ITE Trans. on MTA Vol. 12, No. 4, pp. 211-217 (2024)

Paper

配向性高分子を用いた高品位な焦点可変液晶レンズの作製

大畑拓夢、石鍋隆宏（正会員）、中谷誠和、藤掛英夫（フェロー）

要旨液晶と液晶ポリマーから作製したフレネルレンズからなるアジャスタブルフォーカスレンズを提案する。垂直配向した液晶ポリマーを用い、インプリンティング法によりフレネルレンズを作製し、フレネルレンズ上に均一な垂直配向液晶を実現した。その結果、フレネルレンズの表面構造に起因する光散乱を示さない、高品質で調整可能な焦点の液晶レンズが実現できることが実証された。

キーワード：焦点可変レンズ、液晶レンズ、フレネルレンズ、配向性高分子、インプリント工程

1. Introduction

世界の人口は高齢化している。潜在的な対策は、年齢に関係なくすべての人が積極的な役割を果たすことができる、年齢のない社会の実現である。このような社会を実現する上で重要な課題のひとつは、科学技術を通じて高齢者を支援することであり[1]、自然な視野を提供する二焦点メガネの開発がますます重要になってきている。二重焦点メガネの焦点距離はレンズの位置によって変化するため、このようなメガネは、装着者が視線方向を移動させることで、近傍と遠方の両方の物体に集中することを可能にする。しかし、視野の全範囲で自然な視覚を得ることは困難であるという問題が生じる。したがって、焦点距離を制御できる調整可能な焦点の単レンズの開発が望まれる。

この問題に対処するため、研究者は、液晶とフレネルレンズからなる液晶レンズが単純な構造[8－10]であるという利点を持つ、調整可能な焦点の液晶レンズ[2－7]を提案している。電圧が印加されていない場合、液晶とフレネルレンズの屈折率は等しくなるように設計され、光はフレネルレンズによって集光されず、直進する方向に伝送される。その結果、光はガラスレンズに屈折し、遠くの物体に集光される。しかし、電圧を印加すると液晶のアライメントが変化し、液晶とフレネルレンズの間に屈折率の差が生じる。その結果、フレネルレンズによって近傍の物体に光が集光される。このようにして、レンズの焦点距離は液晶フレネルレンズの組み合わせと屈折率の制御によって制御される。しかし、この構造では、フレネルレンズ表面の凹凸構造により、液晶配列の均一性が低下し、光散乱によりレンズの透過率が低下する。

以上の考察を踏まえ、本研究の目的は、フレネルレンズ表面における液晶分子の配向を均一に制御することにより、光散乱を抑制した高品質なアジャスタブルフォーカス液晶レンズを実現することである。

2. 液晶ポリマーを用いたフレネルレンズ

図 1 に従来の液晶レンズにおける光散乱のメカニズムを示す。一般に、液晶分子の配向方向を制御するために、フレネルレンズの表面に配向膜をコーティングする(図1(a))。液晶はレンズの形状に沿って配向しているため、液晶分子の配列はレンズ表面の凹凸部分で不均一であり、その結果、光散乱が発生する。この問題を解決するためには、レンズの形状に関係なく液晶の配列を均一に制御する方法が必要である。

Received March 22, 2024; Revised May 11, 2024; Accepted June 3, 2024
† Department of Electronics, Graduate School of Engineering, Tohoku University
(Sendai, Japan)
†† Department of Management Science and Technology, Graduate School of Engineering, Tohoku University
(Sendai, Japan)

Paper

Fabrication of High-Quality Adjustable Liquid-Crystal Lens Using Liquid-Crystalline Polymer

Takumu Ohata†, Takahiro Ishinabe†† (member), Masakazu Nakatani† and Hideo Fujikake † (fellow)

Abstract We propose an adjustable-focus lens composed of a liquid crystal and a Fresnel lens fabricated from a liquid-crystalline polymer. Using vertically aligned liquid-crystalline polymers and fabricating Fresnel lenses by the imprinting method, we achieved uniform, vertically aligned liquid crystals on a Fresnel lens. The results demonstrate that a high-quality, adjustable-focus liquid-crystal lens that does not exhibit light scattering caused by the surface structure of the Fresnel lens can be realized.

Keywords: Adjustable-focus lens, Liquid crystal lens, Fresnel lens, Liquid-crystalline polymer, Imprinting process.

1. Introduction

The world's population is aging. A potential countermeasure is the realization of an ageless society in which all people, regardless of age, can play an active role. One of the important issues in realizing such a society is to support the elderly through science and technology [1)], and the development of bifocal glasses that provide a natural field of vision is becoming increasingly important. Because the focal length of bifocal glasses changes depending on the position of the lens, such glasses allow the wearer to focus on both near and far objects by shifting their direction of sight. However, a problem arises in that achieving natural vision in the entire range of the visual field is difficult. Therefore, the development of an adjustable-focus single lens whose focal length can be controlled is desirable.

To address this issue, researchers have proposed adjustable-focus liquid-crystal lenses [2-7)] among which the liquid crystal lenses consisting of a liquid crystal and a Fresnel lens have the advantage of simple structure [8-10)]. In the absence of an applied voltage, the refractive indices of the liquid crystal and Fresnel lens are designed to be equal, light is not focused by the Fresnel lens and is transmitted straight ahead. As a result, light is refracted by the glass lens and focused on a distant object. However, when a voltage is applied, the alignment of the liquid crystal changes, and a difference in refractive index is generated between the liquid crystal and the Fresnel lens. As a result, light is focused by the Fresnel lens onto a nearby object. In this way, the focal length of the lens is controlled by the liquid crystal Fresnel lens combination and by control of the refractive index. However, in this structure, the uneven structure of the Fresnel lens surface reduces the uniformity of the liquid crystal alignment, which results in a decrease in the transmittance of the lens because of light scattering.

Considering the above discussion, the objective of the present study was to realize a high-quality adjustable-focus liquid crystal lens with suppressed light scattering by uniformly controlling the alignment of the liquid crystal molecules on the surface of the Fresnel lens.

2. Fresnel lenses using liquid-crystalline polymers

Figure 1 shows the mechanism of light scattering in conventional liquid-crystal lenses. In general, an alignment film is coated onto the surface of a Fresnel lens to control the alignment direction of the liquid-crystal molecules (Fig. 1(a)). Because the liquid crystal is oriented along the shape of the lens, the alignment of the liquid-crystal molecules is nonuniform in the uneven areas of the lens surface, resulting in light scattering. To solve this problem, a method to uniformly control the liquid crystal alignment irrespective of the shape of the lens is needed.

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† Department of Electronics, Graduate School of Engineering, Tohoku University
(Sendai, Japan)
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(Sendai, Japan)

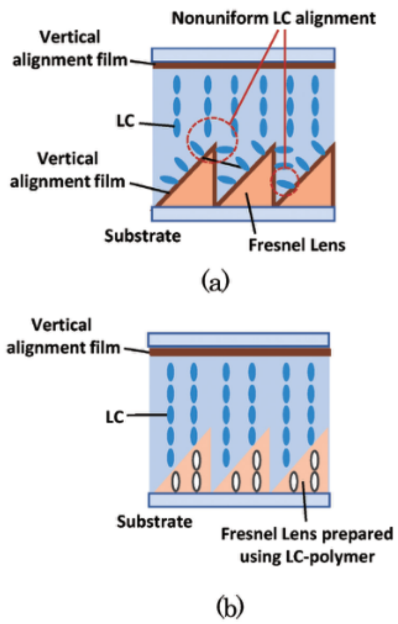


図1 フレネルレンズ表面における液晶のアライメント制御((a)アライメントフィルム、(b)LC-ポリマー使用)。

ここでは、液晶性ポリマーをベースとしたフレネルレンズを提案する(図1(b))[11-14]。垂直配向した液晶ポリマーを用いてフレネルレンズを作製することにより、配向膜を用いることなく液晶ポリマーの配向方向に液晶分子を均一に配向させることができる。その結果、液晶-フレネルレンズ界面での光散乱を抑制することができる。

