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Polarisation rotator consisting of two layers of twisted nematic LC, which shows little dependence on the initial polarisation direction and the wavelength

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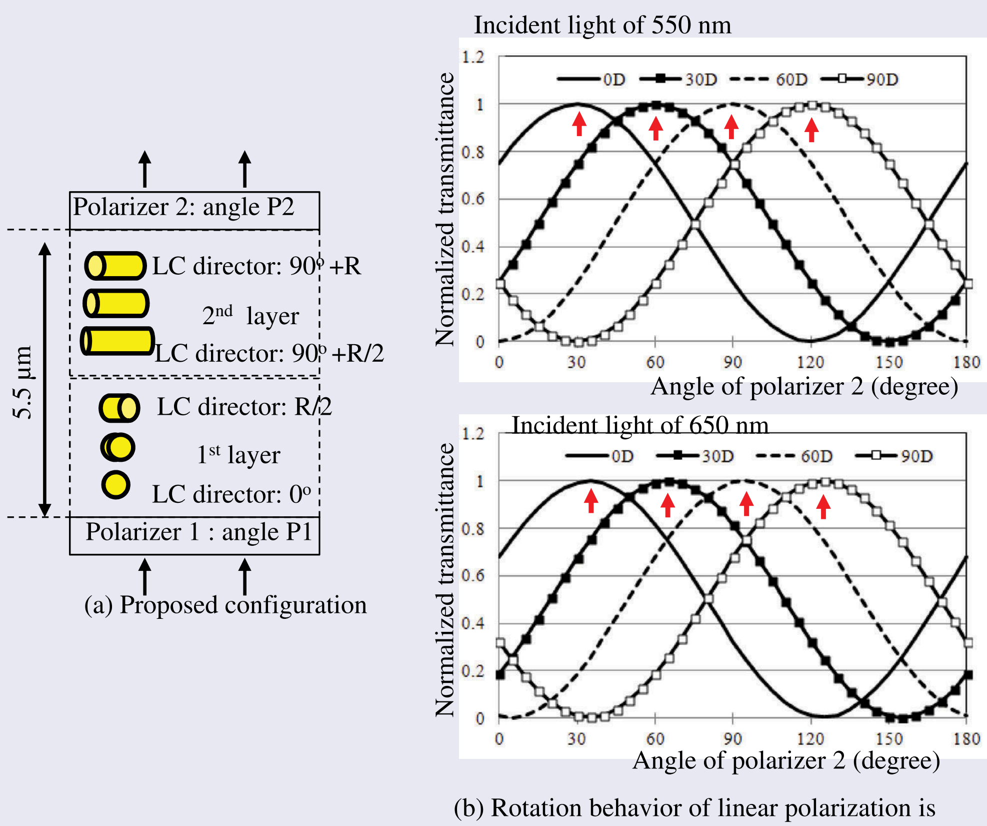
ABSTRACT

Performances of typical HWP (half-wave plate) or the one layer of the twisted nematic LC as the polarisation rotator are affected by the wavelength of the incident light and the initial polarisation direction of the incident linear polarisation. A new configuration that two layers of the twisted LC were aligned with the angular difference of 90°, was considered. Theoretical analysis by Jones matrix was used to derive the change of the polarisation state at the proposed configuration and to investigate the dependence on the wavelength and the initial polarisation direction. Commercial LC simulator was used to quantitatively investigate the effectiveness of the proposed configuration. Theoretical analysis and the calculated results show that the performance of the proposed configuration was less dependent on wavelength as compared with the one layer of twisted nematic LC.



(b) Rotation behavior of linear polarization is similar for incident light of 550nm and 650nm

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1. Introduction

In manipulation of the polarised light, the rotation of the polarisation direction of linearly polarised light is often necessary. Half-wave plate (HWP) had been one of the widely used methods to rotate polarisation direction. But effectiveness of HWP as the polarisation rotator is strongly dependent on the wavelength. And the angle

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between the polarisation direction of linearly polarised light and the optic axis of HWP needs to be appropriately selected to obtain the required rotation angle.[1] Optical media with the property of the optical activity were reported to cause the rotation of the polarisation direction, but generally a very thick medium was needed to rotate tens of degrees of the polarisation direction.[2] The twisted nematic LC had been reported to cause the rotation of the polarisation direction under the specific condition called the adiabatic following.[3–5] Under the condition of the adiabatic following, the direction of the incident polarised light was reported to rotate along the direction of the LC directors. This method was known to be effective only when the polarisation direction of incident light was parallel or perpendicular to the directions of LC directors at the side of the entrance. The reported methods have some merits and demerits and the polarisation rotating needs further improvement.

Hence, the effective method to rotate the polarisation direction of linearly polarised light irrespective of the initial polarisation direction and the wavelength was investigated. For this purpose, the configuration consisting of two layers of twisted nematic LC was newly proposed. In the proposed configuration, the behaviour of the incident linear polarisation of arbitrary polarisation direction was investigated. The dependence on the initial polarisation direction and the wavelength were investigated as well.

