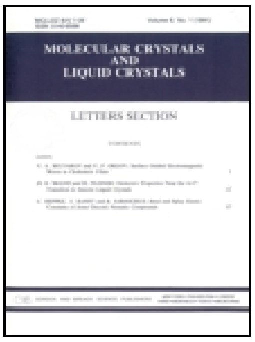
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# Fast-response & Polarization-independent Optical Shutter Using Nano-PDLC Inside a Fabry-Perot Cavity

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*In this paper, we present experimental results obtained for a device incorporating a nano-PDLC inside a Fabry-Perot cavity. Our aim is to produce a fast-response and polarization-independent light shutter with potential applications in e.g. telecommunication systems since nano-PDLC is known for its fast response time. In our chosen example of nano-PDLC with 70 wt% polymer and 30 wt% liquid crystal (E7), we obtained a light shutter with contrast ratio = ∼7.5 under an applied voltage of ∼50 V. Response time is ∼2 to 3ms and transmission is ∼20%. All these device performances, such as operation voltage, transmission and response time can be improved in future by improving the cavity performance and using a faster liquid crystal material. Moreover, comparison in performance is also made for devices with different concentrations of polymer and liquid crystals. Discussion on the residual scattering effect of the nano-PDLC inside the Fabry-Perot cavity is also included. It is interesting to observe that the undesirable effect of the residual scattering of nano-PDLC at low voltages may actually help improve the contrast ratio and/or lower the operation voltage of the device.*

**Keywords** nano-polymer dispersed liquid crystal; nano-PDLC; Fabry-Perot cavity; fast response time; polarization-independent; optical shutter

## 1. Introduction

Polymer Dispersed Liquid Crystal (PDLC) has been intensively investigated in the past due to its high optical efficiency as it doesn't require the use of polarizers [1–2]. It has found commercial applications such as electrically switchable windows. By further increasing the concentration of the polymer content, liquid crystal droplet size decreases and becomes less comparable to the visible light wavelength, hence the scattering effect is also reduced. This also leads to a reduction of contrast ratio. When polymer concentration is high enough, e.g. > ∼70 wt%, the scattering is further reduced and the composite material becomes almost transparent. This is often known as nano-PDLC since the droplet size is now in the nanometer region. Due to its smaller droplet size, the anchoring force on the liquid crystal

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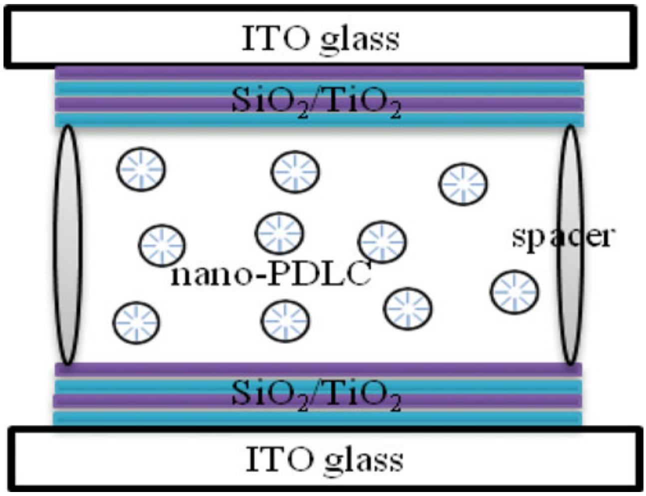


**Figure 1.** Structure of a nano-PDLC Fabry-Perot cavity

molecules also becomes higher (surface to volume ratio increases), this results in fast response time (can be $< 1$ ms by using a suitable liquid crystal material). Moreover it has the property of polarization independence, especially in the normal incident direction. Due to the lack of (or small) scattering, this nano-PDLC has also been proposed for fast-response Phase modulators [3].

In this paper, we propose to use nano-PDLC as a fast response and polarization-independent optical shutter (or intensity modulator). This is achieved by placing the nano-PDLC inside a Fabry-Peort cavity with highly reflective mirrors. Due to the strong resonance effect, a small change in the refractive index in the cavity can result in a large change in intensity. We demonstrate its principle by using results obtained for a nano-PDLC with 70 wt% : 30 wt% polymer to liquid crystal concentration ratio and with mirror reflectivity $= \sim 90\%$.