3. 液晶ポリマーを用いたフレネルレンズの作製

3.1. 液晶性ポリマーフィルムの表面形状制御

液晶ポリマーを用いたフレネルレンズの作製方法を図2に示す。まず、フレネルレンズ(日本徳州工業技研、CF30-0.05、レンズピッチ:50μm)の表面にポリジメチルシロキサン(PDMS、ダウコーニング東レ)をコーティングした。ガラス基板を積層した後、フレネルレンズの型を80°Cで60分間加熱した。その後、CYTOP(CTL-809A、AGC)を型表面に塗布して型放出を改善し、型を200° Cで60分間加熱した(図2(a))。溶媒(プロピレングリコールメチルエーテルアセテート(PGMEA):10wt%)の添加により粘度が最適化された液晶モノマー材料(UCL-011-AC1、DIC)を、その後金型表面に塗布し(図2(b))、真空延伸によりレンズの溝に延伸した(図2(c))。

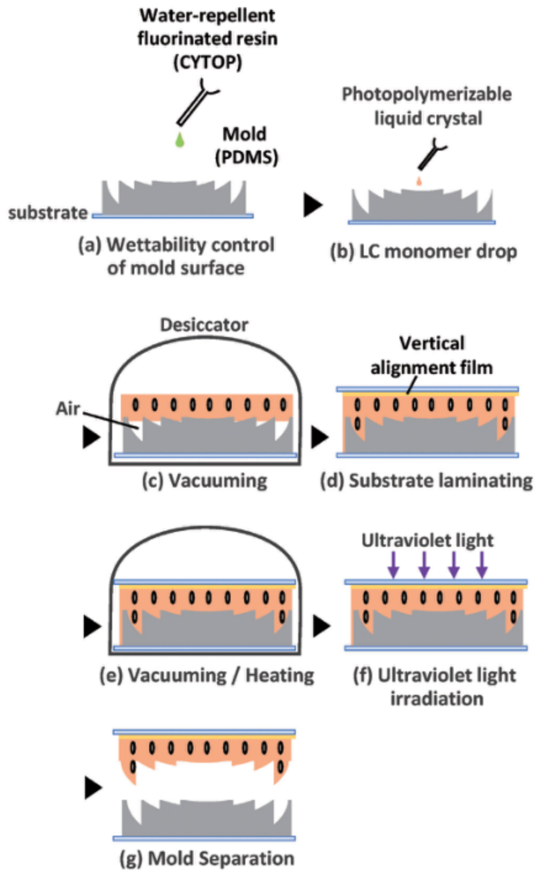


図2 液晶モノマーを用いたインプリント加工によるフレネルレンズの作製方法。

2(d))、再び真空を適用して気泡を除去した(図2(e))。集合体に紫外線(40 mW/cm2、60秒)を照射し、モノマーを光重合させた(図2(f))。フレネルレンズは、基板を剥離して得た(図2(g))15-18)。.

3.2. 液晶分子の配向制御

次に、垂直配向フィルム(SE-4811、日産化学)でコーティングした基板を積層した(図2に示すフレネルレンズ作製法では、CYTOPを表面に塗布した金型を液晶性ポリマーフィルム上に転写した形状である。

したがって、液晶性ポリマーフィルムのバルク配向状態は、CYTOP界面の配向状態に依存する。そこで、まずCYTOPと垂直配向膜の間に挟まれた液晶性ポリマー膜の配向状態を評価し、次に液晶性ポリマー膜上の液晶性分子の配向状態を評価した。

図3に示す方法に従って液晶性ポリマーフィルムを作製した。液晶性モノマー材料を垂直配向フィルムでコーティングした基板上に滴下し(図3(a))、その上にCYTOPでコーティングした基板を積層した(図3(b))。

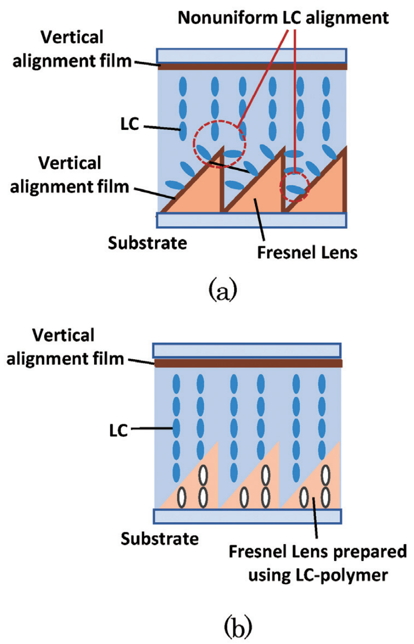


Fig. 1 Alignment control of liquid-crystal on the surface of Fresnel lens by using (a) alignment film and (b) LC-polymer.

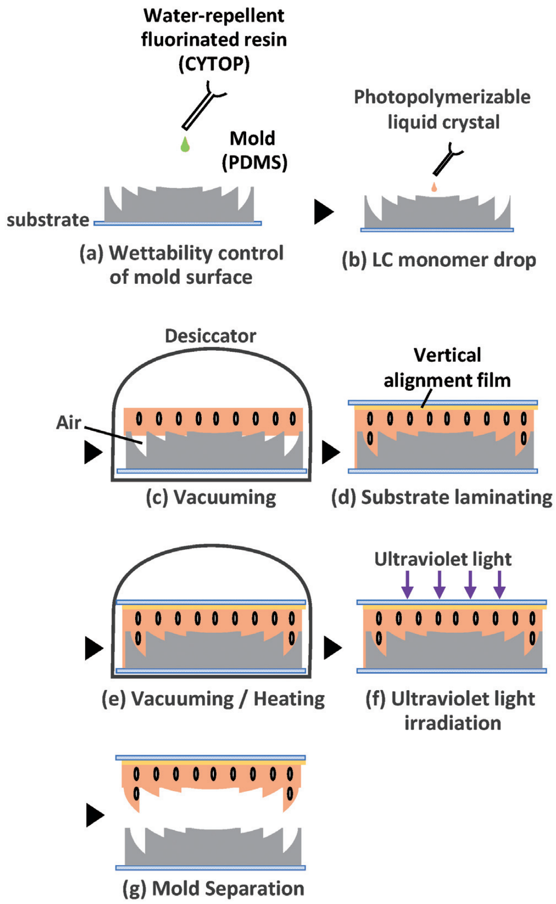


Fig. 2 Fabrication method for Fresnel lens by imprinting process using liquid-crystalline monomers.

We here propose a Fresnel lens based on a liquid-crystalline polymer (Fig. 1(b)) [11-14]. Using vertically aligned liquid-crystalline polymers to fabricate Fresnel lenses, we can uniformly orient the liquid-crystal molecules in the alignment direction of the liquid-crystalline polymer without using an alignment film. As a result, light scattering at the liquid crystal-Fresnel lens interface can be suppressed.

3. Fabrication of Fresnel lens using liquid-crystalline polymer

3.1. Control of surface figuration of liquid-crystalline polymer film

The fabrication method for Fresnel lens using liquid-crystalline polymer is shown in Fig. 2. First, polydimethylsiloxane (PDMS, Dow Corning Toray) was coated onto the surface of a Fresnel lens (Nippon Tokushu Kogaku Jushi, CF30-0.05, Lens pitch: 50 μm); after the glass substrate was stacked, the mold of the Fresnel lens was heated at 80 °C for 60 min. CYTOP (CTL-809A, AGC) was then coated onto the mold surface to improve mold release, and the mold was heated at 200 °C for 60 min (Fig. 2(a)). A liquid-crystalline monomer material (UCL-011-AC1, DIC), whose viscosity was optimized by the addition of a solvent (propylene glycol methyl ether acetate (PGMEA): 10 wt%), was subsequently coated onto the mold surface (Fig. 2(b)) and drawn into the grooves of the lens by vacuum drawing (Fig. 2(c)). A substrate coated with a vertical alignment film (SE-4811, Nissan Chemical) was then stacked (Fig. 2(d))and a vacuum was again applied to remove air bubbles (Fig. 2(e)). The assembly was irradiated with UV light (40 mW/cm2, 60 s) to photopolymerize the monomers (Fig. 2(f)). The Fresnel lens was obtained by peeling off the substrate (Fig. 2(g)) [15-18].