2. Theory

2.1. Rotation of the polarisation direction by a twisted nematic LC medium

Polarisation state propagating through twisted nematic LC medium had been theoretically well known.[3–5] For example, polarisation state in Jones matrix representation can be written as the following equation, at the local principal coordinate system using the E-mode and o-mode.[3]

$$\begin{pmatrix} V'_e \\ V'_o \end{pmatrix} = \begin{pmatrix} \cos x - i\frac{\Gamma \sin x}{2x} & \varphi \frac{\sin x}{x} \\ -\varphi \frac{\sin x}{x} & \cos x + i\frac{\Gamma \sin x}{2x} \end{pmatrix} \begin{pmatrix} V_e \\ V_o \end{pmatrix} = M \begin{pmatrix} V_e \\ V_o \end{pmatrix} \quad (1)$$

In Equation (1), e- and o-mode represent the direction parallel and perpendicular to the LC director at the positions that light rays pass through. The angle ϕ represents the twist angle between LC directors at the entrance and the exit of LC cell. (V'_e, V'_o) and (V_e, V_o) represent e- and o-component of each local principal coordinates at the exit and entrance of the LC cell. Hence, in case of e-mode, the initial polarisation direction is parallel to the direction of LC directors at the side of the entrance of LC medium. And the polarisation state (V_e, V_o) at the entrance can be represented as (1, 0) in the local principal coordinate system. Similarly, o-mode can be represented as (0, 1) in the local principal coordinate system.

Retardation Γ and x are defined as follows:

$$x = \sqrt{\varphi^2 + \left(\frac{\Gamma}{2}\right)^2}, \quad \Gamma = \frac{2\pi}{\lambda}(n_e - n_o)d \quad (2)$$

In Equation (2), λ, d, n_e and n_o represent the wavelength, the thickness of LC layer and the refractive indices of LC, respectively. When LC twist angle ϕ is small enough compared with the overall phase retardation Γ of LC layer, x is approximately equal to the retardation $\mathbf{\Gamma}$ and M of Equation (1) can be approximated as follows:

$$M_0 = \begin{pmatrix} e^{-i\Gamma/2} & 0 \\ 0 & e^{i\Gamma/2} \end{pmatrix} \quad (3)$$

When incident light is e-mode, the polarisation state of light coming out from LC medium can be written as follows:

$$\begin{pmatrix} V'_e \\ V'_o \end{pmatrix} = M_0 \begin{pmatrix} 0 \\ 1 \end{pmatrix} = \begin{pmatrix} e^{-i\Gamma/2} \\ 0 \end{pmatrix} \quad (4)$$

Equation (4) means the polarisation direction of light exiting LC medium is parallel to the direction of LC directors at the side of the exit of LC medium. And the linear polarisation of e-mode rotates by the amount of angle ϕ as illustrated in Figure 1(a). Therefore, twist angle ϕ of LC directors at the entrance and at exit determines the rotated angle of the polarisation direction of the incident linearly polarised light. This phenomenon that the direction of the incident light follows the twist of LC directors as illustrated in Figure 1(a) is known as the adiabatic following. On the other hand, for o-mode, the polarisation state (V_e, V_o) at the entrance can be represented as (0, 1) in the local principal coordinate system. Using Equation (3), the polarisation state of light coming out from LC medium can be written as follows:

$$\begin{pmatrix} V'_e \\ V'_o \end{pmatrix} = M_0 \begin{pmatrix} 0 \\ 1 \end{pmatrix} = \begin{pmatrix} 0 \\ e^{i\Gamma/2} \end{pmatrix} \quad (5)$$

So the linear polarisation of o-mode rotates by the amount of angle ϕ as illustrated in Figure 1(b). If polarisation direction of the incident linear polarisation is not parallel or perpendicular to the directions of LC directors at the entrance, the incident linear polarisation can be decomposed into two components of E- and o-mode. And the polarisation state of each

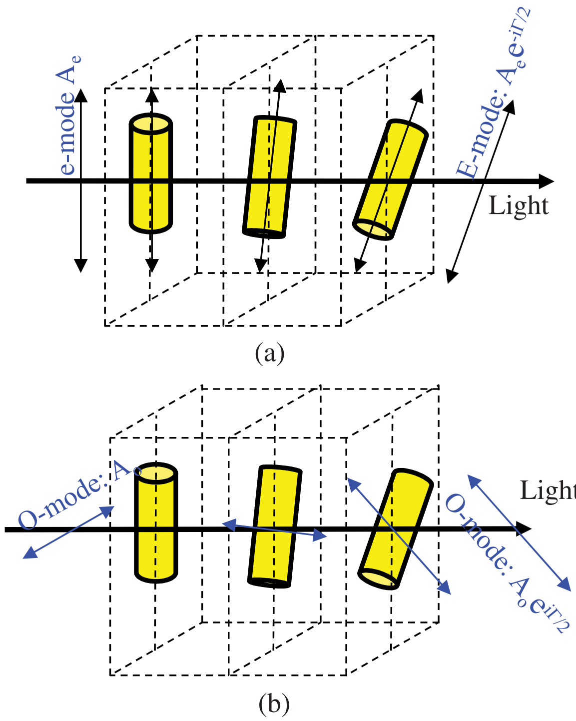

Figure 1. (colour online) Propagation of linear polarisation through twisted nematic LC cell under the condition of the adiabatic following for (a) e-mode and (b) o-mode. Polarisation direction for e-mode and o-mode are parallel and perpendicular to LC directors. As e-mode and o-mode propagate inside LC medium, the phases of -Γ/2 and Γ/2 are approximately induced for e-mode and o-mode, respectively for the condition of small twist angle.

component propagating through LC medium can be approximately determined by the above equations. From Equations (4) and (5), the phases of these two polarisations at the exit can be determined as $(-\Gamma/2)$ and $(\Gamma/2)$. As these phase changes are different, these two components cannot be generally combined into linear polarisation out of LC medium except the case that the phase $(\Gamma/2)$ is the multiple of π. If the configuration of twisted LC medium is designed such that the phase difference between these E- and O-component is zero or multiple of π at the exit, these E- and O-component may be combined into linear polarisation. In that case, linear polarisation can be rotated by the amount of twist angle, irrespective of the polarisation direction. However, the condition that the phase $(\Gamma/2)$ is the multiple of π is strongly dependent on the wavelength though the condition of the small twist angle is relatively little affected by the wavelength.