## 2. Experiment

### *2.1. Structure and Operation Principle of a Nano-PDLC Fabry-Perot Cavity*

Figure 1 shows the structure of our proposed nano-PDLC Fabry-Perot cavity. Basically, it consists of a 5 $\mu$m thick nano-PDLC sandwiched between two reflective dielectric mirrors (reflectivity $\sim$90%) coated on ITO glass substrates. By applying an electric field (through ITO) to the nano-PDLC layer, the LC molecules within the droplets are switched from "partially aligned" orientation to almost parallel alignment (along the electric field). This results in a change of effective refractive index of the nano-PDLC "seen" by the incident light.

In an ideal Fabry Perot cavity, the transmission is given by the Airy function [4]:

$$\mathrm{T} = \frac{1}{1 + \frac{4R^2}{\left(1-R^2\right)^2} \times \sin\left(\frac{2\pi n' d'}{\lambda}\right)^2}.$$

where T is transmittance. *R* is the reflectance of the mirrors, $\lambda$ is wavelength of incident light, $n'$ is effective refractive index of the medium between the two reflective mirrors, $d'$ is effective thickness ( = cell gap of nano-PDLC in our case) of cavity. The transmission is high (ideal case = 1) when constructive interference occurs inside the cavity as a result of multiple reflections that occur inside the cavity (known as resonance condition). On the other hand, transmission is close to zero when destructive interference occurs inside the cavity. As the value of R increases, this resonance condition can become highly sensitive to values of $n'$, $d'$ and $\lambda$. Thus, in the case of nano-PDLC, it is possible to change the output transmission significantly by simply varying a small amount of effective refractive index of the nano-PDLC under an applied electric field.

### *2.2. Fabrication of Nano-PDLC Fabry-Perot Cavity*

Two ITO glass substrates ($\sim$2 cm $\times$ 2 cm) are coated with a stack of multiple layers of high-low refractive index dielectric layers ($SiO_2/TiO_2$). The reflectivity was chosen to be $\sim$90% (with centre wavelength of $\sim$633 nm) in this experiment. Dielectric mirrors were preferred over metallic mirrors due to its smaller absorption and stronger adhesion to the surface of the ITO glass substrates. One of the mirrors is then sprayed with 5 um ball spacers. No alignment layer is required for nano-PDLC (or, in general, PDLC). The two mirror substrates are then assembled and glued with UV epoxy to form a Fabry-Perot cavity. The cell is then filled with a mixture of 30 wt% liquid crystals (E7 with $\Delta n = \sim 0.22$ and $\Delta\varepsilon = \sim +13.78$) and 70 wt% monomer (NOA65) under capillary action. The mixture was then UV cured to form nano-PDLC.

## 3. Experimental Results & Discussion

Figure 2 shows the spectrum of the fabricated nano-PDLC Fabry-Perot cavity described above in the visible light region around 600 nm. By applying a voltage to the device, it can be seen that there is a small shift of the resonance peak wavelength. The shift is to a smaller wavelength value as the voltage increases. This is caused by a decrease of effective refractive index of the nano-PDLC "seen" by the incident light as voltages increases since molecules become more aligned with electric field and light "sees" the effective refractive index of $\sim n_o$ at high voltage. 110 V was the maximum voltage that we applied to the device. The total shift is about 2.5 nm. Moreover, it can be seen that the transmission also increases as the voltage increases. The reason for much lower transmission at 0 V and low voltage states is believed to be due to the small residual scattering at these states. This small residual scattering is then further enhanced by resonance inside the cavity as a result of the multiple reflections. This effect may actually help enhance the contrast ratio of the electro-optic switching further as to be discussed later.

