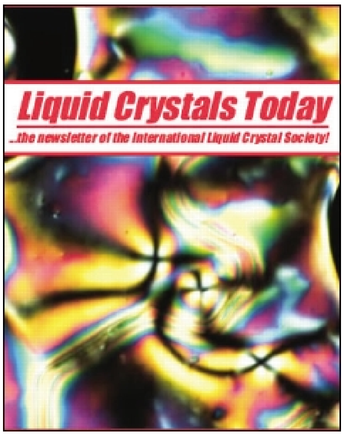

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Yi-Hsin Lin[a]; Hongwen Ren[b]; Shin-Tson Wu[b]
[a] Department of Photonics and Institute of Electro-Optical Engineering, National Chiao Tung University, Hsinchu, Taiwan 30010, ROC [b] College of Optics and Photonics, University of Central Florida, Orlando, Florida 32816

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Polarisation-independent liquid crystal devices

Yi-Hsin Lin[a]*, Hongwen Ren[b] and Shin-Tson Wu[b]

[a]*Department of Photonics and Institute of Electro-Optical Engineering, National Chiao Tung University, Hsinchu, Taiwan 30010, ROC;* [b]*College of Optics and Photonics, University of Central Florida, Orlando, Florida 32816, USA*

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Liquid crystal (LC) devices can be used as amplitude modulators and phase modulators. Most LC devices are polarisation-dependent and require at least one polariser. As a result, the optical efficiency is greatly reduced. In this paper, we review some of our recently developed polarisation-independent LC devices. For amplitude modulation, we report two polariser-free devices which combine light scattering with dye absorption: dye-doped polymer-dispersed liquid crystal (PDLC) and dye-doped LC gels. For phase modulation, we also present two examples: residual phase type, e.g., voltage-biased PDLC, Polymer-Stabilised Cholesteric Texture (PSCT), and homeotropic LC gels; and double-layered structure, such as thin polymer film-separated orthogonal LC layers, and double-layered LC gels. Potential applications of these polarisation-independent LC devices for displays, laser beam steering and adaptive optics are emphasised.

Keywords: liquid crystal devices; polarisation-independent; polariser-free; amplitude modulation; phase modulation

1. Introduction

Liquid crystal (LC) devices have been widely used as amplitude and phase modulators (*1*). The most popular examples of amplitude modulators are LCD TVs, desktop computers, notebook computers and cell phones. In these devices, two crossed polarisers and compensation films are employed in order to obtain a high-contrast ratio and wide viewing angles. However, due to the use of polarisers the overall optical efficiency of a wide-view LCD panel is only $\sim$5%. It is highly desirable to develop polariser-free LCD devices. On the other hand, phase-only modulation (*2*) has been widely used in adaptive optics, optical cross-connect switching, laser beam steering and low-cost electro-optical sensors. Potential applications include self-adjusted eye-glasses, tunable-focus lenses (*3, 4*), electrically tunable gratings and prisms (*5*) and spatial light modulators (*6*). LC phase modulators have some desirable features, including being electrically controllable without any mechanical moving part, low cost, light weight and having low power consumption.

Several LC configurations have been developed for realising phase modulations, such as homogeneous cell (*7*), polymer network liquid crystal (PNLC) (*8*) and sheared polymer network liquid crystal (SPNLC) (*9, 10*). However, these devices require a linearly polarised light so that their optical efficiency is greatly reduced unless a linearly polarised laser beam is employed.

In this paper, we review the underlying physics and device structure for realising polarisation-independent LC amplitude and phase modulations. Examples include three amplitude modulators: a polymer-dispersed liquid crystal (PDLC) confined in a 90° twisted cell (T-PDLC) (*11, 12*), a dye-doped PDLC (*11*) and dye-doped LC gels (*13–15*), and two phase modulators: residual phase type (*16–18*) and double-layered structures (*19, 20*).

2. LC amplitude and phase modulations

Generally speaking, a monochromatic plane-polarised wave contains three components: amplitude, phase and polarisation. When the light wave propagates through an LC cell, the light wave is modulated by the LC layer in amplitude, phase or both. (*21*) The schematic figures of LC amplitude modulation and phase modulation are depicted in Figure 1. How can we achieve a polarisation-independent LC amplitude or phase modulation, since the LC refractive index is polarisation sensitive?