If x is selected to be π, M of Equation (1) becomes a 2-by-2 identity matrix. That means any linear polarisation is rotated by the amount of the angle ϕ. As x in Equation (2) depends on the wavelength, the rotation of the polarisation direction irrespective of the incident polarisation direction would be possible for the twisted LC cell designed for a specific wavelength.

2.2. Configuration of two layers of twisted nematic LC medium

When the LC twist is small enough compared with the overall phase retardation Γ, the absolute sizes of the phase change for e- and o-mode, are the same but with the opposite sign as shown in Equations (4) and (5). If these phase differences can be compensated, the wavelength dependence may be reduced. For this purpose, the configuration of two layers of twisted nematic LC, where the directions of n_e and n_o are interchanged, was considered for the first time. The proposed configuration was illustrated in Figure 2. LC directors of each layer were homogeneously aligned with the twist angle of $R/2$. The direction of LC directors of the first LC layer was selected to be zero and the angle of LC directors at the exit of the first LC layer was selected to be $R/2$ as illustrated in Figure 2(b). Angles of LC directors at the entrance and the exit of the second LC layer were selected to be $R/2 + 90^o$ and $R + 90^o$, respectively. Four local coordinate systems at the entrance and exit of these two layers were illustrated in Figure 2(c).

Figure 3 illustrates the schematic diagram of the polarisation state at the entrance and the exit of the first and the second LC layer under the condition that LC twist R was much smaller than the retardation Γ of the LC layer. Propagation direction of the light and the direction of LC director at the entrance of the first LC layer were selected as the z- and x-axis. Based on the behaviour of e-mode and o-mode of Equations (4) and (5), the effect of the proposed configuration on the polarisation state was derived as follows. Incident light polarised to the x-axis corresponded to e-mode at the entrance of the first LC layer. The first LC layer induced the polarisation rotation of $R/2$ and the phase change of $-i\Gamma/2$. Hence, the polarisation state of this light became the polarisation direction of $R/2$ and phase of $-i\Gamma/2$ at the exit of the first LC layer. When this light entered the second LC layer, the polarisation direction of $R/2$ was perpendicular to the LC director at the entrance of the second LC layer. This polarisation corresponded to o-mode at the entrance of the second LC layer in the local principal coordinate system. Then, the second LC layer additionally induced the polarisation rotation of $R/2$ and the phase change of $i\Gamma/2$, to the polarisation state of light entering the entrance of the second layer. As a result, polarisation state coming from the exit of the second layer had the polarisation direction of $R/2 + R/2 = R$ and the phase change of $(-i\Gamma/2 + i\Gamma/2) = 0$.

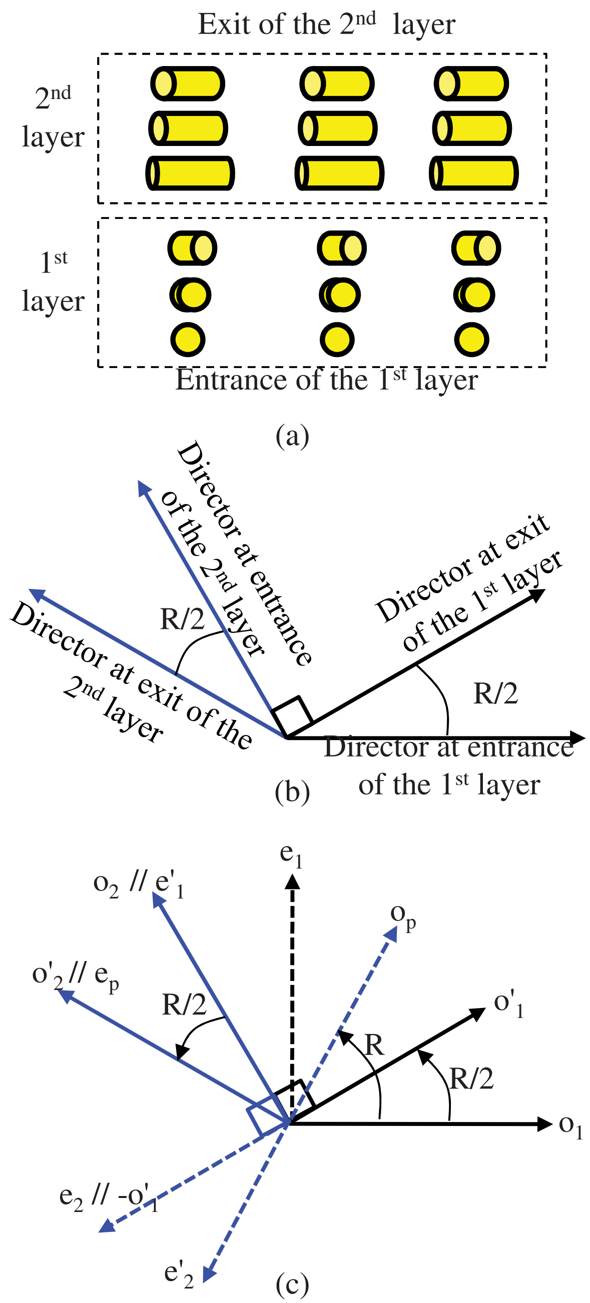

Figure 2. (colour online) Schematic diagram of the configuration of two layers of twist nematic LC for the polarisation rotation of angle *R*. (a) Alignment of two layers of twisted LC. LC directors align homogeneously with the twist angle of *R*/2. (b) Azimuth angle of LC directors at the exit and the entrance for the first and the second LC layer. LC directors at the exit of the first layer and entrance of the second layer are perpendicular. (c) Local coordinate system of e- and o- mode. Subscript 1 and 2 represent the first and second layer. Prime symbol represent the e- and o- mode at the exit.