3.2. Alignment control of liquid-crystal molecules

In the Fresnel lens fabrication method shown in Fig. 2, the shape of a mold with CYTOP coated onto its surface is transferred onto a liquid-crystalline polymer film.

The bulk alignment state of the liquid-crystalline polymer film thus depends on the alignment state at the CYTOP interface. We therefore first evaluated the alignment state of the liquid-crystalline polymer film sandwiched between CYTOP and the vertical alignment film and then the alignment state of the liquid crystal molecules on the liquid-crystalline polymer film.

We prepared liquid-crystalline polymer films according to the method shown in Fig. 3. A liquid-crystal monomer material was dropped onto a substrate coated with a vertical alignment film (Fig. 3(a)), and a substrate coated with CYTOP was stacked on top (Fig. 3(b)). We removed the air bubbles by using a desiccator

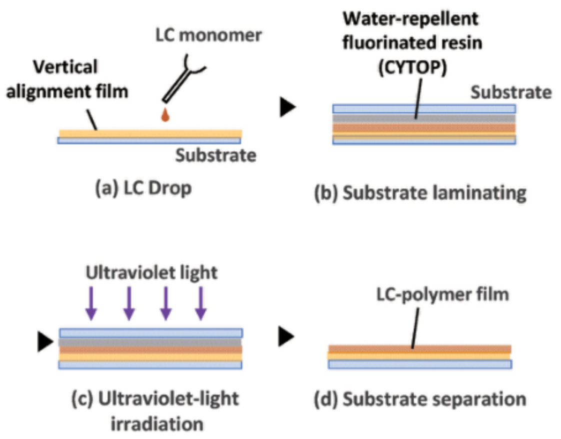


図3 CYTOPを用いた垂直配向液晶ポリマーフィルムの作製。

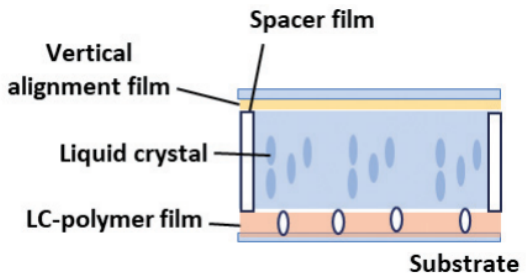


図4 液晶ポリマーフィルム上の液晶配列を評価するために使用した液晶セルの構造。

デシケーターを用いて気泡を除去し、試料を50° Cで加熱した後、室温まで冷却し、液晶モノマーの均一な垂直配向を実現した。その後、試料に紫外線照射(40 mW/cm^2 、60秒)を行い(図3(c))、基板を剥離した(図3(d))。

次に、液晶ポリマーフィルム上の液晶の配向状態を評価するために、図4に示す液晶セルを作製した。まず、液晶性モノマー材料(UCL-011-AC1、DIC)に添加剤型配向剤(D2-6PC5、東洋・山形大学)[19]を1wt%添加し、混合物を50° Cで撹拌した。

この混合物を洗浄したガラス基板上にスピンコートした。得られた薄膜にN_2雰囲気下、40mW/cm^{2}の紫外線を60秒間照射し、垂直配向した液晶性ポリマー薄膜を形成した。次に、スペーサーフィルムと垂直配向フィルム(SE4811、日産化学)を液晶ポリマーフィルムに塗布し、空セルを作製した。液晶材料(E-7, LCC)を注入して液晶セルを作製した。
液晶性ポリマーフィルムと液晶の配向状態を、液晶性ポリマーフィルムの実験値と理論値を比較することで評価した。

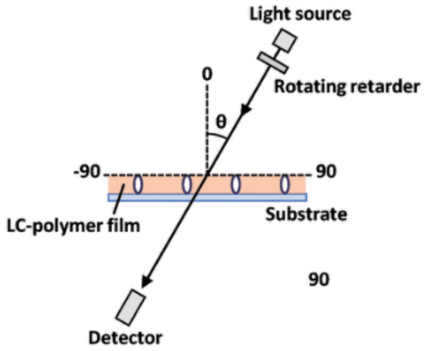


図5 エリプソメーターで測定した角度-位相遅れ特性における入射角の定義。

角度-位相リターデーション特性図に示すように、作製した試料の角度-位相遅れ特性を測定した。3 と 4 を分光エリプソメーター(M-2000, J. A. Woolam)を用いて測定し、これらの試料の特性の違いから液晶の相遅延を導き出した。基板に垂直な方向は、図5に示すように0° と定義される。
垂直配向した液晶分子の位相遅れ$\delta(\theta)$の理論式は、次のように表される。

$$\delta(\theta) = d\left(\frac{n_{\parallel}}{n_{\perp}}\sqrt{n_{\perp}^2 - sin^2\theta} - \sqrt{n_{\parallel}^2 - sin^2\theta}\right) \quad (1)$$

ここで、nとn*はそれぞれ液晶分子の長軸に平行な偏光と垂直な偏光の屈折率を表し、θは入射光の角度を表し、dは膜厚[20]を表す。

図6は、液晶性ポリマーフィルムと液晶の実験値と理論値の一致を示しており、液晶性ポリマーフィルムと液晶の実験値と理論値が一致していることが確認された。

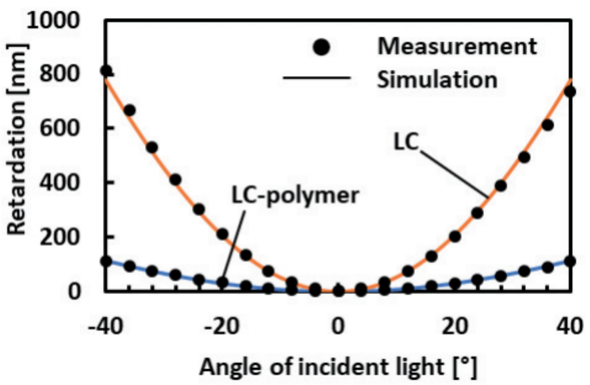


図6 液晶ポリマーフィルムと液晶の角度-位相遅れ特性の実験値と理論値の比較。

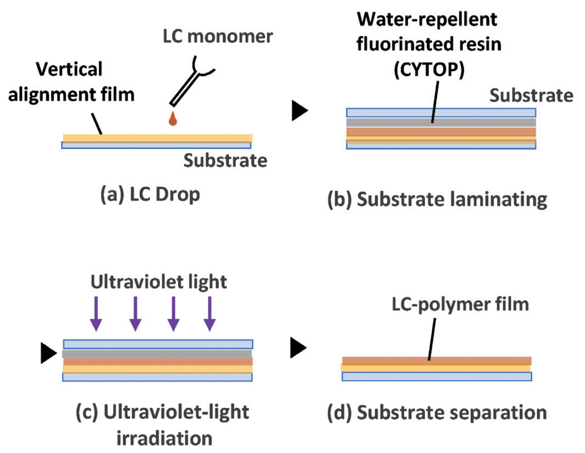


Fig. 3 Fabrication of vertically aligned liquid-crystalline polymer film using CYTOP.

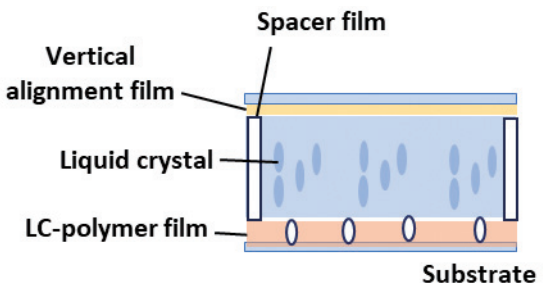


Fig. 4 Structure of the liquid-crystal cell used to evaluate liquid-crystal alignment on liquid-crystalline polymer film.

and heated the sample at 50 °C, and then cooled it to room temperature to achieve a uniform vertical alignment of liquid-crystal monomers. The sample was then subjected to UV irradiation (40 mW/cm^2, 60 s) (Fig. 3(c)), and the substrate was peeled off (Fig. 3(d)).

