Lecture 6

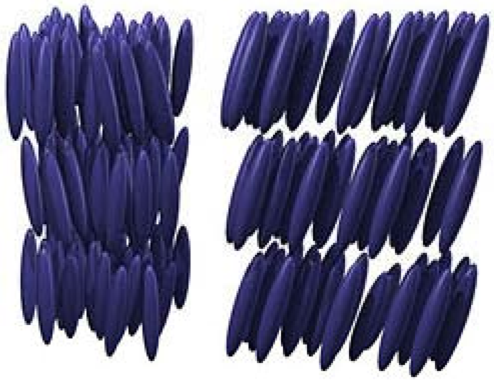
Electro-Optic Effects in Liquid Crystals

EO Polymer

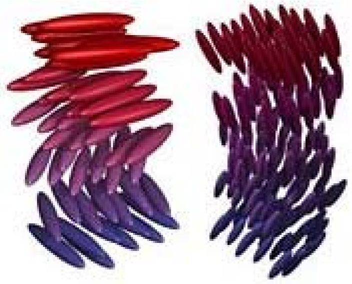
Organic materials with elongated (cigar-like) molecules or flat (disc-like) molecules can give rise to optical anisotropy. For instance, an organic molecule, p-methoxybenzylidene-p’-n-butylanilane (MBBA) has three liquid phases, the nematic phase which exists at temperature 21 – 47 ^{o}C, and the smectic 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, $\Delta\varepsilon = \varepsilon_{//} - \varepsilon_{\wedge}$, can be > 0 or < 0, $\varepsilon_{//}$ and $\varepsilon_{\wedge}$ are the dielectric permitivity for an electric field parallel and perpendicular to the optic axis), reoriented by the application of an electric field.

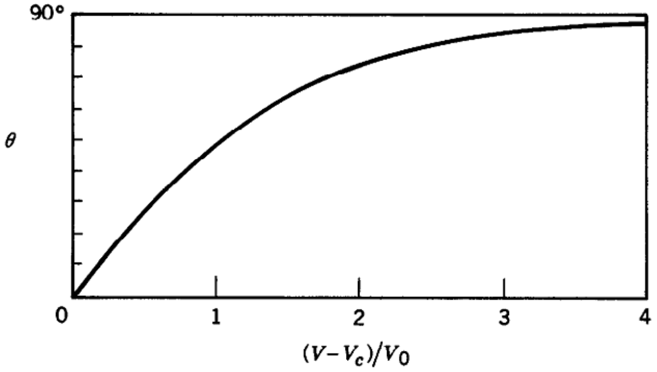
We use the liquid crystals most frequently in their switching behaviors under an external electric field. The molecules in the liquid crystal tend to rotate in such a way that the direction of the maximum dielectric permitivity coincides with the field. Since the liquid crystal is very anisotropic, the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

Consider the case where $\Delta\varepsilon > 0$, 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 is aligned at an angle θ with respect to the z-axis. The extraordinary refractive index seen by light propagating parallel to electric field (x-axis) is given by

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

where n_e and n_o are the extraordinary and ordinary refractive indices. The angle θ depends on the field strength.