Incident light polarised to the *y*-axis was perpendicular to LC director at the entrance of the first LC layer and corresponded to o-mode at the entrance of the first LC layer. This light became the polarisation state of the direction of (90^{o} + $R/2$) and the phase of $i\Gamma/2$ by the first LC layer. When this light entered the second LC layer, the polarisation direction of angle (90^{o} + $R/2$) corresponded to e-mode at the entrance of the second LC layer. Then, the second LC layer induced the rotation of $R/2$ and the phase change of $-i\Gamma/2$, additionally. As a result, the polarisation state coming from the exit of the second layer became the polarisation state of direction of (90^{o} + R) and the zero phase change. Any linear polarisation incident on the proposed configuration can be decomposed into E- and O-component. Each component will propagate through the proposed configuration with the change of rotation angle *R* and the zero phase change at the exit of the second LC layers. At the exit of the second LC layer, the phases of E- and O-component are the same. Hence, E- and O-component can combine to be linear polarisation while the polarisation direction is changed by the amount of angle *R*.

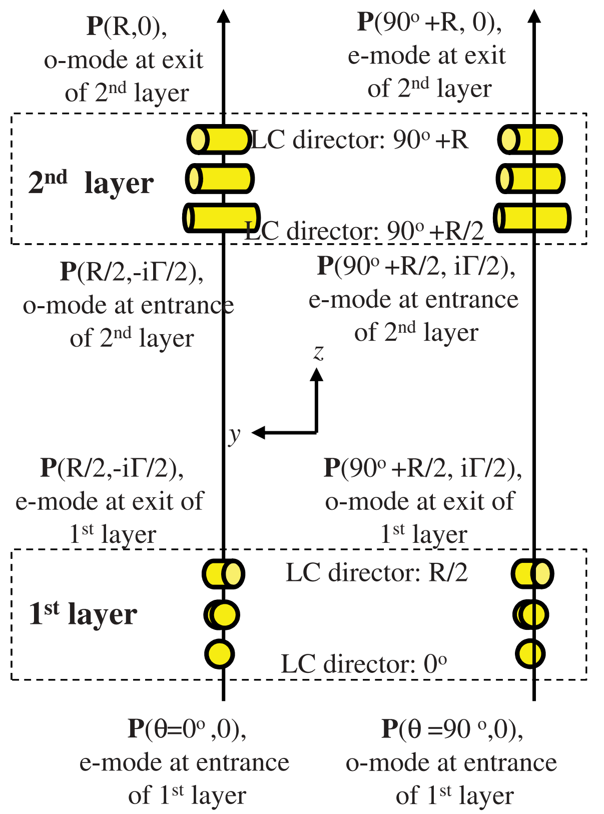

Figure 3. (colour online) Schematic analysis of linear polarisation of E-mode and O-mode through the configuration of two layers of the twisted nematic LC for the small twist angle. Linear polarisation **P** is represented by the polarisation angle and phase.

If this schematic analysis of the effect of the proposed configuration is correct, it means that the proposed configuration can rotate the linearly polarised light by the angle *R*, irrespective of the initial polarisation direction. The adiabatic following condition that the change of LC twist is small enough compared with the overall phase retardation Γ of LC layer is also little dependent on the wavelength. Hence, the phenomenon of the polarisation rotation is expected to be little affected by the wavelength of the incident light.

Change of the polarisation state by the proposed configuration has been analysed by the Jones matrix representation. The angle R is equal to 2φ. For e-mode, polarisation state through the first LC layer can be represented as

$$M\begin{pmatrix}1\\0\end{pmatrix}_{e_1o_1} = \begin{pmatrix}\cos x - i\frac{\Gamma \sin x}{2x}\\ -\varphi\frac{\sin x}{x}\end{pmatrix}_{e_1'o_1'} \equiv \begin{pmatrix}Y\\ -\beta_0\end{pmatrix}_{e_1'o_1'} \quad (6)$$

Local coordinate system for the polarisation illustrated in Figure 2(c) is noted on the lower right side of each Jones vector. For o-mode, polarisation state through the first LC layer can be represented as

$$M\begin{pmatrix}0\\1\end{pmatrix}_{e_1o_1} = \begin{pmatrix}\varphi\frac{\sin x}{x}\\ \cos x + i\frac{\Gamma \sin x}{2x}\end{pmatrix}_{e_1'o_1'} \equiv \begin{pmatrix}\beta_0\\ Y^*\end{pmatrix}_{e_1'o_1'} \quad (7)$$

Hence, the polarisation change by the first LC layer for the polarisation state $(a,\ b)$ can be represented as

$$M\begin{pmatrix}a\\b\end{pmatrix}_{e_1o_1} = \begin{pmatrix}aY + b\beta_0\\ bY^* - a\beta_0\end{pmatrix}_{e_1'o_1'} \quad (8)$$

As E- and O- component of Equation (8) is represented in the local coordinates of the exit of the first LC layer, these are changed into the values at the local coordinates of the entrance of the second LC layer and then M for the second LC layer is applied:

$$M\begin{pmatrix}-bY^* + a\beta_0\\ aY + b\beta_0\end{pmatrix}_{e_2o_2} = \begin{pmatrix}-b + 2a\beta_0 Y + 2b{\beta_0}^2\\ a + 2b\beta_0 Y^* - 2a{\beta_0}^2\end{pmatrix}_{e_2'o_2'} \quad (9)$$