Next, we fabricated the liquid-crystal cell shown in Fig. 4 to evaluate the alignment state of the liquid crystal on the liquid-crystalline polymer film. First, 1 wt% of an additive-type alignment agent (D2-6PC5, Toyo and Yamagata University) [19] was added to the liquid-crystalline monomer material (UCL-011-AC1, DIC) and the mixture was stirred at 50 °C.

This mixture was then spin-coated onto a cleaned glass substrate. The resultant film was irradiated with UV light at 40 mW/cm^2 for 60 s under a N_2 atmosphere to form a vertically aligned liquid-crystalline polymer film. A spacer film and the substrate with a vertical alignment film (SE4811, Nissan Chemical) were then applied to the liquid-crystalline polymer film, and the empty cell was fabricated. The liquid-crystal cell was fabricated by injecting the liquid-crystal material (E-7, LCC).

We evaluated the alignment state of the liquid-crystalline polymer film and the liquid crystal by comparing experimental and theoretical values of the

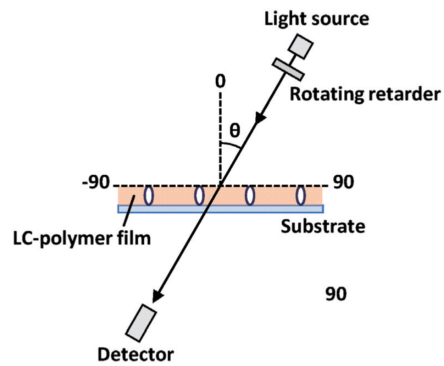


Fig. 5 Definition of the angle of incidence in the angle-phase retardation properties measured by the ellipsometer.

angle-phase retardation properties. We measured the angle-phase retardation properties of the samples fabricated in Figs. 3 and 4 by using a spectroscopic ellipsometer (M-2000, J. A. Woolam) and derived the phase retardation of the liquid crystals from the difference in the properties of these samples. The direction perpendicular to the substrate is defined as 0°, as shown in Fig. 5.

The theoretical formula for the phase retardation $\delta(\theta)$ for vertically aligned liquid-crystal molecules is expressed as:

$$\delta(\theta) = d\left(\frac{n_{\parallel}}{n_{\perp}}\sqrt{n_{\perp}^2 - sin^2\theta} - \sqrt{n_{\parallel}^2 - sin^2\theta}\right) \quad (1)$$

where $n_{\parallel}$ and $n_{\perp}$ represent the refractive indices for polarization parallel and perpendicular to the long axis of the liquid crystal molecules, respectively, θ represents the angle of incident light and d represents the film thickness [20].

Figure 6 shows agreement between the experimental and theoretical values for the liquid-crystalline polymer film and the liquid crystal, confirming that the liquid-

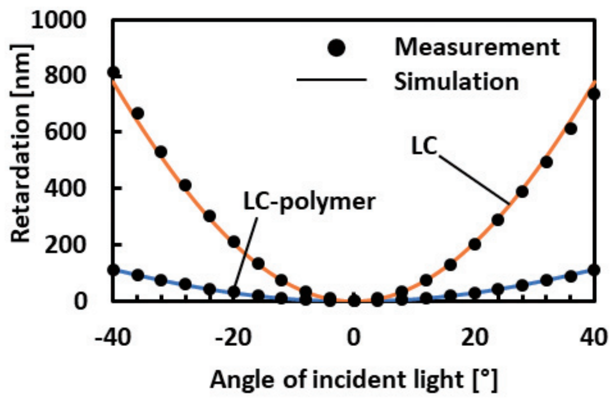


Fig. 6 Comparison of experimental and theoretical values of the angle-phase retardation properties of liquid-crystalline polymer films and liquid crystals.

結晶性ポリマーはCYTOP界面に垂直に配向しており、液晶性ポリマーフィルム上の液晶性分子もポリマーフィルムに垂直に配向している。

3.3. 表面形状を制御した液晶ポリマーフィルムの作製と特性評価

液晶ポリマーフィルムの表面形状を制御することでフレネルレンズを作製し、その後、その特性を評価した。作製したフレネルレンズの構造を干渉顕微鏡(Contour GT, Bruker)を用いて評価し、その形状を元のフレネルレンズの形状と比較した。その結果、液晶ポリマーを用いて作製したフレネルレンズは、オリジナルレンズと同じレンズ構造であることが確認された(図7)。また、作製したフレネルレンズのレンズ機能も確認した。観察によると、作製したフレネルレンズは光散乱がなく、紙に印刷された物体が拡大されており、作製した結晶性ポリマーフィルムがレンズとして機能していることが確認された(図8)。ここで、レンズの周辺に白い雲があるのは、周囲の光が反射しているためである。

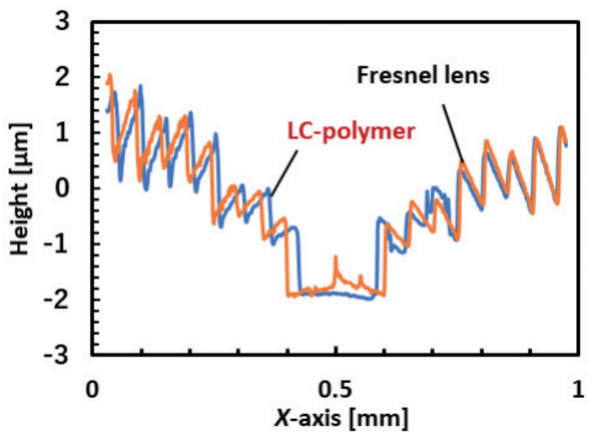


図7 液晶ポリマーで作製したフレネルレンズとオリジナルフレネルレンズの形状比較。

図8 液晶ポリマーフィルムで作製したフレネルレンズの観察結果。

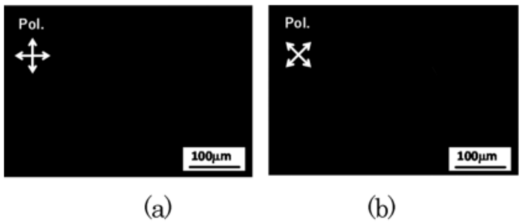


図9 液晶ポリマーを用いたフレネルレンズの直交偏光板による偏光顕微鏡像(偏光方向は(a)上下左右、(b)45度角)。

図9は、直交偏光板下で観察した、作製したフレネルレンズ中心の偏光顕微鏡像である。液晶性ポリマーフィルムは、入射偏光方向に関係なく暗く見える。また、試料全体にわたってフィルムが暗く見え、フレネルレンズの形状と均一な垂直配向を持つことを確認した。

4. 液晶ポリマーで作製したフレネルレンズを用いた液晶レンズの評価

液晶レンズは、セクション3で説明したフレネルレンズを用いて作製し、液晶アライメントとレンズ機能の2つの観点から評価した。

4.1. 液晶レンズの評価

液晶ポリマーで作製したフレネルレンズを用いて、図2に示す手順で液晶レンズを作製し、液晶のアライメントとレンズ機能を評価した。液晶材料にはネガ型液晶(MLC-2037, Merck)を用いた。作製した液晶レンズを直交偏光板の間に配置して観察した。観察結果を図10に示す。

図10(a)から、作製した液晶レンズは、偏光子の吸収軸に沿って十字型の暗状態であることがわかる。

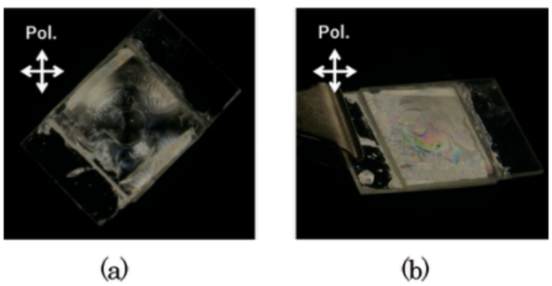


図10 直交偏光板下で作製した液晶レンズの観察結果;(a) 通常観察、(b) 斜め観察。

crystalline polymer was vertically aligned to the CYTOP interface and the liquid-crystal molecules on the liquid-crystalline polymer film are also vertically aligned to the polymer film.