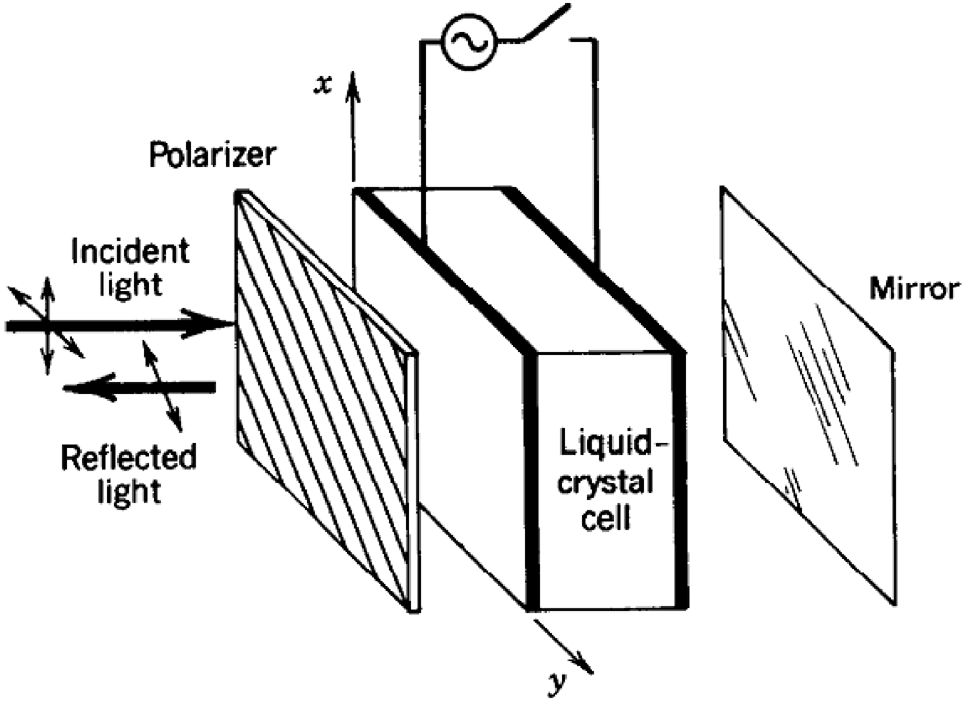
$$\theta = \begin{cases} 0, & V \le V_c \\ \dfrac{\pi}{2} - 2\tan^{-1}\exp\left(-\dfrac{V - V_c}{V_0}\right), & V > V_c, \end{cases}$$



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.

Nematic LC Retarders and Modulators

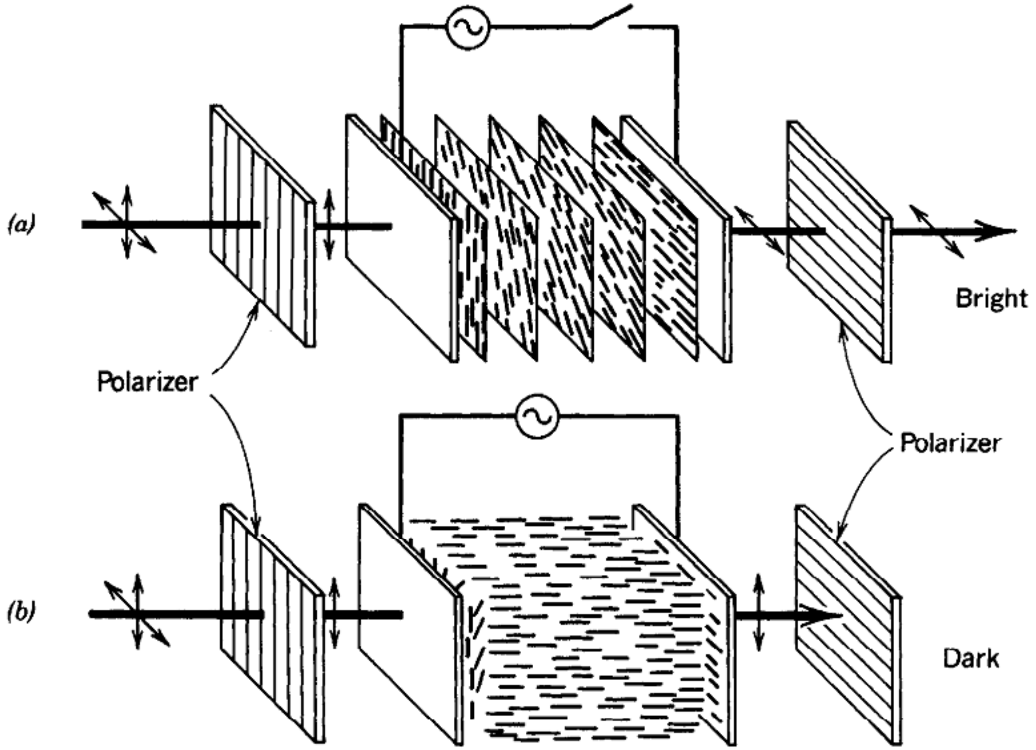
The liquid-crystal cell is sealed between optically flat glass windows with antireflection coatings. A typical thickness of the liquid crystal layer is d = 10 um and typical values of $\Delta n = n_e - n_o = 0.1$ to 0.3. The retardation Γ is typically given in terms of the retardance $Q = (n_e - n_o)d$



A liquid-crystal cell provides a retardation $\Gamma = \pi/2$ in the absence of the field ("off" state), and $\Gamma = 0$ in the presence of the field ("on" state). After reflection from the mirror and a round trip through the crystal, the plane of polarization rotates 90° in the "off" state, so that the light is blocked. In the "on" state, there is no rotation, and the reflected light is not blocked.