Equation (9) represents the polarisation state by the proposed configuration of the two twisted LC layers. E- and O-components of Equation (9) are represented in the local coordinates of the exit of the second LC layer. The angle between the LC director at the entrance of the first LC layer and the exit of the second LC layer is $90^{\circ} + R$. If the local coordinate system with the angle of R to the coordinate system of the entrance of the first LC layer is selected, E-component of Equation (9) become O-component and O-component become negative value of E-component. Hence, Equation (9) can be written as

$$\begin{pmatrix}a + 2b\beta_0 Y^* - 2a{\beta_0}^2\\ b - 2a\beta_0 Y - 2b{\beta_0}^2\end{pmatrix}_{e_po_p} = \begin{pmatrix}a\\b\end{pmatrix}_{e_po_p} + \beta_0\begin{pmatrix}2bY^*\\ -2aY\end{pmatrix}_{e_po_p} - {\beta_0}^2\begin{pmatrix}2a\\2b\end{pmatrix}_{e_po_p} \quad (10)$$

If the Jones vector of Equation (10) becomes $(a,\ b)$ in the local coordinate system of $(e_p\ o_p)$, it means that the rotation of the polarisation direction of the initial polarisation $(a\ b)$ by the angle of R. In Equation (10), the effect of β_0 is represented in terms of $O(\beta_0)$ and $O({\beta_0}^2)$. The size of β_0, which is defined as $\varphi \sin x/x$, can be treated as the deviation and Jones vector approaches $(a\ b)$ for small β_0. Equation (10) agrees with the condition of the small twist angle and/or $x = \pi$ as β_0 approaches zero at the condition of the small twist angle and/or small sin x.

3. Simulation

Commercial software (Techwiz LCD 1D simulator) was used to investigate the effectiveness of the proposed configuration for the twist angle R of 30°, 60° and 90°, compared with the one twisted LC layer.[6] The set-ups for the simulation were illustrated in Figure 4. LC directors at the entrance and the exit of LC layer were homogeneously aligned with the uniform twist as illustrated in Figure 4. $(n_e - n_o)$ of 0.11 were selected. Mechanical properties of LC were k_{11} = 11.4 pN, k_{22} = 4.8 pN and k_{33} = 11.5 pN. The pitch of LC was selected to be infinite and a strong anchoring condition was used. For $x = p$ at the wavelength of 550 nm, thickness of each LC layer shown in Table 1 was determined from Equation (2). Figure 4(a) illustrated the configuration of one twisted

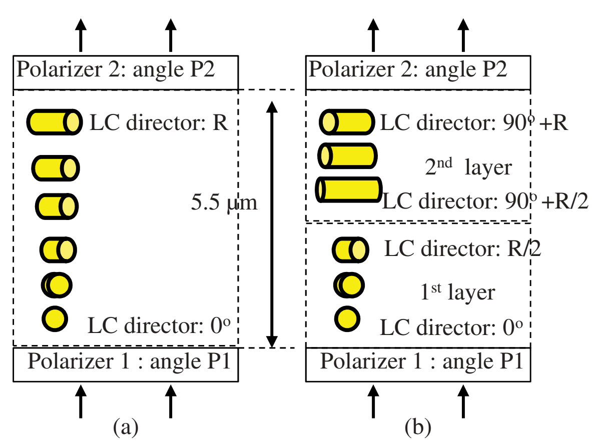

Figure 4. (colour online) Setup for simulation for (a) the known configuration of one layer of twisted LC (b) the newly proposed configuration of two layer of twisted LC. P1 and P2 represent the angle of transmittance axis at the polariser P1 and P2.

Table 1. Simulation condition for the configuration of two layer and one layer of the twisted LC where ($n_e - n_o$) is 0.11.

Simulation condition of Two layer			
R:Total twist	30 degree	60 degree	90 degree
$(\Gamma/2\pi)^2$	143/144	35/36	15/16
d(μm)	4.98	4.93	4.84
Simulation condition of one layer			
ϕ: twist of a layer	30 degree	60 degree	90 degree
$(\Gamma/2\pi)^2$	35/36	8/9	3/4
d(μm)	4.93	4.71	4.3

LC layer with the retardation Γ and the rotation angle R. Figure 4(b) illustrated the proposed configuration of two layers of twisted nematic LC medium where two layers of the retardation Γ/2 and twist angle $R/2$ were placed between the crossed polarisers. P1 and P2 represented the direction of the transmittance axes of the polariser 1 and 2. The condition of the transmittance axis of polariser 1, P1 was selected as 0°, 30°, 60° and 90°, while direction of LC directors at the entrance was selected to be 0°. Light through polariser of P1 at the angle of 0° and 90° corresponded to e-mode and o-mode. Polarisation direction of the incident linear polarisation was controlled by the change of angle P1 of the polariser 1. As the axes of these polarisers varied, the transmittance through these two configurations was calculated. The calculated transmittance was normalised to the transmittance of the parallel polarisers without any LC medium between the polarisers. If the polarisation direction of the linear polarisation became parallel to the transmittance axes of polariser 2 by the LC layer, the normalised transmittance would be calculated to be 100% at the specific angle of P2. To investigate the dependence on the wavelength, transmittance for the wavelength of 450 and 650 nm as well as 550 nm were calculated as well.