3.3. Fabrication and characterization of liquid-crystalline polymer films with controlled surface shape

We fabricated Fresnel lenses by controlling the surface shape of the liquid-crystalline polymer film and subsequently characterized the lenses. The structure of the fabricated Fresnel lens was evaluated using an interference microscope (Contour GT, Bruker), and its shape was compared with that of the original Fresnel lens. The results confirmed that the Fresnel lens fabricated using the liquid-crystalline polymer had the same lens structure as the original lens (Fig. 7). The lens function of the fabricated Fresnel lens was also confirmed. The observations show that the fabricated Fresnel lens has no light scattering and the object printed on paper was magnified, confirming that the fabricated crystalline polymer film functions as a lens (Fig. 8). Here, a white cloudiness on the periphery of the lens is due to the reflection of ambient light.

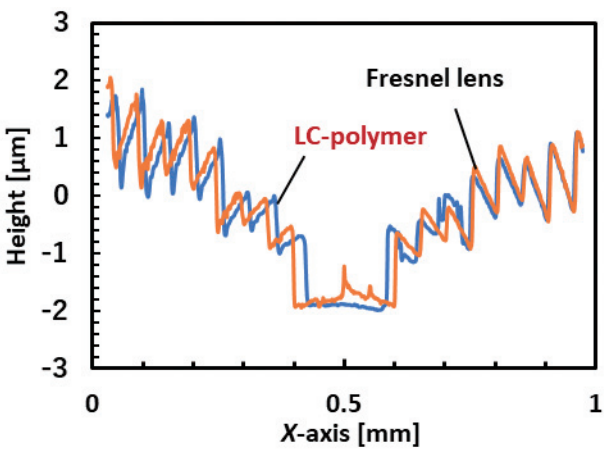


Fig. 7 Comparison of shape between a Fresnel lens fabricated with a liquid-crystalline polymer and the original Fresnel lens.

Fig. 8 Observation result for Fresnel lens fabricated with liquid-crystalline polymer film.

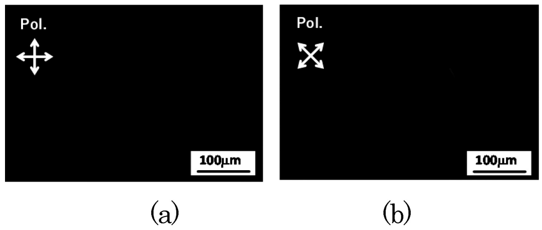


Fig. 9 Polarizing microscope images of Fresnel lens using liquid-crystalline polymer under orthogonal polarizer, where polarization directions are (a) Up/down and left/right and (b) 45-degree angle.

Figure 9 shows the polarizing microscope images of the fabricated Fresnel lens center observed under an orthogonal polarizer. The liquid-crystalline polymer film appears dark irrespective of the direction of incident polarization. We also confirmed that the film appeared dark over the entire sample and had a Fresnel lens shape and a uniform vertical alignment.

4. Evaluation of liquid crystal lenses using Fresnel lenses fabricated with liquid-crystalline polymer

Liquid-crystal lenses were fabricated using the Fresnel lenses described in Section 3 and were evaluated from two perspectives: liquid-crystal alignment and lens function.

4.1. Evaluation of liquid-crystal lenses

Using Fresnel lenses fabricated with liquid-crystalline polymer, we fabricated liquid-crystal lenses according to the procedure shown in Fig. 2; we subsequently evaluated the alignment of the liquid crystal and the lens function. A negative liquid crystal (MLC-2037, Merck) was used as the liquid-crystal material. The fabricated liquid-crystal lens was placed between orthogonal polarizers for observation; the observation results are shown in Fig. 10.

From Fig. 10(a), we can see that the fabricated liquid crystal lens has a cross-shaped dark state along the absorption axis of the polarizer. When we observed the

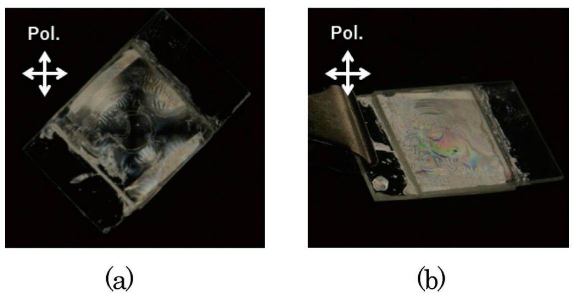


Fig. 10 Observations of the fabricated liquid-crystal lens under orthogonal polarizer; (a) normal observation and (b) oblique observation.

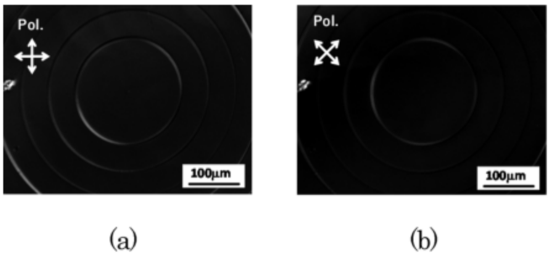


図11 直交偏光板下の液晶レンズの偏光顕微鏡像(偏光方向は(a)上下左右、(b)45度角)。

Fig. 12 Fabricated liquid crystal lens under voltage-off condition.

斜め方向から試料を観察したところ、液晶の複屈折のため、試料は表面全体に光を透過した(図10(b))。これらの結果は、フレネルレンズの表面の傾きが1度以下であることから、液晶が基板に対してほぼ垂直であることを示している。ここで、図10(a)の偏光板の軸から45°ずれた方向の光漏れは、偏光軸の見かけの角度の変化による液晶の複屈折によるものである。この結果から、液晶ポリマーで作製したフレネルレンズ上の液晶は、基板に対してほぼ垂直に配向していることが確認された。

偏光顕微鏡を用いた直交偏光下での液晶レンズの観察結果を図11に示す。液晶の配列方向はフレネルレンズの構造のステップによってわずかに変化するが、フレネルレンズの形状による光散乱は起こらないことがわかった。

作製した液晶レンズの観察結果を図12に示す。電圧オフ状態では、液晶ポリマーと液晶のアライメントが垂直に一致し、液晶とフレネルレンズの屈折率が一致していることから、レンズ機能を持たないことが確認された。また、フレネルレンズ形状に起因する光散乱は起こらず、作製したデバイスが高い透過率を示すことも確認した。

4.2. 電圧印加下における液晶の配向制御

提案する液晶レンズは、液晶性ポリマーと、対向する基板上にコーティングされた垂直配向フィルムを用いて、液晶分子の配向を制御する。一般に、液晶分子の印加電圧下での配向方向は、両方の基板に配向処理(摩擦など)を施すことで制御される。しかし、提案したレンズでは、液晶ポリマー上の液晶の配向方向を制御することはできない。そこで本研究では、反対側の基板にのみ摩擦処理を施すことで、印加電圧下での液晶配列の方向を制御した。一般に、摩擦強度RSは次式で表される。

$$RS = Nl\left(1 \pm \frac{2\pi rn}{60v}\right) \quad (2)$$

ここで、Nは摩擦回数、lは杭接触長(mm)、vはステージの移動速度(mm/s)、rはローラー半径(mm)、nはローラー回転速度(mm/s)[21－24]である。図 13 に示す LC セルを作製し、杭の接触長を変化させた。次に、電圧を印加したときの液晶分子の配向状態を評価した。

直交偏光板下で作製したLCセルの観察結果を図14に示す。この結果から、杭の接触長が0.3mmの場合、液晶の配向方向は均一ではないが、杭の接触長が0.6mm以上の場合、印加電圧下で液晶の配向方向を均一に制御できることが確認された。

杭接触長 0.6 mm の条件で作製した液晶レンズの偏光顕微鏡観察結果を Fig.15 に示す。ここで、図15(b)に見られる斜線は、フレネルレンズの構造の段差による光透過率の低さによるものである。

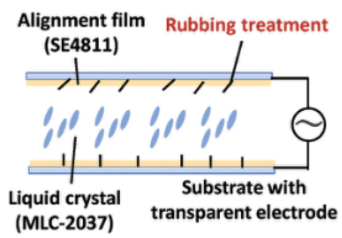
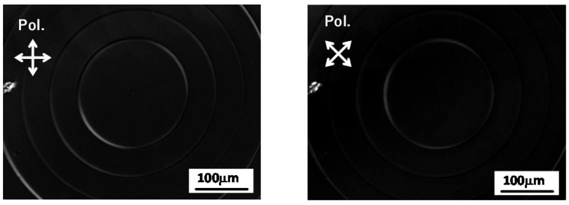


図 13 評価に用いた液晶デバイスの構造。



(a) (b)

Fig. 11 Polarizing microscope images of liquid-crystal lens under orthogonal polarizer, where polarization directions are (a) Up/down and left/right and (b) 45-degree angle.

