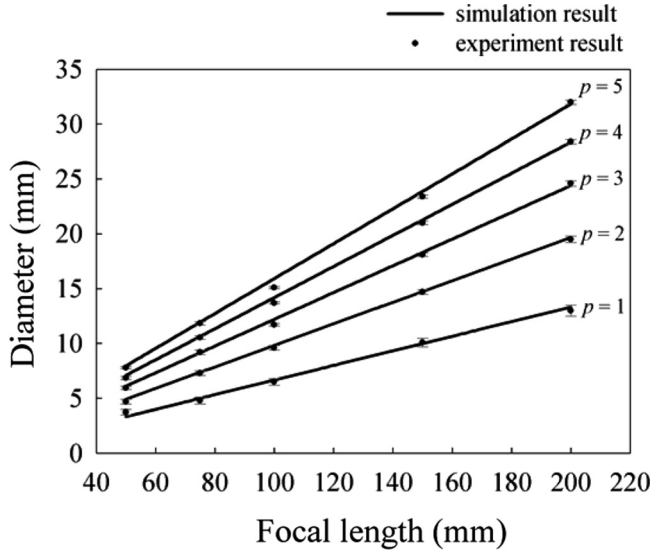
Figure 5. Plot of diameter of the *p*th fringe patterns versus the focal length of the convex lens used for projection of the fringe patterns where the filled circle and the line denote the measured results and the simulation results from Eq. (7), respectively.
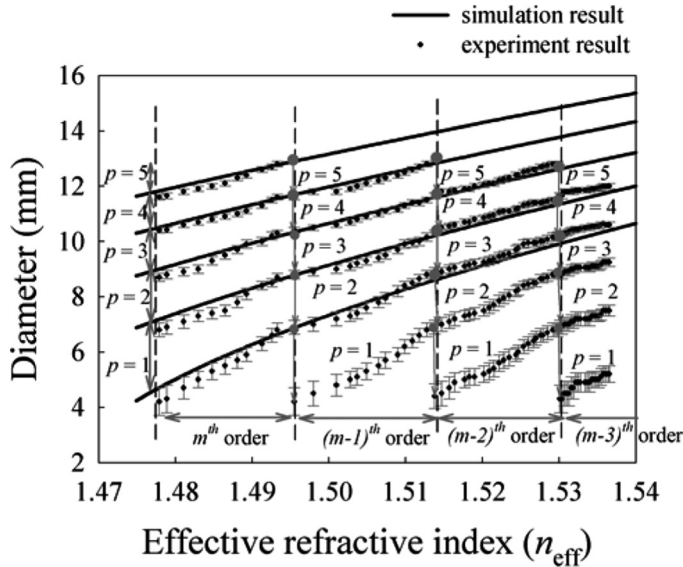
fringe ring is generated. Figure 4 shows small amount of the effective refractive index variation is required to scan the whole area with moving fringes. In our sample, the required effective refractive index was about 0.02, which can be obtained with small bias tilting angles of LC molecules. The simulated results using Eq. (7) match well with the measured results, which show we can construct multiple sets of the reference fringe patterns theoretically with a high precision. In obtaining the experimental and simulation results of Figure 4, the focal length of the used convex lens was 75 mm. The fractional order at the center, *e* was 0.625 in calculation.

Figure 5 shows D_p variation as a function of focal lengths of lens used for projection of the fringe patterns where the filled circles and the lines denote the measured results and the simulation results from Eq. (7), respectively. The focal length of a convex lens can control the projection area for measuring. At a given line width of fringe patterns, the sampling number through the scanning is also determined by the focal length of the convex length.