4. Results and analysis

Figure 5 illustrates the calculated normalised transmittance at the twist angle $R = 30^{\circ}$ at the wavelength of 450, 550 and 650 nm for one LC layer and the newly proposed configuration of two LC layers of Figure 4. At 550 nm where sin x = 0, the calculated transmittance for two configurations approached 100% when the angle P2 of the polariser 2 was at the angle of P1 + 30° irrespective of the initial polarisation direction P1. But for 450 and 650 nm, the calculated result showed quite different trend. For the proposed configuration, the maximum transmittance of ~100% occurred near the angle of

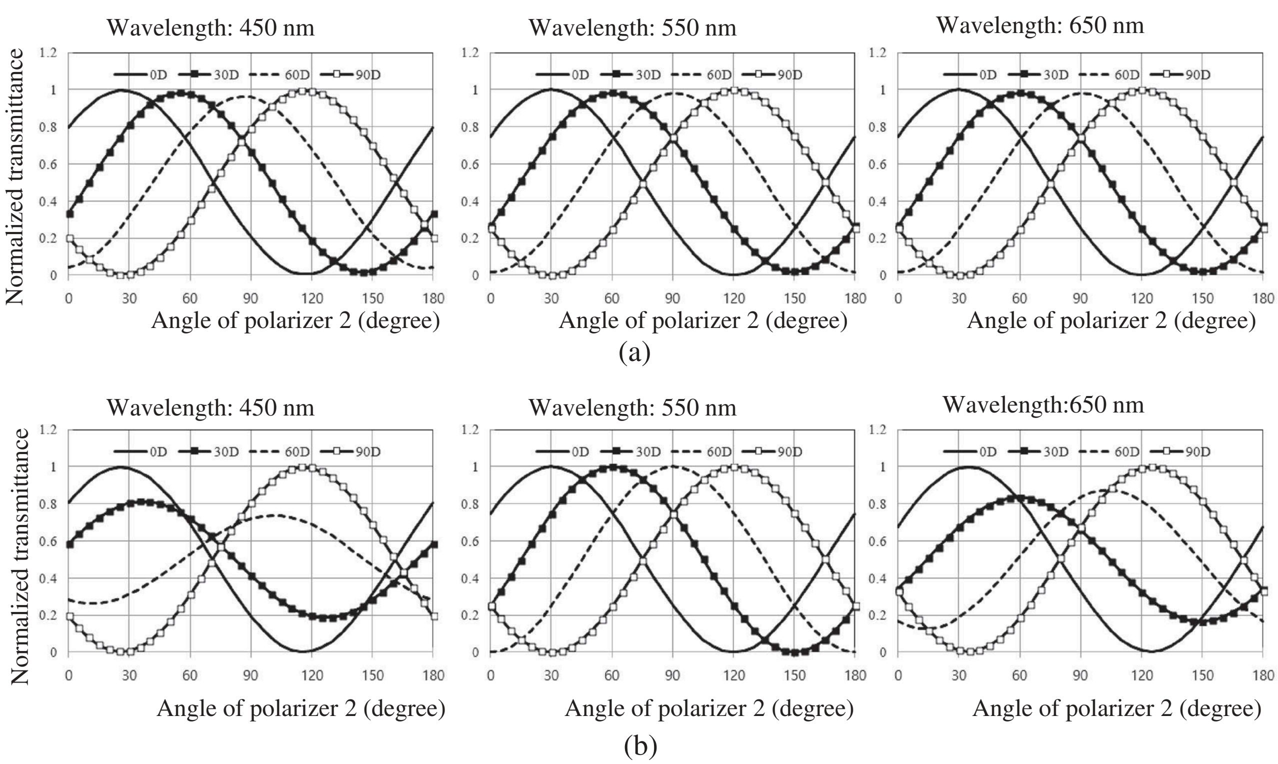

Figure 5. Calculated normalised transmittance for the rotation angle R = 30° for the configuration of (a) the newly proposed two layer of twisted LC and (b) the one layer of the twisted LC at the wavelength of 450 nm, 550 nm and 650 nm. Horizontal axis and vertical axis represent the angle P2 of transmittance axis of polariser 2 and the normalised transmittance. Numbers on the upper side of the graph represent the angle P1 of transmittance axis of polariser 1, which is equivalent to the incident polarisation direction. Conditions of retardation and cell gap were designed for the wavelength of 550 nm.

P1 + 30° for 450 and 650 nm similar to the wavelength of 550 nm. For the configuration of one LC layer, maximum transmittance of the lower value occurred at the angle far from P1 + 30° for P1 of 30° and 60°. The calculated result showed that the two layers of twisted nematic LC was effective to rotate the polarisation direction by the amount of twist angle R = 30° at the different polarisation direction of P1 even for the wavelength where sin x is not zero.

Figures 6 and 7 illustrate the calculated normalised transmittance at the twist angle R = 60° and 90 °. The result showed the trend similar to the twist angle R = 30°. Yet, maximum transmittance occurred at angles slightly smaller than P1 + R for 450 nm and at angles slightly larger than P1 + R for 650 nm for the proposed configuration.

These maximum angles for the conditions of the wavelength of 450, 550 and 650 nm and the various initial polarisation directions of Figures 5–7 are illustrated in Figure 8 for the proposed configuration. In Figure 8, the deviation of the angle tended to increase for larger R. The decrease of maximum angle for the wavelength of 450 nm and the increase of the maximum angle for the wavelength of 650 nm can be related to Equation (10). When the wavelength was not 550 nm, sin x was not zero and terms of $O(\beta_0)$ in Equation (10) could not be neglected. For the wavelength of 450 and 650 nm, sin x became positive and negative values, respectively. As the sign of E- and O-component of $O(\beta_0)$ was opposite, this would make one of (a, b) smaller and the other larger. Hence polarisation direction for the wavelength of 450 and 650 nm would be affected oppositely.