Figure 3 shows a comparison of the electro-optic switching (T-V curves) between a) a normal nano-PDLC test cell without Fabry-Perot cavity and b) a nano-PDLC Fabry-Perot cavity. From Fig.3 a), we see that in a normal test cell without Fabry-Perot cavity, the intensity modulation is very small due to very small (almost no) scattering effect with a contrast ratio (CR) = $\sim$1.09. However, by placing the nano-PDLC inside the Fabry-Perot cavity, under an application voltage of $\sim$50 V, we can achieve almost a full swing of the transmission change (from minimum to maximum) with a contrast ratio of $\sim$7.5. The maximum contrast ratio could be limited by the dark state and hence the performance of the cavity. Moreover, the maximum transmission in our device so far is around 20% and the value of *Finesse* (free spectral range / full width half-maximum) is not so high. This

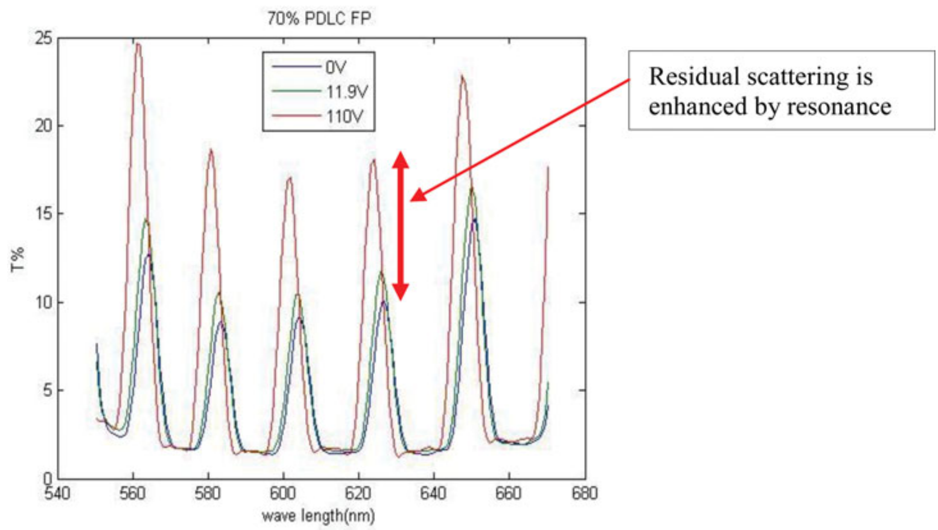


**Figure 2.** Spectrum of the nano-PDLC Fabry-Perot cavity with 70 wt% polymer in the visible light region around the 600 nm. Resonance Peaks shift to a shorter wavelength as applied voltage increases. Residual scattering at low voltages (0 V & 11.9 V) is enhanced by the resonance inside the cavity, resulting in much reduced transmission of the resonance peaks at low voltages

is believed to be caused by the defects due to a non-ideal Fabry-Perot cavity [5]. Various factors can contribute to the defects: e.g. cavity loss (absorption, scattering etc), non-ideal parallelism of the two mirrors, roughness of the mirror surfaces, non-ideal collimation of the light source etc. These defects, in general, cause a decrease in sharpness of the peaks (or *Finesse*) and also reduction in the maximum transmission. By improving the performance

