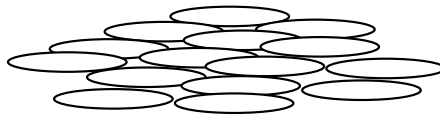
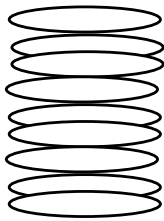


## 6. Electro-Optic Effects in Liquid Crystals

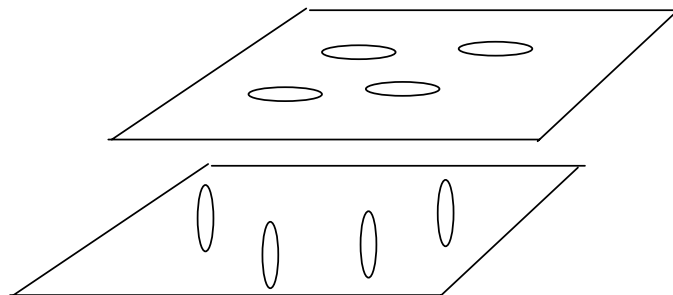
Organic materials with elongated (cigar-like) molecules or flat (disc-like) molecules can give rise to optical anisotropy. For instance, an organic molecule, p-methoxybenzylidene-p'-n-butylaniline (MBBA) has three liquid phases, the nematic phase which exists at temperature 21 – 47 °C, and the smectic phase, and the cholesteric phase. In the nematic phase, there is a long range orientational order of the axes of the molecules, while the center of the molecules are randomly distributed:



In the smectic phase, the crystal exhibits one-dimensional translational order as well as orientational order:



In the cholesteric phase, the orientational order also exists; the molecules are in rows with each row has a well-defined angle for the molecular direction:



The smectic phase is closest to the solid phase, while the nematic and cholesteric phases have the greatest E-O uses. As we raise the temperature, solid phase (low temperature) → smectic liquid phase → nematic liquid phase → isotropic liquid.

Due to the orientational ordering of these anisometric structures, the smectic and nematic liquid crystals are uniaxially symmetric, with the optic axis parallel to the axes of the molecules, while that of the cholesteric liquid crystal is defined only locally.

The refractive index difference between the ordinary and extra-ordinary indices is denoted by  $\Delta n = n_e - n_o$ . In the nematic liquid crystal, the optic axis may be reoriented by the application of an electric field. Usually they tend to rotate in such a way that the direction of maximum dielectric constant coincides with the direction of the electric field. (In all known nematic and smectic liquid crystals,  $\Delta n > 0$ . The dielectric anisotropy,  $\Delta\epsilon = \epsilon_{//} - \epsilon_{\perp}$ , can be  $> 0$  or  $< 0$ ,  $\epsilon_{//}$  and  $\epsilon_{\perp}$  are the dielectric permittivity for an electric field parallel and perpendicular to the optic axis).

We use the liquid crystals most frequently in their switching behaviors under an external electric field. The molecules in the liquid crystal tend to rotate in such a way that the direction of the maximum dielectric permittivity coincides with the field. Since the liquid crystal is very anisotropic, the change can be detected optically, in time constant of  $\sim 10^{-3}$  s.

Consider the case where  $\Delta\epsilon > 0$ , which is characteristic of molecules having a longitudinal dipole moment. Let's assume the initial orientation of the optic axis is along the z-axis, and the electric field (say, along the x-axis) is perpendicular to the z-axis. In this case the optic axis will align at an angle  $\theta$  with respect to the z-axis. The extraordinary refractive index seen by light propagating parallel to electric field (x-axis) is given by

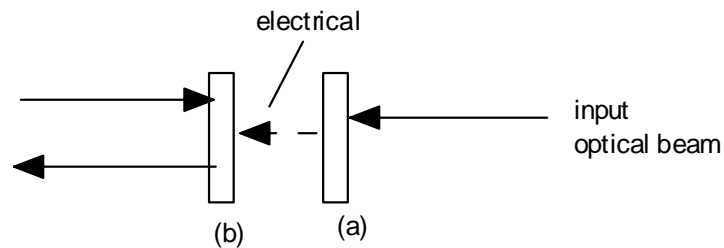
$$\frac{1}{n_e^2(\theta)} = \frac{\cos^2(\theta)}{n_o^2} + \frac{\sin^2(\theta)}{n_e^2} \quad (1)$$

where  $n_e$  and  $n_o$  are the extraordinary and ordinary refractive indices. The angle  $\theta$  depends on the field strength. In a strong field  $\theta$  is zero and the birefringence (defined as  $n_e(\theta) - n_o$ ) vanishes. When the field is small or zero,  $\theta$  return to  $90^\circ$  and birefringence reappears.