Table 2 showed the normalised transmittance through the proposed configuration of two twisted LC layers at the designed rotations angles of P1 + R for the wavelength of 450, 550 and 650 nm. The transmittance decreased for larger twist angle. But in Table 2, the transmittances at the angle of P1 + R were still larger than 90%, even when the angle of the maximum transmittance deviated from P1 + R. For example, at the condition of R = 60°, the wavelength of 450 nm and the initial polarisation direction of 60°, the maximum transmittance occurred at the angle of 112° while the transmittance at the angle of 120° was 94%.

HWP of the uniaxial material can be used as the polarisation rotator for the different amount of the rotation angle, but it is known to be strongly dependent on the wavelength and the angle between the optic axis of HWP and the polarisation direction had to be

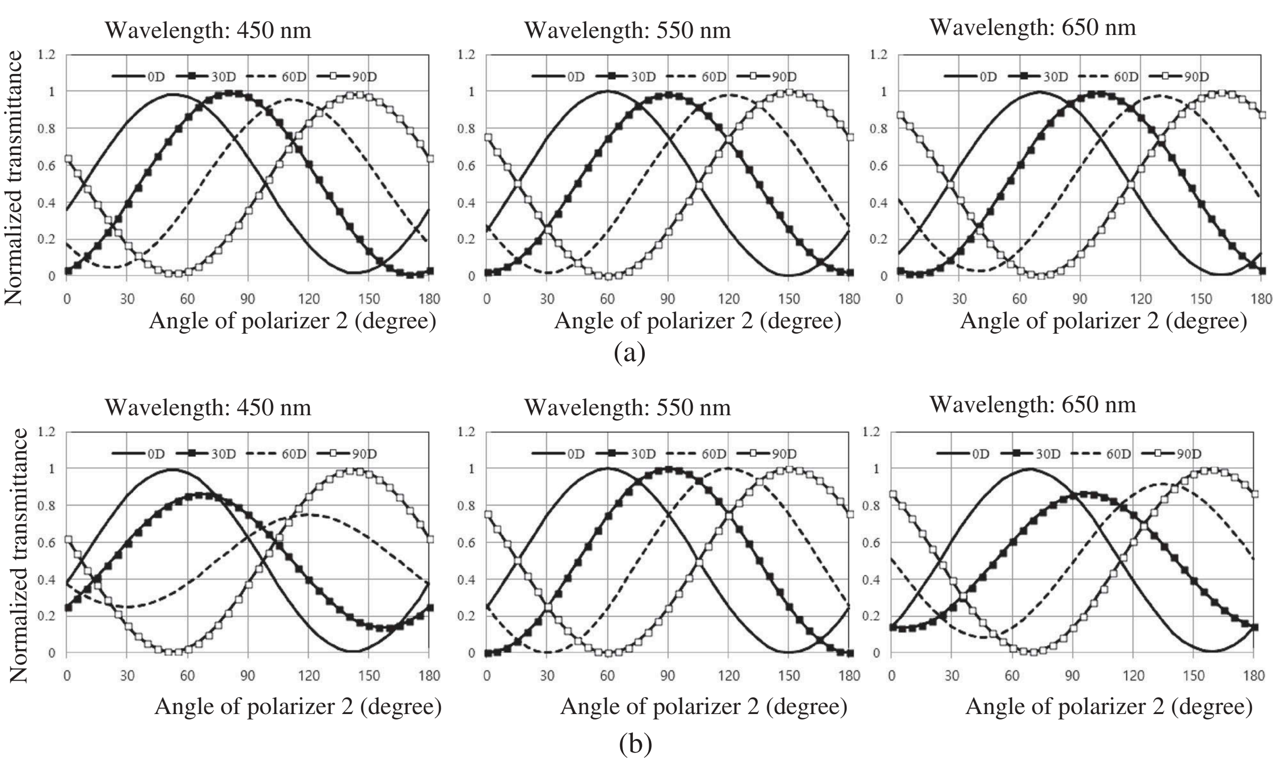

Figure 6. Calculated normalised transmittance for the rotation angle R = 60° for the configuration of (a) the newly proposed two layer of twisted LC and (b) one layer of the twisted LC at the wavelength of 450 nm, 550 nm and 650 nm. Horizontal axis and vertical axis represent the angle P2 of transmittance axis of polariser 2 and the normalised transmittance. Numbers on the upper side of the graph represent the angle P1 of transmittance axis of polariser 1. Conditions of retardation and cell gap were designed for the wavelength of 550 nm.