We can reconstruct a real surface profile from sets of the fringe pattern distortions by using Eqs. (8) and (9) as shown in Figure 6. Figure 6(a) shows the object surface profile used in our experiment. Figures 6(b) and (c) show the distorted fringe patterns projected on the object shown in Figure 6(a) at applied voltage conditions of 0 V and 2.8 V, respectively. Figure 6(b) shows that the radius of the first bright ring pattern is distorted in the projected region with the depth difference by 1 mm. The second bright ring is distorted also in the projected region with the same depth difference. When we consider the reference plane as the lowest surface shown in Figure 6(a), the fringe patterns in the left part of Figure 6(b), with undistorted ring shape, can be the reference fringe patterns at analyzing depth profile in each *p*th order projection pattern. When we extracted the depth information along the distorted first ring pattern, the first depth, *h* of the object was 0.9998 mm from
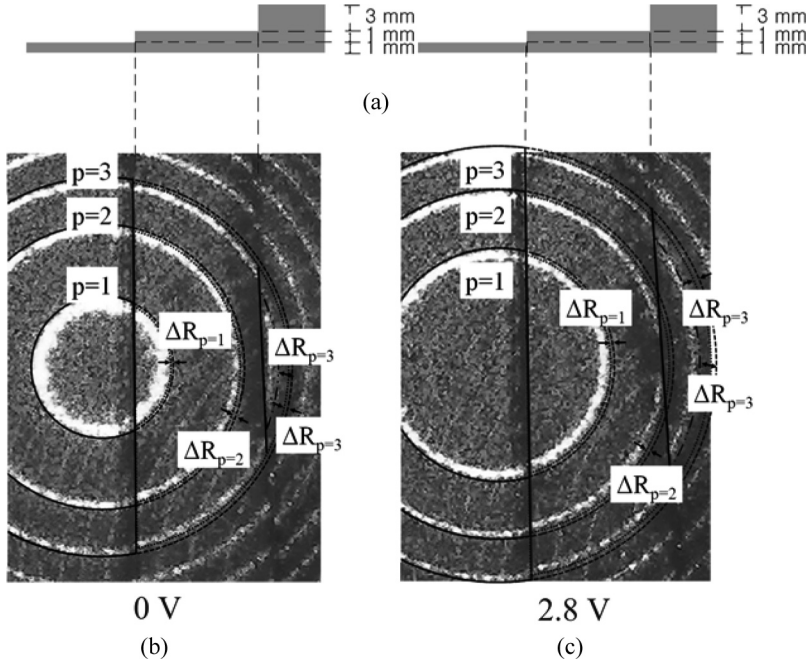
Figure 6. (a) The real surface profile of the object used in our experiment. (b) and (c) are the distorted fringe patterns projected on the object at applied voltage conditions of 0 V and 2.8 V, respectively.

Eqs. (8) and (9) by using the radius of the reference ring, $R_1 = 2.2$ mm and the distortion amount of the radius, $\Delta R_1 = 0.02$ mm. When the same depth was obtained along the line of the second ring pattern, the measured values were $R_2 = 4.15$ mm and $\Delta R_2 = 0.05$ mm. Thus, the extracted depth was 1.2 mm. In case of $p = 3$, the distortions of R_3 was appeared twice with the depth differences from the reference plane by 1 mm and 4 mm. When we measured the 1 mm depth along the third fringe ring, the extracted depth was 1.0998 from the values of $R_3 = 6.26$ mm and $\Delta R_3 = 0.06$ mm. We could get the depth of 4 mm also with the distortion of the third ring pattern where the calculated depth was 4.03 mm from $\Delta R_3 = 0.22$ mm. The extracted depth values matched well with the real surface profile. To obtain the observing whole area, sets of distorted patterns can be used as shown in Figure 6(c).

Conclusions

We demonstrated the optical surface scanning profilometer by using an electrically tunable LC-FP cell. The LC-FP cell can generate multiple sets of circularly symmetric fringe ring patterns as reference patterns within relatively low driving voltages by using the electrically controllable effective refractive index of the LC layer in extraordinary rays. The resonant mode analysis shows that the real surface profile can be obtained by analyzing the amount of distortions of the projected fringe patterns. We expect our 3-D optical surface profilometer device and our scanning method would be a useful tool for miniaturized medical imaging applications such as 3D tooth-form scanning systems [4,5].

Acknowledgments

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