3. Polarisation-independent LC amplitude modulators

Several mechanisms can be used for amplitude modulations, e.g., light scattering, absorption or combination of both. In order to obtain a polarisation-independent LC amplitude modulation, we can

*Corresponding author. Email: yilin@mail.nctu.edu.tw

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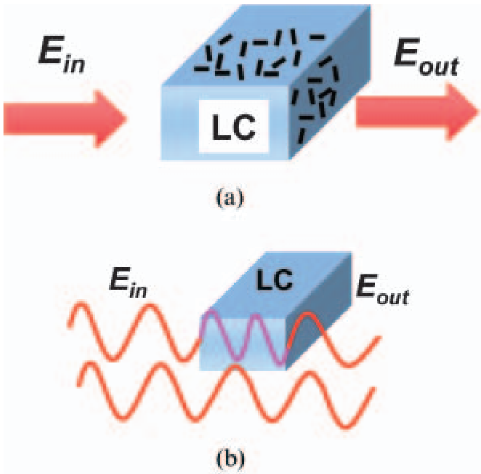

Figure 1. Schematic (a) LC amplitude modulation and (b) phase modulation.

randomly arrange LC directors to eliminate the polarisation dependency. By means of polymer networks, the LC directors can be randomly distributed in polymer domains. The refractive index mismatch and polydomain structures result in polarisation-independent scattering. However, light scattering makes the device translucent, rather than black. For display applications, we need a good black state. To achieve this, we can add a small amount (2–3 wt%) of dichroic dye molecules into randomly orientated LC directors, which, in turn, absorb the incident light regardless of its polarisation. Moreover, the combination of scattering and absorption, which is analogous to a piece of white paper written with ink, makes the polarisation-independent amplitude modulation more efficient.

3.1 T-PDLC

We have demonstrated a scattering-type amplitude modulator using a polymer-dispersed liquid crystal confined in a T-PDLC (*11*). The T-PDLC exhibits a higher contrast ratio than a conventional PDLC although its cell gap is thinner. Unlike the traditional PDLC cell, our polyimide-buffed substrates are rubbed in orthogonal directions, similar to a 90° twisted nematic cell. Due to the surface pinning effect (*12*) in a thin cell, T-PDLC has smaller LC droplets and better uniformity, as shown in Figure 2. Therefore, T-PDLC not only preserves the advantage of polarisation independence but also exhibits a higher light-scattering efficiency.

3.2 Dye-doped T-PDLC

The scattering-type T-PDLC is switched between translucent and transparent states, instead of black and white. To realise a black and white state for display applications, we added a ~2 wt% black dye to the T-PDLC cell to increase light absorption (*11*). The bottom ITO electrode was etched into a segmented number '8', and a piece of white paper was put behind the bottom substrate serving as a diffusive reflector. Figure 3 shows the displayed image at $V=20\ V_{rms}$. The on-state T-PDLC is highly transparent so that the reflected image appears white. Since the display does not require a polariser, the viewing angle is wide and the display is bright under room light conditions. The display contrast ratio was measured to be ~10:1, limited by the dichroic ratio of the employed dye molecules. Further increasing the dye concentration would enhance the display contrast ratio at the tradeoffs of lower bright-state reflectance and slower response time.

The contrast ratio of the dye-doped T-PDLC was still not good enough, for several reasons (*22*). First, there is the solubility problem which means some dyes are dissolved not only in the LC host but also in the polymer matrix. The dyes dissolved in the polymer matrix affect the light scattering and also change the absorbance. Second, the order parameter

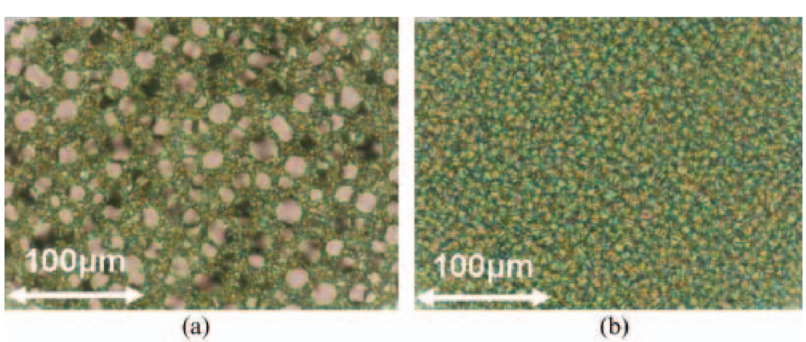

Figure 2. Phase separation morphologies of (a) PDLC and (b) T-PDLC observed from a polarised optical microscope. The cell gap of both cells was d~8 μm. The T-PDLC has a ~1.5× smaller and more uniform droplet size than PDLC (*11*).