Fig. 12 Fabricated liquid crystal lens under voltage-off condition.

sample from the oblique direction, the sample transmitted light over the entire surface because of the birefringence of the liquid crystal (Fig. 10(b)). These results indicate that the liquid crystal is almost perpendicular to the substrate, as the inclination of the surface of the Fresnel lens is less than 1 degree. Here, the light leakage at an orientation 45° off the axis of the polarizer in Fig. 10(a) is due to the birefringence of the liquid crystal caused by the change in the apparent angle of the polarization axis. From the results, we confirmed that the liquid crystal on the Fresnel lens fabricated with the liquid-crystalline polymer was almost vertically aligned to the substrate.

The results of observations of the liquid-crystal lens under orthogonal polarization using a polarizing microscope are shown in Fig. 11. We found that the alignment direction of liquid crystal slightly changes by the steps in the structure of the Fresnel lens, however, no light scattering is caused by the shape of the Fresnel lens.

The observation results for the fabricated liquid-crystal lens are shown in Fig. 12. In the voltage-off state, the device was confirmed to not have a lens function because the alignment of the liquid-crystalline polymer and the liquid crystal were vertically aligned, and the refractive indices of the liquid crystal and Fresnel lens matched. We also confirmed that light scattering caused by the Fresnel lens shape did not occur and that the fabricated device exhibited a high transmittance.

4.2. Alignment control of liquid crystal under an applied voltage

The proposed liquid-crystal lens uses a liquid-crystalline polymer and a vertically aligned film coated onto the opposite substrate to control the alignment of the liquid-crystal molecules. In general, the alignment direction of liquid crystal molecules under an applied voltage is controlled by applying an alignment treatment (e.g., rubbing) to both substrates. However, in the proposed lens, the alignment direction of liquid crystal on the liquid-crystalline polymer cannot be controlled. Therefore, in the present study, we controlled the direction of liquid-crystal alignment under an applied voltage by applying a rubbing treatment only to the opposite substrate. In general, the rubbing strength RS is expressed as

$$RS = Nl\left(1 \pm \frac{2\pi rn}{60v}\right) \quad (2)$$

where l is the pile contact length (mm), r is the roller radius (mm), N is the number of rubbings, v is the movement speed of the stage (rpm), and n is the roller revolution speed (mm/s) [21-24]. We fabricated the LC cell shown in Fig. 13 and varied the pile contact length. We then evaluated the alignment state of the liquid crystal molecules when a voltage was applied.

The observation results for the fabricated LC cells under the orthogonal polarizer are shown in Fig. 14. From the results, we confirmed that, when the pile contact length was 0.3 mm, the alignment direction of the liquid crystal was not uniform, whereas when the pile contact length was 0.6 mm or more, the alignment direction of the liquid crystal could be uniformly controlled under an applied voltage.

The polarizing microscope observations of the liquid-crystal lens fabricated under the condition of a 0.6 mm pile contact length are shown in Fig. 15. Here, the oblique lines seen in Fig. 15(b) are due to the low light transmission caused by the steps in the structure of the Fresnel lens.

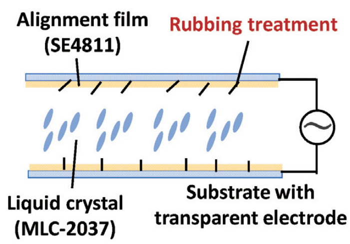


Fig. 13 Structure of the liquid-crystal device used for evaluation.

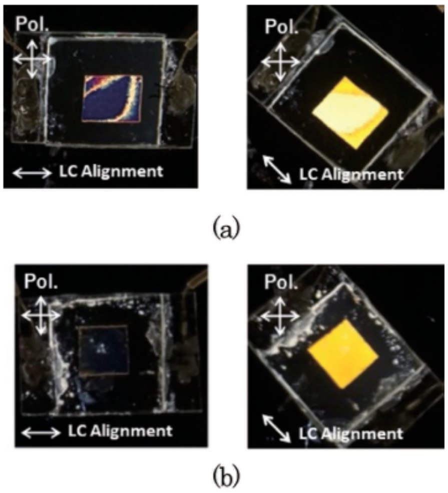
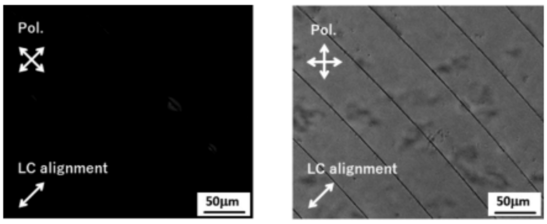


図14 杭接触長が(a)0.3mm、(b)0.6mmの反対側の基板について、摩擦強度を変えて作製した液晶セルの観察結果。



(a) (b)

図15 摩擦方向に対する偏光方向が(a)0度、(b)45度である反対側の基板に対して、杭接触長0.6mmの条件で作製した液晶レンズの偏光顕微鏡観察結果。

入射偏光方向が電圧オン状態の液晶分子の配向方向と一致する場合、デバイスは暗くなり(図15(a))、入射偏光方向が液晶の配向方向から45度離れている場合、液晶の複屈折によりデバイスは明るくなった(図15(b))。光透過率は試料表面全体で均一であり、これらの結果からフレネルレンズ上の液晶は印加電圧に対して均一な配向を持つことが確認された。

5. Conclusion

本研究では、液晶ポリマーを用いたフレネルレンズの作製について検討し、レンズ上の液晶分子の均一な配列制御を実証することで、二焦点ガラス用の高品質可変焦点液晶レンズを実現した。

その結果、液晶ポリマーを金型表面に塗布し、垂直配向フィルムを塗布した基板を積層することで、垂直配向フレネルレンズを作製できることがわかった。また、作製したフレネルレンズ上の液晶分子は、フレネルレンズの表面構造に起因する光散乱を伴わず、基板に対してほぼ垂直に配向していることが示された。

作製した液晶レンズは、電圧オフ状態で光散乱を伴わない高い透過率を示し、また、電圧印加時に液晶の配向を均一に制御できることを確認した。以上の結果から、高性能液晶レンズが実現できることが実証された。