Because of these electrically induced reorientation of the optic axis, the phase retardation of a thin layer of properly oriented liquid crystal can be switched from zero to  $2\pi(n_e - n_o) l/\lambda$  and back with an applied electric field.

## 6.2 Spatial Light Modulator

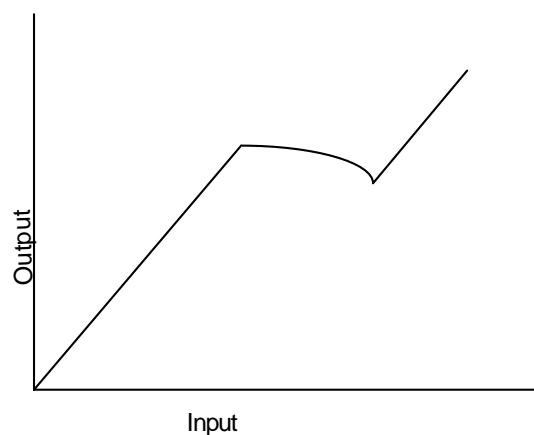
Spatial light modulator is a light modulation device specially made for 2-dimensional I/O applications. (An LCD is a special case of SLM). It uses the phase/amplitude information of input to phase/amplitude modulate another optical beam.



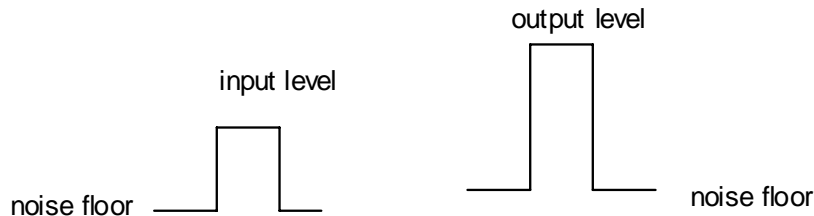
For a single channel, the input and output are at different planes, with several features:

1. Incident optical beam can have a wavelength different from that of the output, this can be viewed as a wavelength converter.
2. The conversion is facilitated through electrical/optical conversion in between.
3. The incident light can effect the voltage drop (and thus  $\Delta n$ ) at the output plane (b).
4. For digital application, the SLM can be used to re-shape the input beam and amplify it.
5. When many single channels are operated in parallel, we have parallel processing.

It should be noted that the input/output signal can be either analog or digital, with the SLM optimized for different specifications. A transfer curve between the input and output optical beam can look like:



For digital applications, the critical specifications are the input sensitivity, and contrast ratio.



The input sensitivity is related to the optical input energy required to achieve a  $\pi$  modulation of phase at the output.

The contrast ratio is defined as the ratio of the maximum achievable intensity to the minimum achievable intensity at the output. The contrast ratio is quite dependent on the noise level of the system including channel noise and the cross-talk between channels.

For analog application, both the input and output beams consist of sinusoidal modulation, the critical specifications are ac power efficiency, linear dynamic range, noise figures etc.

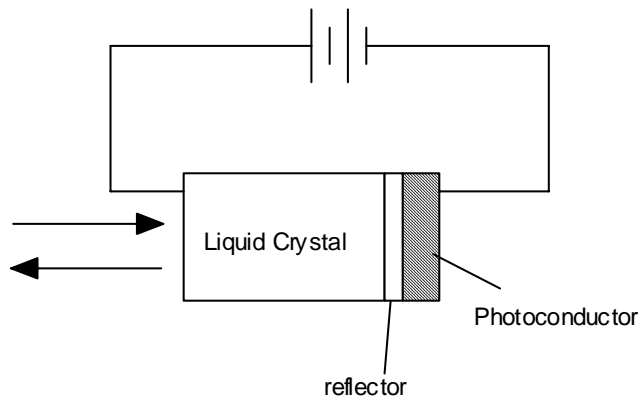
The ac power efficiency is defined as the ratio of the ac electrical power converted to ac electrical power input to the system, in other words, it is the square of the ratio of the ac optical power output to ac optical power input, if both input and output conversion efficiency is unity.