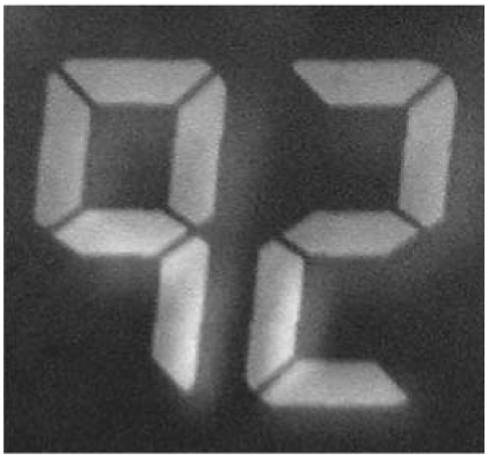

Figure 3. The displayed image using a dye-doped T-PDLC reflective display at $V=20\ V_{rms}$. White paper was placed behind the bottom substrate as a diffusive reflector. Black dye concentration: 2%, LC/polymer mixture: NOA65: *E48*=40:60, $d=6.7\,\mu m$ (*11*).

of dye is not as good as the LC host. Third, the dye concentration we used is low and its dichroic ratio is not high enough.

3.3 Dye-doped LC gels

To avoid the possibility of dye molecules being dissolved into the polymer matrix, we considered a polymer network structure. Here, we demonstrate a guest–host LCD using a dye-doped dual-frequency liquid crystal gel and dye-doped LC gels to realise polariser-free, fast response, and high contrast reflective display (*13–15*). The light modulation mechanisms of the dye-doped LC gel are schematically depicted in Figure 4(a). At $V=0$, the cell does not scatter light and the absorption is rather weak because the dye molecules are aligned perpendicular to the substrates, as shown in Figure 4(a). Therefore, the dye-doped LC gel has the highest reflectance. When the applied voltage exceeds a threshold, the LC directors and dye molecules are tilted away from the electric field because the LC has a negative $\Delta\varepsilon$. Under such a circumstance, the gel is switched into a micron-sized domain structure. The tilted direction is random because the substrates do not have any alignment treatment. As a result, the reflectance is reduced due to the light scattering of the gel and absorption of the dyes. As the applied voltage increases further, the liquid crystals and dye molecules are reoriented in the *x*–*y* plane, so that light scattering and dye absorption efficiency reach their maxima and the display appears black and is polarisation-independent. The dye-doped LC gel is not only polariser-free, but also bendable and trimable because of the gel-like structure when the glass substrates are replaced by plastic substrate, as shown in Figure 4(b) (*15*).

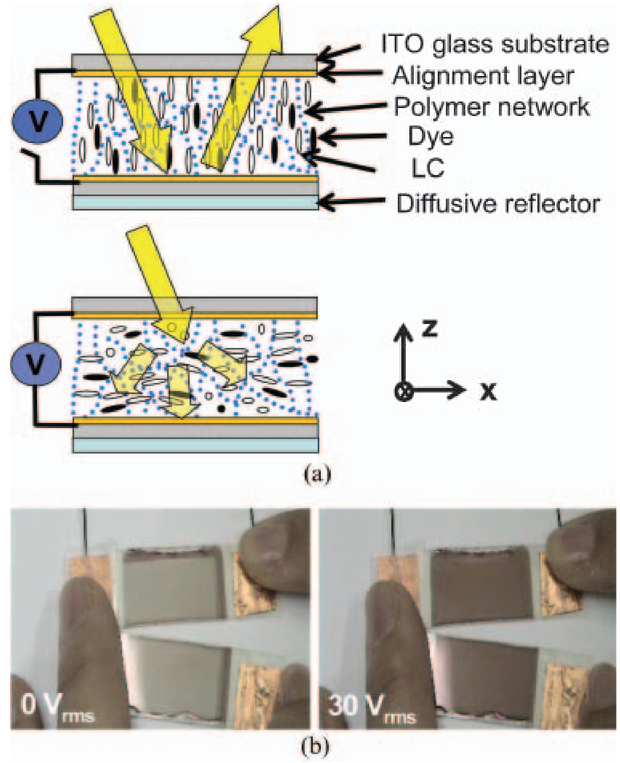

Figure 4. (a) Structure and operating principles of the dye-doped LC gel. (b) The dye-doped LC gel is trim-able (*15*).