Acknowledgment

本研究は、日本学術振興会科学研究費補助金(No.JP22H01537)の助成を受けた。

References

1) Osamu Sawaji "Measures to Address Japan's Aging Society" Japan Policy-Related News (2021)
2) Oleg Pishnyak, Susumu Sato, Oleg D. Lavrentovich, "Electrically tunable lens based on dual-frequency nematic liquid crystal," Appl. Opt., 45(19), pp.4576-4582 (2006)
3) V.S. Bezruchenko, A.A. Muravsky, A.A. Murauski, A.I. Stankevich, U.V. Mahilny, "Tunable liquid crystal lens based on pretilt angle gradient alignment," Mol. Cryst. Liq., 626, pp.222-228 (2016)
4) A. Jamali, D. Bryant, Y. Zhang, A. Grunnet-Jepsen, A. Bhowmik, P.J. Bos, "Design of a large aperture tunable refractive Fresnel liquid crystal lens," Appl. Opt., 57, B10 (2018)
5) A.K. Srivastava, X.Q. Wang, S.Q. Gong, D. Shen, Y.Q. Lu, V.G. Chigrinov, H.S. Kwok, "Micro-patterned photo-aligned ferroelectric liquid crystal Fresnel zone lens," Opt. Lett., 40, 1643 (2015)
6) X. Wei, J. Zheng, Y. Wang, Z. Gao, L. Sun, Y. Lu, S. Zhuang, "Multi-imaging characteristics of electrically controlled on-axis holographic polymer-dispersed liquid-crystal Fresnel lens," Opt. Eng., 54, 037110 (2015)
7) X. -Q. Wang, W. -Q. Yang, Z. Liu, W. Duan, W. Hu, Z. -G. Zheng, D. Shen, V.G. Chigrinov, H. -S. Kwok, "Switchable Fresnel lens based on hybrid photo-aligned dual frequency nematic liquid crystal," Opt. Mater. Express, 7(1) pp.8-15 (2017)
8) Dieter Cuypers, Rik Verplancke, Herbert De Smet, "Miniature Liquid Crystal Lens Optimizations," Proceedings of the International Display Workshops, pp.1360-1363 (2019)
9) Dieter Cuypers, Rik Verplancke, Herbert De Smet, "Thin Switchable Liquid Crystal Fresnel Lenses," Proceedings of the International Display Workshops, pp.728-729 (2021)
10) A. Muramatsu, E. Hikosaka, S. Shichijyo, "A New Generation of Eyeglasses Pioneered Through Liquid Crystal Lens Technology," Proceedings of the International Display Workshops, pp.19-22 (2021)
11) J. Küpfer, H. Finkelmann, "Nematic liquid single crystal elastomers," Makromol. Chem. Rapid Commun. 12, pp.717-726 (1991)
12) R.A. M. HIKMET and J. LUB, "Anisotropic Networks And Gels Obtained By Photopolymerisation In The Liquid Crystalline State: Synthesis And Applications," Progress in polymer science, 21(6), pp 1165-1209 (1996)
13) J. Lub, D.J. Broer, R.T. Wegh, E. Peeters, B.M. I van der Zande, "Formation of Optical Films by Photo-Polymerisation of Liquid Crystalline Acrylates and Application of These Films in Liquid Crystal Display Technology," Liq. Cryst., 429, pp.77-99 (2005)
14) Ewa Andrzejewska, Maciej Andrzejewski, "Polymerization Kinetics of Photocurable Acrylic Resins," Polymer chemistry, 36(4), pp 665-673 (2000)
15) Carlos Sánchez, Frank Verbakel, Michael J. Escuti, Cees W.M.

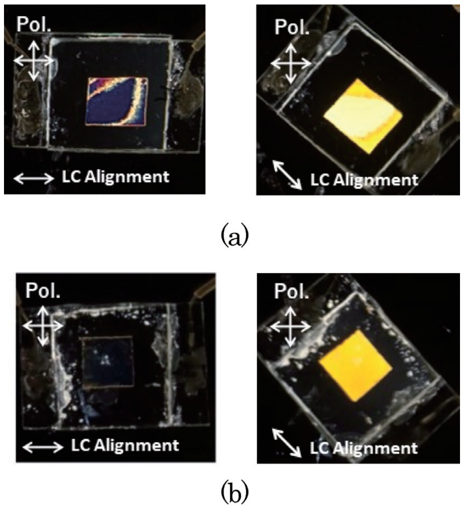


Fig. 14 Observations of liquid-crystal cells fabricated by changing rubbing strength for opposite substrate, where pile contact length is (a) 0.3 mm, (b) 0.6 mm.

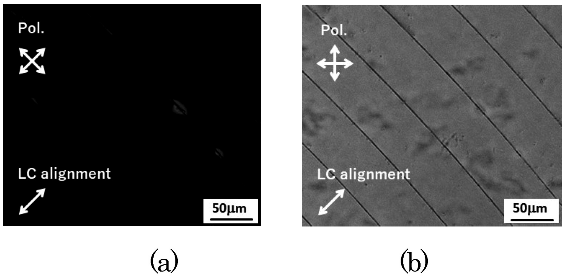


Fig. 15 Polarizing microscope observations of liquid crystal lenses fabricated under the condition of a 0.6 mm pile contact length for the opposite substrate, where polarization direction to the rubbing directions are (a) 0 degrees and (b) 45 degrees.

When the direction of incident polarization matched the orientation direction of the liquid-crystal molecules in the voltage-on state, the device was dark (Fig. 15(a)); when the incident polarization direction was 45 degrees from the orientation direction of the liquid-crystal, the device was bright because of the birefringence of the liquid crystal (Fig. 15(b)). Light transmission is uniform over the entire surface of the sample, and these results confirm that the liquid crystals on the Fresnel lens have a uniform orientation under an applied voltage.

5. Conclusion

In this study, we investigated the fabrication of Fresnel lenses using liquid-crystalline polymers and demonstrated control of the uniform alignment of liquid-crystal molecules on the lenses to realize high-quality variable-focus liquid-crystal lenses for bifocal glasses.

The results showed that a vertically aligned Fresnel lens could be fabricated by coating the liquid-crystalline polymer onto the mold surface and stacking a substrate coated with a vertical alignment film. The results also showed that the liquid-crystal molecules on the fabricated Fresnel lenses aligned almost vertically to the substrate without light scattering due to the surface structure of the Fresnel lens.

The fabricated liquid-crystal lenses exhibited high transmittance without light scattering in a voltage-off state, and we also confirmed that the alignment of the liquid crystals could be uniformly controlled when a voltage was applied. The above results demonstrate that high-performance liquid-crystal lenses can be realized.

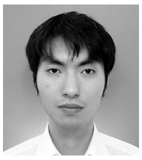
Acknowledgment

This research was supported by a JSPS Grant-in-Aid for Scientific Research (No. JP22H01537).

References

1) Osamu Sawaji "Measures to Address Japan's Aging Society" Japan Policy-Related News (2021)
2) Oleg Pishnyak, Susumu Sato, Oleg D. Lavrentovich, "Electrically tunable lens based on dual-frequency nematic liquid crystal," Appl. Opt., 45(19), pp.4576-4582 (2006)
3) V.S. Bezruchenko, A.A. Muravsky, A.A. Murauski, A.I. Stankevich, U.V. Mahilny, "Tunable liquid crystal lens based on pretilt angle gradient alignment," Mol. Cryst. Liq., 626, pp.222-228 (2016)
4) A. Jamali, D. Bryant, Y. Zhang, A. Grunnet-Jepsen, A. Bhowmik, P.J. Bos, "Design of a large aperture tunable refractive Fresnel liquid crystal lens," Appl. Opt., 57, B10 (2018)
5) A.K. Srivastava, X.Q. Wang, S.Q. Gong, D. Shen, Y.Q. Lu, V.G. Chigrinov, H.S. Kwok, "Micro-patterned photo-aligned ferroelectric liquid crystal Fresnel zone lens," Opt. Lett., 40, 1643 (2015)
6) X. Wei, J. Zheng, Y. Wang, Z. Gao, L. Sun, Y. Lu, S. Zhuang, "Multi-imaging characteristics of electrically controlled on-axis holographic polymer-dispersed liquid-crystal Fresnel lens," Opt. Eng., 54, 037110 (2015)
7) X. -Q. Wang, W. -Q. Yang, Z. Liu, W. Duan, W. Hu, Z. -G. Zheng, D. Shen, V.G. Chigrinov, H. -S. Kwok, "Switchable Fresnel lens based on hybrid photo-aligned dual frequency nematic liquid crystal," Opt. Mater. Express, 7(1) pp.8-15 (2017)
8) Dieter Cuypers, Rik Verplancke, Herbert De Smet, "Miniature Liquid Crystal Lens Optimizations," Proceedings of the International Display Workshops, pp.1360-1363 (2019)
9) Dieter Cuypers, Rik Verplancke, Herbert De Smet, "Thin Switchable Liquid Crystal Fresnel Lenses," Proceedings of the International Display Workshops, pp.728-729 (2021)
10) A. Muramatsu, E. Hikosaka, S. Shichijyo, "A New Generation of Eyeglasses Pioneered Through Liquid Crystal Lens Technology," Proceedings of the International Display Workshops, pp.19-22 (2021)
11) J. Küpfer, H. Finkelmann, "Nematic liquid single crystal elastomers," Makromol. Chem. Rapid Commun. 12, pp.717-726 (1991)
12) R.A. M. HIKMET and J. LUB, "Anisotropic Networks And Gels Obtained By Photopolymerisation In The Liquid Crystalline State: Synthesis And Applications," Progress in polymer science, 21(6), pp 1165-1209 (1996)
13) J. Lub, D.J. Broer, R.T. Wegh, E. Peeters, B.M. I van der Zande, "Formation of Optical Films by Photo-Polymerisation of Liquid Crystalline Acrylates and Application of These Films in Liquid Crystal Display Technology," Liq. Cryst., 429, pp.77-99 (2005)
14) Ewa Andrzejewska, Maciej Andrzejewski, "Polymerization Kinetics of Photocurable Acrylic Resins," Polymer chemistry, 36(4), pp 665-673 (2000)
15) Carlos Sánchez, Frank Verbakel, Michael J. Escuti, Cees W.M.