Twisted Nematic LC Modulators

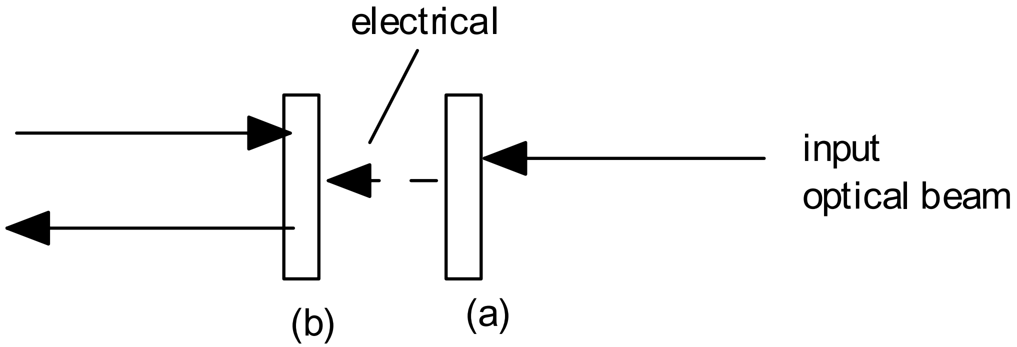
A twisted nematic liquid-crystal cell is a thin layer of nematic liquid crystal placed between two parallel glass plates and rubbed so that the molecular orientation rotates helically about an axis normal to the plates (the axis of twist).



A twisted nematic liquid-crystal switch. (a) When the electric field is absent, the LC cell acts as a polarization rotator; the light is transmitted. (b) When the electric field is present, the cell's rotatory power is suspended and the light is blocked.

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- or amplitude- modulate another optical beam.

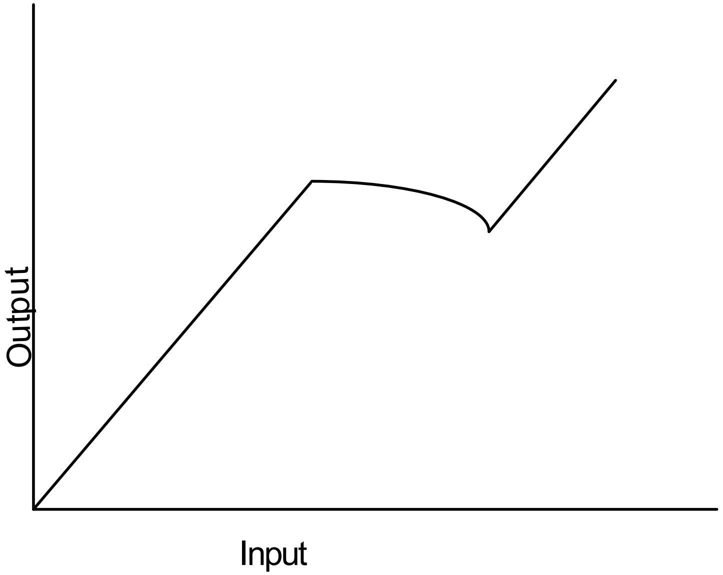


For a single channel, the input and output are at different planes, with several features:

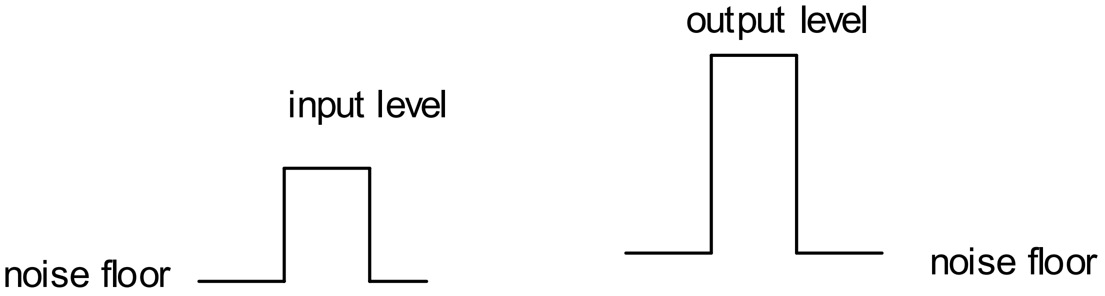
1. Incident optical beam can have a wavelength different from that of the output, this can be viewed as a wavelength converter.
2. The conversion is facilitated through electrical/optical conversion in between.
3. The incident light can give rise to a voltage drop (and thus Δn) at the output plane (b).

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 optical 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 the contrast ratio.



The input sensitivity is related to the optical input energy required to achieve a π 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.

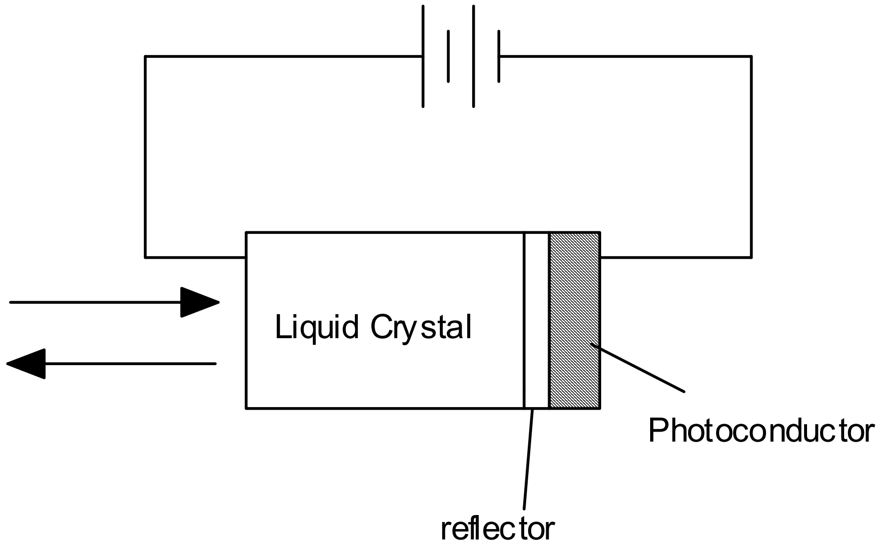
The ac power efficiency is defined as the ratio of the ac electrical power converted to ac electrical power input to the system, in other words, it is the square of the ratio of the ac optical power output to ac optical power input, if both input and output conversion efficiency is unity.

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

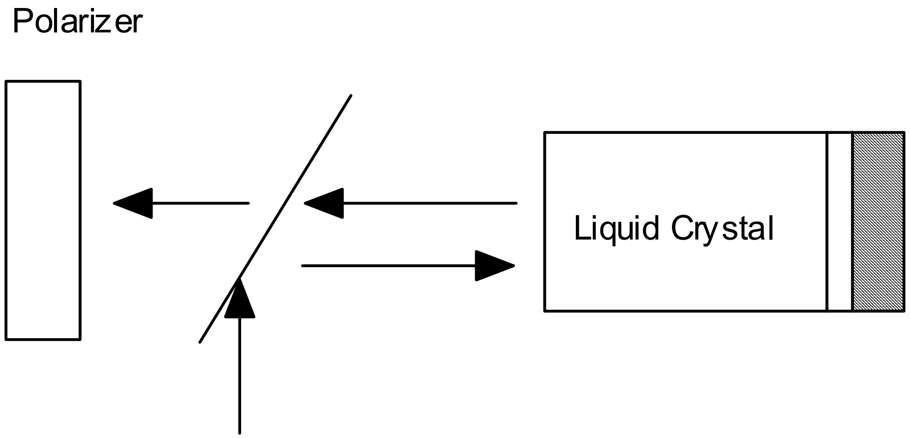
The linear dynamic range is dynamic range between the noise floor and the 1-dB compression point of the output. (This is different from the two-tone spurious free dynamic range).