4. Polarisation-independent LC phase modulators

When considering phase modulations, a scattering effect is undesirable. Here we present two types of polarisation-independent LC phase modulations: residual phase type and double-layered type.

4.1 Residual phase type

In the residual phase type polarisation-independent LC phase modulators, all the LC directors have same tilt angle except their orientations are random, as Figure 5(a) shows. The projected LC director distribution in the *x*–*y* plane is depicted in Figure 5(b).

Let us consider a randomly polarised quasi-monochromatic light incident to a sample at normal angle. The electric field of the incident light can be written as:

$$\vec{E}(\vec{r},t)_{input} \sim \sum_j \left[a_j(\vec{r},t)\cdot\left(A_{0x}(\vec{r},t)\hat{x}+A_{0y}(\vec{r},t)\hat{y}\right)_j\right], \quad (1)$$

where $A_{0x}(\vec{r},t)$ and $A_{0y}(\vec{r},t)$ are two complex numbers that are functions of position ($\vec{r}$) and time

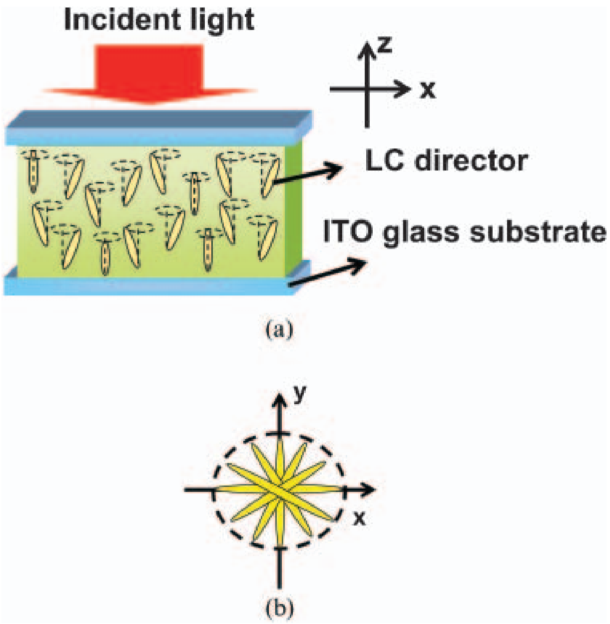

Figure 5. (a) Residual phase type of LC phase modulators at voltage-off state, and (b) the projected LC directors of (a) in the x–y plane.

(t), and they satisfy the following relationship: $A_{0x}(\vec{r},t)^2 + A_{0y}(\vec{r},t)^2 = 1$. The coefficient $a_j(\vec{r},t)$ is a complex weighting factor for the j^{th} component and $\left(A_{0x}(\vec{r},t)\hat{x} + A_{0y}(\vec{r},t)\hat{y}\right)_j$ represents the polarisation of the j^{th} component. The LC cell has the same averaged refractive index for all the polarisation states of incident light when the beam size is large enough and LC directors are randomly distributed. When an unpolarised light propagates into the polarisation-independent LC phase modulator, the output light becomes:

$$\vec{E}(\vec{r},t)_{output} \sim e^{-i\delta} \cdot \sum_j \left[a_j(\vec{r},t) \cdot \left(A_{0x}(\vec{r},t)\hat{x} + A_{0y}(\vec{r},t)\hat{y}\right)_j\right]. \quad (2)$$