The dynamic range is range of signal above the noise, it is much like the contrast ratio.

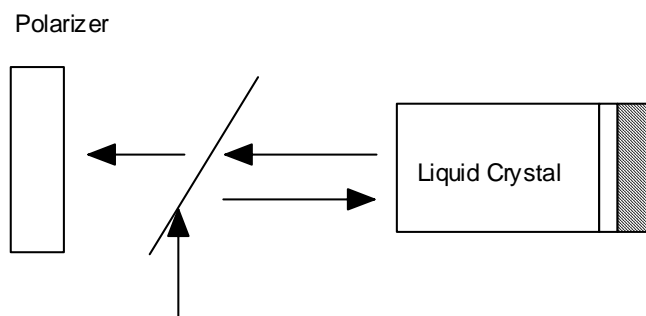
The linear dynamic range is dynamic range between the noise floor and the 1-dB compression point of the output. (This is different from the two-tone spurious free dynamic range).

There are other specifications for a system of many 2D channels. These include resolution, frame rate, storage time, crosstalk, etc.

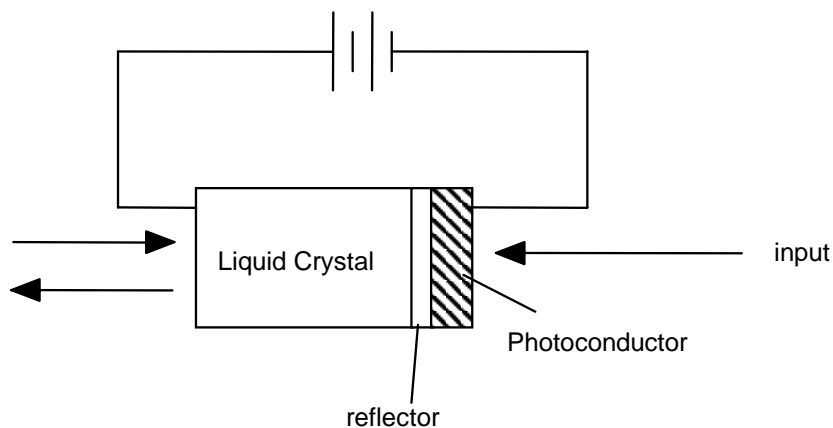
As mentioned earlier, the liquid crystal light valve is an example of a spatial light modulator. Its principle of operation is longitudinal electro-optic effect across the liquid crystal. A simple configuration is as shown below:



In the reflective mode, the input light passes through the liquid crystal and is modulated by the voltage across the material. Since the light travels through the material twice (after reflected by the high reflectivity reflector), the electro-optic effect causes a change in the original polarization of the light beam so that it can be picked up by a polarizer.



To complete the operation of the SLM, an input light beam can be used to change the photoconductivity of the photoconductor and thus changes the voltage across the liquid crystal.



**Polymers.** Compared to  $\text{LiNbO}_3$  and III-V semiconductors, organic polymers are relatively immature EO materials [1], but they also possess a great potential for more advanced modulators. The advantages of EO polymers mostly come from the applicability of spin-coating technique. This not only makes it possible to integrate polymer EO devices with various electronic and optoelectronic components [2], but also creates the opportunity to fabricate multiple devices stacked in the vertical direction. Metal electrodes can be buried between different polymer layers, this makes the electrode design very flexible. To lower the fabrication cost, polymer EO devices can be fabricated directly on top of optical submounts. The optical refractive index of polymers is close to that of single-mode optical fiber. This provides a good match between the polymer waveguide mode and the fiber mode. Besides EO modulators, polymers are also candidate materials for fabricating LEDs, fiber lasers and amplifiers, wavelength converters, variable optical attenuators, tunable filters and optical switches.