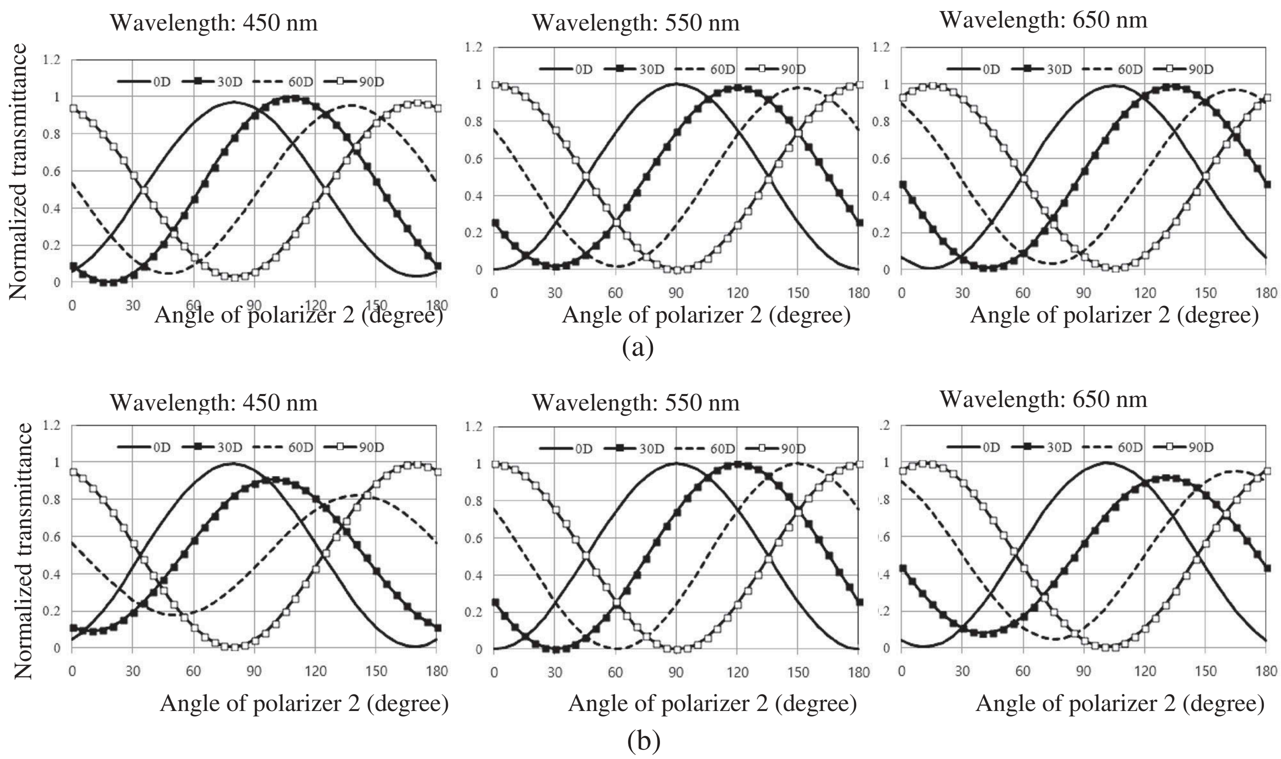

Figure 7. Calculated normalised transmittance for the rotation angle R = 90° for the configuration of (a) the newly proposed two layer of twisted LC and (b) one layer of the twisted LC at the wavelength of 450 nm, 550 nm and 650 nm. Horizontal axis and vertical axis represent the angle P2 of transmittance axis of polariser 2 and the normalised transmittance. Numbers on the upper side of the graph represent the angle P1 of transmittance axis of polariser 1. Conditions of retardation and cell gap were designed for the wavelength of 550 nm.

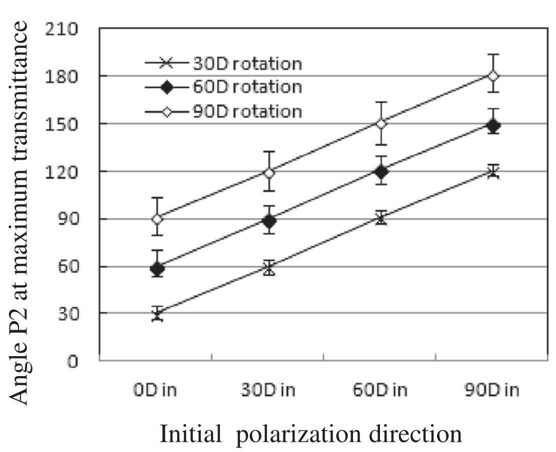

Figure 8. Angles of the polariser 2 when the transmittance was the maximum for the wavelength 450,550 and 650 nm for the proposed configuration whose condition was designed for the wavelength of 550 nm. 30D, 60D and 90D rotation on the upper left side represent the rotation angles R. The horizontal axis represents the incident polarisation direction of the linearly polarised light. The vertical axis represents the angle of the polariser 2 when the transmittance was the maximum. Lower and upper error bar on the graph represent the angle of polariser 2 at the maximum transmittance for 450, 650 nm.

Table 2. Normalised transmittance for the proposed configuration of two twisted LC Layer at the designed angle of P1 + R for the wavelength of 450, 550 and 650 nm and the polarisation direction P1 of 0, 30, 60 and 90° of the incident linear polarisation.

Total Twist R	wave length	0D in	30D in	60D in	90D in
30 degree	450nm	0.99	0.98	0.96	0.99
	550nm	1.00	0.98	0.98	1.00
	650nm	0.99	0.98	0.97	0.99
60 degree	450nm	0.97	0.97	0.94	0.97
	550nm	1.00	0.98	0.98	1.00
	650nm	0.97	0.97	0.95	0.97
90 degree	450nm	0.94	0.95	0.91	0.94
	550nm	1.00	0.98	0.98	1.00
	650nm	0.93	0.94	0.92	0.93

aligned. For the proposed configuration the initial polarisation direction of the incident light need not be aligned with respect to the direction of LC director. And the proposed configuration show the less dependence on the wavelength, compared with the one layer of twisted LC or HWP of the uniaxial material.

Reactive mesogen had been reported to produce the film of the various anisotropic structures similar to LC layer and commercialised for the application such as stereoscopic 3D display using the patterned retarder. [7–9] Using materials like RM, a layer of twisted LC medium can be made as the film.

5. Conclusion

Effective of polarisation rotation using the twisted LC medium were investigated. Configuration of the one layer of twisted LC was mostly only for the designed specific wavelength as it strongly depended on the wavelength. The performance of the proposed configuration using two layers of twisted LC had shown to be less dependent on the wavelength and be effective to rotate the polarisation direction irrespective of the initial polarisation direction.

While the amount of the rotation angle cannot be changed in the proposed structure, the proposed structure may be used as the polarisation rotator for the lights of multiple wavelengths, irrespective of the initial polarisation direction.

Disclosure statement

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