The output and incident lights have the same polarisation states except for a phase difference δ as shown in Equation (2). As the applied external electric field increases, the LC directors (here the LC $\Delta\varepsilon > 0$) are reoriented along the electric field direction. However, the projected LC directors in the voltage-on state remain similar, except for a smaller diameter. Therefore, such a device is polarisation independent in all the voltage states. The phase shift (δ) between the voltage-on and voltage-off states is:

$$\delta = \frac{2\pi}{\lambda} \cdot (n_{ave}(V) - n(0)) \cdot d, \quad (3)$$

where λ is the light wavelength, d is the LC cell gap, $n(0)$ is the refractive index of LC at $V = 0$, and $n_{ave}(V)$ is the averaged refractive index at a voltage-on state which is also related to the tilt angle of LC directors. In Equation (3), the phase difference is dependent on the applied voltage because the reorientation of the LC directors is electrically tunable. The reason that we label this device as 'residual phase' is because it requires the same tilt angle on the LC directors as are normally obtained from moving from a biased voltage state to another higher biased voltage state. As a result, the available phase change is relatively small ($<1\pi$), although it is polarisation independent. Several approaches have been carried out to realise such a phase modulation (*16–18*). For example, we can use UV light to illuminate a normal-mode polymer-stabilised cholesteric texture (PSCT) (*17*) in the homeotropic state with the presence of a bias voltage (40 V_{rms}) in order to obtain polymer networks perpendicular to the glass substrates. After the polymerisation process, the applied voltage is removed and a focal conic texture is formed due to the competition between the intrinsic spiral structure and the polymer constraint, as Figure 6(a) shows. In this state, the cell is translucent because of strong

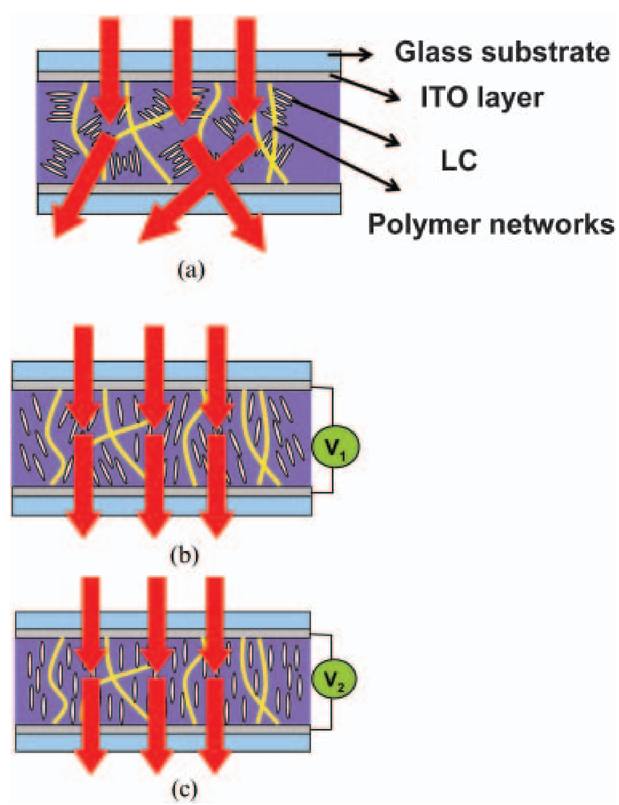

Figure 6. The schematic structure and operating principles of PSCT at (a) $V = 0$, (b) $V_1 = V_s$, and (c) $V2 > V_1$. The residual phase between (b) and (c) can be used for a phase modulator (*17*).

light scattering originating from the poly-domain focal conic structures. As the voltage reaches saturation level, the electric field unwinds and transforms the spiral LC structures into a nearly homeotropic state. The PSCT cell is transparent, as shown in Figure 6(b). All the LC directors have the same tilt angle, but are randomly oriented. As the voltage exceeds *Vs*, more LC directors are aligned towards the vertical direction, as shown in Figure 6(c). Although the phase change between Figure 6(b) and Figure 6(c) is small, it is scattering-free, polarisation-independent, hysteresis-free and has a fast response time.

Besides PSCT, two more such polarisation-independent LC phase modulators using PDLC (*16*), and homeotropic LC gels (*18*) with their LC orientations, shown in Figure 7, have been demonstrated. The remaining phase shift at λ=633 nm is around 0.1 π and the voltage is relatively high (~60–200 V), but the response time is fast because of the strong anchoring and small domain sizes from the polymer networks.