EO polymers are synthetic organic materials mixed with two components: one is the nonlinear optical (NLO) chromophore molecules as active element, the other is some standard polymers (such as PMMA) as host. Nonlinear optical chromophores are synthesized organic molecules that possess a large electric dipole moment and strong optical nonlinearity. They can be dispersed into the polymer matrix in different ways: either dissolved as guest, or chemically connected to the polymer molecules to form side-chain polymer, cross-linked polymer, or main-chain polymer. When the chromophoric polymer is heated up around 100-200 °C, the chromophore molecules become mobile, and their electric dipoles can be aligned to the same direction by applying a strong electric field (100-200V/ $\mu\text{m}$ ). After the polymer is cooled down under a high electric field, the alignment of the electric dipoles is “frozen”, and macroscopic optical nonlinearity is achieved. This process is called “poling”. Many poling techniques have been developed, such as electrode poling (electrodes are deposited for applying the poling electric field), corona (corona discharge is used to create the poling electric field), photo-induced poling, etc. It is possible to pole adjacent areas in opposite directions, which can facilitate the high-speed push-pull Mach-Zehnder modulator design [3]. To form an optical waveguide, optical confinement in the vertical direction is usually achieved by sandwiching the core EO layer between two cladding layers of different polymer material with lower refractive index ( $\Delta n \sim 0.1$ ). Optical confinement in lateral direction can be achieved either by dry etching or photo-

bleaching (exposing the areas outside the waveguide under high-intensity light at certain wavelength to reduce the refractive index). The resulted waveguides typically have propagation loss less than 3 dB/cm, generally due to absorption and scattering.

After poling, the initially isotropic EO polymer becomes uniaxial, with the extraordinary optical axis parallel to the direction of the poling field. This direction is also chosen as the z-axis in the principal coordinate system. The extraordinary and ordinary indices are:

$$n_e \approx n + 2\Delta, \quad n_o \approx n - \Delta \quad (2)$$

where  $n \sim 1.6$  is the isotropic refractive index before poling,  $\Delta$  is a small number ( $\sim 0.1$ ) depending on poling electric field and material. The corresponding EO tensors take the form of [4]

$$\begin{bmatrix} 0 & 0 & r_{13} \\ 0 & 0 & r_{13} \\ 0 & 0 & r_{33} \\ 0 & r_{13} & 0 \\ r_{13} & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \quad (3)$$

Note that in the tensor  $r_{13} = r_{23} = r_{42} = r_{51}$ . For various EO polymers,  $r_{33}$  is about 3 times larger than  $r_{13}$ . The actual value of  $r_{33}$  depends on the chromophore type, the mixing density in the polymer, and the poling electric field. Usually,  $r_{33}$  increases linearly with the poling field, but so does the optical loss and  $\Delta$  in Eq. (2). The reported  $r_{33}$  values at 1.3-1.6  $\mu\text{m}$  optical wavelength range from a few pm/V to around 100 pm/V, with 15-20 pm/V being the typical value. Compared to  $\text{LiNbO}_3$ , at the same modulation electric field,  $r_{33}$  needs to be around 80 pm/V for the EO polymer to give the same index change as the  $\text{LiNbO}_3$ .

From Eq. 3, the index ellipsoid for EO polymers in the presence of electric field is represented by

$$x^2 \left( \frac{1}{n_o^2} + r_{13} E_z \right) + y^2 \left( \frac{1}{n_o^2} + r_{13} E_z \right) + z^2 \left( \frac{1}{n_e^2} + r_{33} E_z \right) + 2yzr_{13} E_y + 2zxr_{13} E_x = 1 \quad (4)$$

Since  $r_{33}$  is about 3 times larger than  $r_{13}$ , it is desirable to apply the modulation electric field along z-axis. In this case  $E_x = E_y = 0$ , and the resulted index ellipsoid takes the same form as before for  $\text{LiNbO}_3$ . The subsequent analysis for the index change is therefore exactly the same as that for z-cut  $\text{LiNbO}_3$  crystal. Similar to the z-cut  $\text{LiNbO}_3$  crystal, the TM mode has a much more efficient modulation than the TE mode in polymer EO waveguides. Polymer EO

modulators are generally polarization dependent, although a polarization-independent design has been attempted with compromised efficiency [5].

Major problems with polymer EO devices are the stability issues. Upon thermal aging, the alignment of chromophore molecules can be relaxed, and the polymer materials can be oxidized and become yellowish in color. These effects can also arise from photo absorption, most severely with blue light that can be generated as harmonics when illuminated with 1.3-1.6  $\mu\text{m}$  light. Humidity in the environment tends to make things even worse, since water incursion enhances the photo absorption in polymer material. Another disadvantage with polymer EO devices is the difficulty in facet cleaving, as facet polishing for polymer waveguides is not as convenient as for  $\text{LiNbO}_3$  waveguides. These problems, together with the efforts to improve the EO properties of polymers, make the polymer EO device research a very active and intense research area.

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