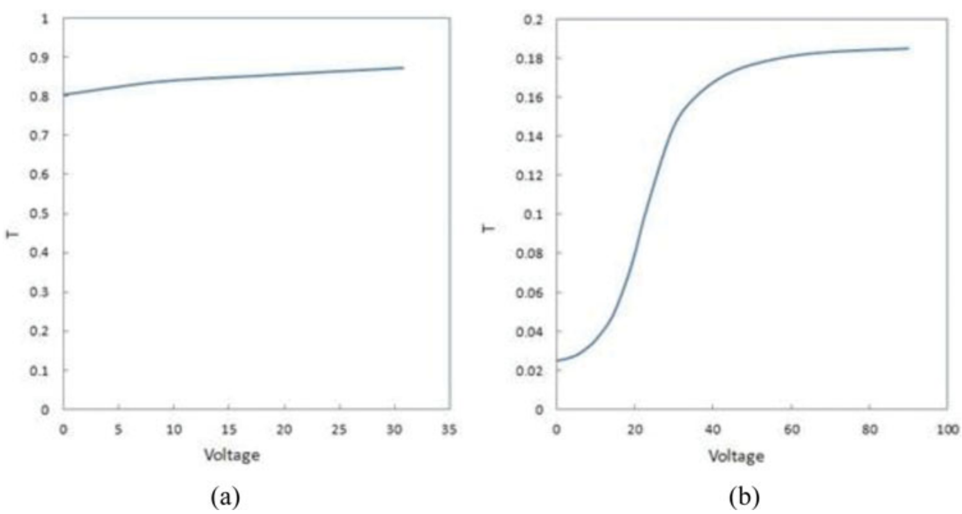


**Figure 3.** Transmission (X100%) vs. Voltage (T-V) curves of (a) nano-PDLC in a normal test cell and (b) nano-PDLC inside a Fabry-Perot cavity

**Table 1.** Comparison of results with different polymer concentration

| Polymer concentration (wt%) | CR of normal test cells | CR with F-P cavity | Driving voltage (V) | Response time (ms) |
|---|---|---|---|---|
| 50 | 5.172 | 73.1 | ∼10 | 37 |
| 60 | 2.56 | 22.75 | ∼15 | 21.6 |
| 70 | 1.09 | 7.4 | ∼50 | 3.2 |
| 75 | 1.04 | 4.82 | ∼90 | 1.5 |



of the cavity in future, we expect to be able to increase the transmission further and also reduce the operation voltage further (since cavity becomes more sensitive and a smaller change of refractive index is required for a given transmission change). Furthermore, by using a faster liquid crystal material (instead of E7), we also expect to achieve a faster response time (in this example, response time is about 2 to 3 ms).

Apart from 30 wt% wt liquid crystal to 70 wt% polymer ratio, we also fabricated similar Fabry-Perot devices and normal test cells but with different wt% of liquid crystal and polymer as shown in Table 1. As the polymer concentration increases from 50 wt% to 75 wt%, the contrast ratio of normal test cells (no FP cavity) decreases due to less scattering. However, by placing the nano-PDLC (or PDLC in the case of lower wt% of polymer) inside the Fabry-Perot cavity, we see that contrast ratio of the devices is increased in all cases with an enhancement factor of $\geq 5$ to 10 (In future, by improving the cavity performance such as Finesse, we expect to improve this factor even further). Moreover, as expected, as the% of polymer increases from 50% to 75%, the driving voltage increases and the response time also decreases.

In principle, due to the scattering effect of PDLC and residual scattering effect of nano-PDLC, their behavior inside a Fabry-Perot cavity can be much more complicated than those in a common nematic liquid crystal Fabry-Perot cavity [6]. However, it is interesting to note that this residual scattering of a non-ideal nano-PDLC may be used to further enhance the contrast ratio of a nano-PDLC cavity. This is due to the fact that the small residual scattering (e.g. at off-state), after going through the multiple reflections inside the cavity, can be enhanced. This means, under an applied voltage, the optical transmission can be increased (or decreased) more quickly than expected for a given applied voltage. For example, for a given applied voltage, the transmission change may be only ∼10% if there is no scattering effect (i.e. purely due to switching closer to or further away from the resonance condition). However, with scattering, the transmission change may be enhanced to e.g. 20% to 30%. This can lead to an overall increase in contrast ratio for a given applied voltage change. We expect to continue to investigate this interesting effect in these devices in future.

## 4. Conclusion

In summary, we have presented experimental results obtained for a nano-PDLC inside a Fabry-Peort cavity. In our chosen example with 70 wt% polymer and 30wt% liquid crystal, we can achieve a fast-response and polarization-independent optical shutter with contrast ratio of ∼8:1 under an applied voltage of ∼50 V. Response time is about 2 to 3 ms and the output transmission is ∼20%. This can have potential as a fast-response optical shutter in e.g. telecommunication systems. In future, by improving the performance of the cavity such as Finesse, we expect to reduce operation voltage further and also increase the optical transmission and contrast ratio. Moreover, by using a different liquid crystal material, we expect to further reduce the response time to $< 1$ ms.

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