4.2 *Double-layered structure*

Another approach to achieving polarisation independence is to stack two identical homogeneous LC layers together in orthogonal directions (*19, 20*), as shown in Figure 8(a). The projected LC directors in the *x–y* plane at different voltages are illustrated in Figure 8(b). The underlying principle is that an unpolarised light can be decomposed into two linear eigen-modes, say *x* and *y* linearly polarised lights. After propagating through the two stacked LC layers, each eigen-mode experiences a phase shift δ_1 and δ_2, respectively. After propagating through the

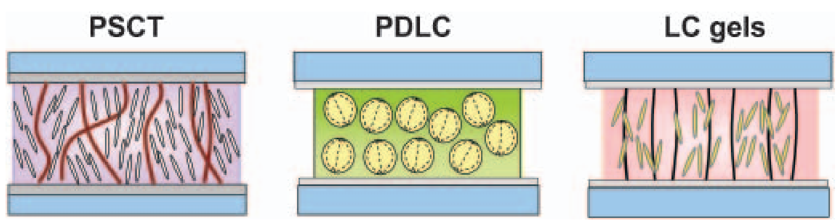

Figure 7. Residual phase type LC phase modulators using PSCT, PDLC, and LC gel (*16–18*).

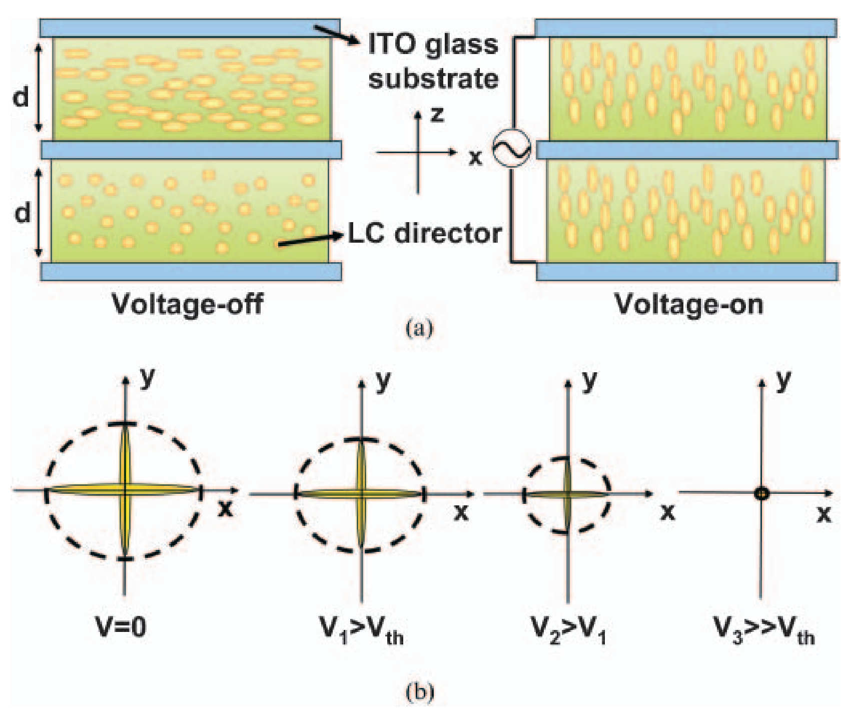

Figure 8. Double-layered type LC phase modulators. (a) A doubled-layered homogeneous cell. (b) Projected LC directors in the *x–y* plane at difference voltages.

LC modulator at $V=0$ V_{rms}, the outgoing electric field can be expressed as:

$$\vec{E}(\vec{r},t)_{output} \sim \sum_j \left[a_j \cdot \left(e^{-i\cdot\delta_1} \cdot A_{0x} \cdot e^{i\varphi_x} \cdot \hat{x} + e^{-i\cdot\delta_2} \cdot A_{0y} \cdot e^{i\varphi_y} \cdot \hat{y}\right)\right]_j \quad (4)$$

If the two LC layers are identical, that means δ_1 is equal to δ_2, then Equation (4) is reduced to Equation (2). Therefore, the output polarisation remains the same and the device is polarisation-independent. When the applied voltage exceeds a threshold, the distribution of the projected LC directors remains the same but its radius gets smaller, as shown in Figure 8(b). Thus, this double-layered device is indeed polarisation-independent in all voltage states. The total phase shift (δ) of double-layered LC phase modulators between the voltage-on and voltage-off states is:

$$\delta = \frac{2\pi}{\lambda} \cdot (n_e - n_o) \cdot d \quad (5)$$

where n_e is the extraordinary refractive index of the LC. The total phase shift depends on the birefringence of the employed LC.