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

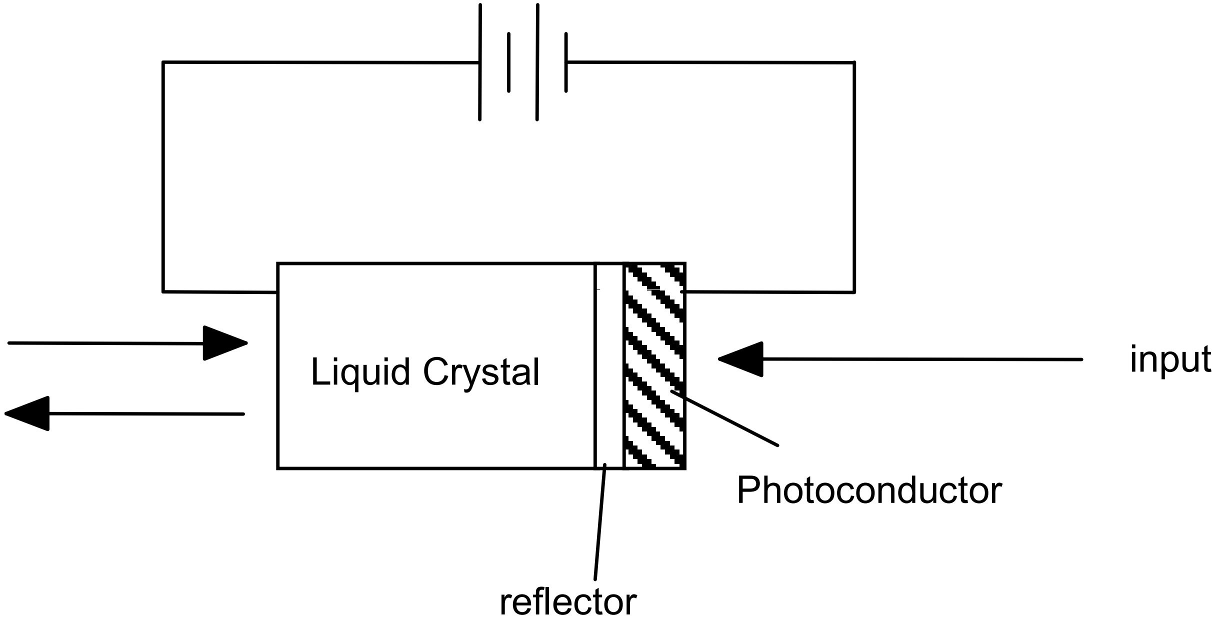
As mentioned earlier, the liquid crystal light valve is an example of a spatial light modulator. Its principle of operation is longitudinal electro-optic effect across the liquid crystal. A simple configuration is as shown below:



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.



Electro-Optic Polymers

Compared to $LiNbO_3$ and III-V semiconductors, organic polymers are relatively immature EO materials for modulators presently.

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, but also creates the opportunity to fabricate multiple devices stacked in the vertical direction.

Metal electrodes can be buried between different polymer layers. Polymer EO devices can be fabricated directly on top of optical submounts.

The refractive index of polymers is close to that of single-mode fiber, providing 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 with two components: the nonlinear optical (NLO) chromophore molecules (active), plus some polymers (e.g. PMMA) host.

Nonlinear Optical chromophores are 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 to 100-200 ^{o}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/μm). With the high electric field on during cooling, 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.

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 materials 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 or less, 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: $n_e \approx n + 2\Delta, \quad n_o \approx n - \Delta \qquad (2)$

where n ~ 1.6 is the isotropic refractive index before poling, Δ is a small number (~ 0.1) depending on poling electric field and material. The corresponding EO tensors take the form of:

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

For EO polymers, r_{33} ~ 3 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 Δ in Eq. (2). At 1.3-1.6 μm wavelength range, r_{33} ~ from a few pm/V to around 100 pm/V. Compared to $LiNbO_3$, r_{33} needs to be around 80 pm/V for the EO polymer to give the same Δn as $LiNbO_3$.

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 $LiNbO_3$. The subsequent analysis for the index change is therefore exactly the same as that for $LiNbO_3$ crystal.

Major issues 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.

Humidity in the environment tends to make things even worse, since water incursion enhances the photo absorption in polymer material.