Bastiaansen, Dirk J. Broer, "Printing of Monolithic Polymeric Microstructures Using Reactive Mesogens," Adv. Mater., 20, pp.74-78 (2008)
16) R. Plamont Icon, F. Lancia Icon, A. Ryabchun Icon, "A Reactive mesogens for ultraviolet-transparent liquid crystal polymer networks," Liq. Cryst., 47(11), pp.1569-1581 (2020)
17) Lin Yan, Xiao-Mei Zhao, George M. Whitesides, "Patterning a Preformed, Reactive SAM Using Microcontact Printing," J. Am. Chem. Soc., 120, pp.6179-6180 (1998)
18) Younan Xia, John A. Rogers, Kateri E. Paul and George M. Whitesides, "Unconventional Methods for Fabricating and Patterning Nanostructures," Chem. Rev., 99, pp 1823–1848 (1999)
19) Yuichi Momoi, Musun Kwak, Donsik Choi, Youngseok Choi, Kyongdeuk Jeong, Tomonori Koda, Osamu Haba, Koichiro Yonetake, "Polyimide-free LCD by dissolving dendrimers," Journal of the Society for Information Display, 20(9), pp.486-492 (2012)
20) Yuji Ohno, Takahiro Ishinabe, Tetsuya Miyashita, Tatsuo Uchida, "Highly Accurate Method for Measuring Ordinary and Extraordinary Refractive Indices of Liquid Crystal Materials, Cell Thickness and Pretilt Angle of Liquid Crystal Cells Using Ellipsometry," J. Appl. Phys., 48 (2009)
21) Yumiko Sato, Kazutoshi Sato and Tatsuo Uchida, "Relationship between Rubbing Strength and Surface Anchoring of Nematic Liquid Crystal," J. Appl. Phys., 31, L579 (1992)
22) T. Uchida, M. Hirano, H. Sakai, "Director orientation of a ferroelectric liquid crystal on substrates with rubbing treatment: The effect of surface anchoring strength," Liq. Cryst., 5(4), pp1127-1137 (1989)
23) Wenjun Zheng, Chih-Hung Lu, Yi-Chih Ye, "Effects of Mechanical Rubbing on Surface Tension of Polyimide Thin Films," J. Appl. Phys., 47, 1651 (2008)
24) A. Sakunosuke, Y. Shibata, K. Munehiro, A. Tadashi, "Self-Consistent Explanation of the Untwist Alignment of Ferroelectric Nematic Liquid Crystals with Decreasing Cell Thickness and Deviation of the Surface Easy Axis Experimented upon Using the Brewster Angle Reflection Method," Crystal, 14(2), 157 (2024)



Takumu Ohata received a B.E. degree from Tohoku University, Sendai, Japan, in 2022. He is a Master's student in the Department of Electronic Engineering at the Graduate School of Engineering, Tohoku University. His research interest is the adaptive liquid crystal lens using LC-polymers.

Takahiro Ishinabe received his B.S., M.S., and Ph. D. degrees in Electronic Engineering from Tohoku University, Sendai, Japan, in 1995, 1997, and 2000, respectively. From 2000 to 2002, he was a Research Fellow of the Japan Society for the Promotion of Science, and from 2003 to 2012, he was an Assistant Professor, and from 2013 to 2023, he was an Associate Professor in the Department of Electronics, Graduate School of Engineering, Tohoku University. Since 2023, he has been a Professor in the Department of Management Science and Technology, Graduate School of Engineering, Tohoku University. He has also been a Visiting Professor in the CREOL, The College of Optics and Photonics, University of Central Florida from 2010 to 2011. He has been performing research on advanced liquid crystal displays such as wide viewing angle LCD, reflective full-color LCD, field sequential color LCD, and flexible LCD. He is a fellow of the Society for Information Display.

Masakazu Nakatani received his M.S. in Engineering from Nara Institute of Science and Technology (NAIST) in March 2010 and Ph.D. in Engineering from Nagaoka University of Technology in December 2020. From 2010-2016, he joined Clean Venture 21, a low-concentration photovoltaics venture company, as a researcher; from 2020-2022, he worked as a postdoctoral researcher at Osaka University, studying light control by cholesteric liquid crystals. In February 2023, he joined Graduate School of Engineering, Tohoku University as an Assistant Professor.

Hideo Fujikake received M.E and Ph.D. degrees from Tohoku University, Japan, in 1985 and 2003, respectively. In 1985, he joined the Japan Broadcasting Corporation (NHK). In 1988-2012, he worked for NHK Science and Technology Research Laboratories. From 2006, he was a visiting professor at Department of Physics, Graduate School of Science, Tokyo University of Science. Since 2012, he has been a professor at the Department of Electronic Engineering, Tohoku University. He received the Best Paper Award from the Institute of Electronics, Information and Communication Engineers (IEICE) in 2001 and 2017, the Best Paper Award from the Japanese Liquid Crystal Society (JLCS) in 2001, 2015 and 2020, the Niwa-Takayanagi Best Paper Award from the Institute of Image Information and Television Engineers of Japan (ITE) in 2003 and 2009, and the Electronics Society Award from IEICE in 2013. His current interests are concerned with flexible liquid crystal displays and functional optical devices including holography. He also served as a Japan Chapter Chair in IEEE Consumer.

Bastiaansen, Dirk J. Broer, "Printing of Monolithic Polymeric Microstructures Using Reactive Mesogens," Adv. Mater., 20, pp.74-78 (2008)

16) R. Plamont Icon, F. Lancia Icon, A. Ryabchun Icon, "A Reactive mesogens for ultraviolet-transparent liquid crystal polymer networks," Liq. Cryst., 47(11), pp.1569-1581 (2020)
17) Lin Yan, Xiao-Mei Zhao, George M. Whitesides, "Patterning a Preformed, Reactive SAM Using Microcontact Printing," J. Am. Chem. Soc., 120, pp.6179-6180 (1998)
18) Younan Xia, John A. Rogers, Kateri E. Paul and George M. Whitesides, "Unconventional Methods for Fabricating and Patterning Nanostructures," Chem. Rev., 99, pp 1823–1848 (1999)
19) Yuichi Momoi, Musun Kwak, Donsik Choi, Youngseok Choi, Kyongdeuk Jeong, Tomonori Koda, Osamu Haba, Koichiro Yonetake, "Polyimide-free LCD by dissolving dendrimers," Journal of the Society for Information Display, 20(9), pp.486-492 (2012)
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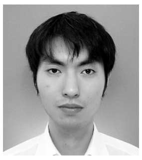

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