Figure 9 depicts the two types of double-layered LC structures developed. On the left is a double-layered phase modulator using a thin anisotropic polymer film to separate the LC layers (*19*), and on the right is a double-layered LC gel (*20*). Polarisation-independent LC phase modulators using a twisted-nematic (T) LC cell (*23*) also belong to this category because the LC directors in the bulk region of a TN cell are reoriented by the electric field, but the LC directors near the two substrate boundaries are orthogonal to each other. Under such a circumstance, the LC cell looks like a double-layered structure having a LC layer as cell separator.

The polarisation-independent LC amplitude modulators and phase modulators we introduced are summarised in Tables 1 and 2, respectively. The scattering-type T-PDLC is polarisation-independent; it has a high scattering efficiency even in a thin cell because of the surface pinning effect. The dye-doped T-PDLC shows the black and white state by combining scattering and absorption effects. The dye-doped LC gels can further improve the electro-optical performance by polymer network structures. As for the polarisation-independent LC phase

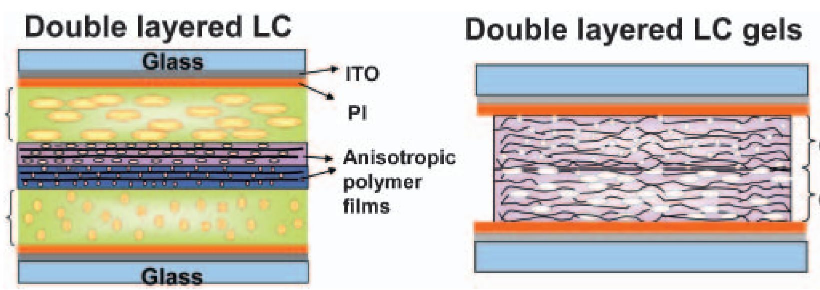

Figure 9. Doubled-layered LC phase modulators using pure LC (left) and LC gels (right) (*19–20*).

Table 1. Summary of polariser-free LC amplitude modulators (*11–15*).

Mechanism	LC mode	CR	Response time (ms)	Max. Reflectance (%)	V_{th}/V_{op} (V_{rms}/V_{rms})	Cell gap (µm)
Scattering	TPDLC	900:1	15	95	7/20	6.5
Scattering	Dye-doped TPDLC	10:1	15	40	7/20	6.7
absorption	Dye-doped LC gels	450:1	6.5	55	7/30	5

Table 2. Summary of polarisation-independent LC phase modulators (*16–20*).

Mechanism	LC mode	Total phase shift (π)	Response time (ms)	Operating voltage range (V_{rms})	Cell Gap (µm)
Residual phase type	PDLC	0.05	3	26–55	22
	PSCT	0.025	0.9	40–160	25
	LC gels	0.08	0.8	130–180	23
Double-layered structure	Double-layered LC	8.1	300	0–50	24
	Double-layered LC gels	1.2	0.7	0–180	16

modulators summarised in Table 2, residual phase type has a small phase shift and fast response. On the contrary, the double-layered LC has a large phase shift, but slow response. The response time can be shortened by using double-layered LC gels; however, the trade-off is the increased driving voltage.

5. Conclusion

We reviewed several polarisation-independent LC devices for amplitude and phase modulations. In amplitude modulation, we discussed the operation principles of T-PDLC, dye-doped T-PDLC, and dye-doped LC gels. In phase modulation, we demonstrated two types of phase modulation: residual phase type and double-layered structure. A polarisation-independent LC device is an inevitable trend for all the amplitude modulators and phase modulators. Besides polarisation independence, colour dispersion and phase difference at oblique angles will be the next important issues to overcome in order to achieve a broadband phase modulator with a large off-axis tolerance. Better dye materials should be developed for display applications. More new polarisation-independent mechanisms should be explored. Finally, we expect this work to inspire more researchers to delve into this area and develop more promising approaches.

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