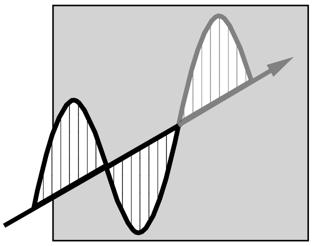
Prof T D Wilkinson

4B20 Crib 2015

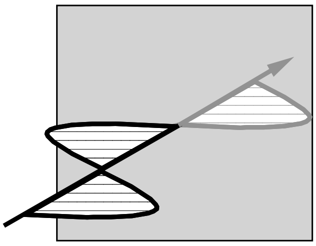
Q1 a) [20%] When electromagnetic radiation enters a different medium, such as water or a piece of glass, it interacts with the medium in a very complex manner. The effect of this interaction can be expressed through either reflection or refraction as expressed in the next section of this document. A simple way of expressing certain interactions between the radiation and the medium is the medium's *refractive index*. This is the ratio of the speed of light *c* to the speed of light in the medium *v*.

$$n = \frac{c}{v}$$

Optical anisotropy is a result of the molecular structure of the material and its interaction with the light. If a material has a structure such that when E field of the light passing through it in any direction sees the same refractive index, then the light travels as the same speed in any direction. Such a material is optically isotropic. If a material has a molecular structure such that the light sees different refractive indices for different orientations of E field then it is optically anisotropic.



Vertical sees n_e



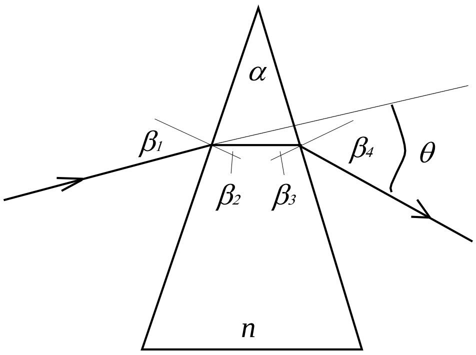
Horizontal sees n_o

3 materials – liquid crystals, quartz, stressed polymers

The other parameter that is very important to a display applications is a materials transmissive properties. Its overall transmission and function of the wavelength of the light are vital for any materials operation as a component in a display technology.

[*Well answered section except the last part where most put dielectric anisotropy which is only useful for LCDs]*

b) [35%] The refraction of the rays at each surface dictate the how light will pass through the a prism.



From Snell's law we have:

$$n \sin \beta_2 = \sin \beta_1 \qquad n \sin \beta_3 = \sin \beta_4$$

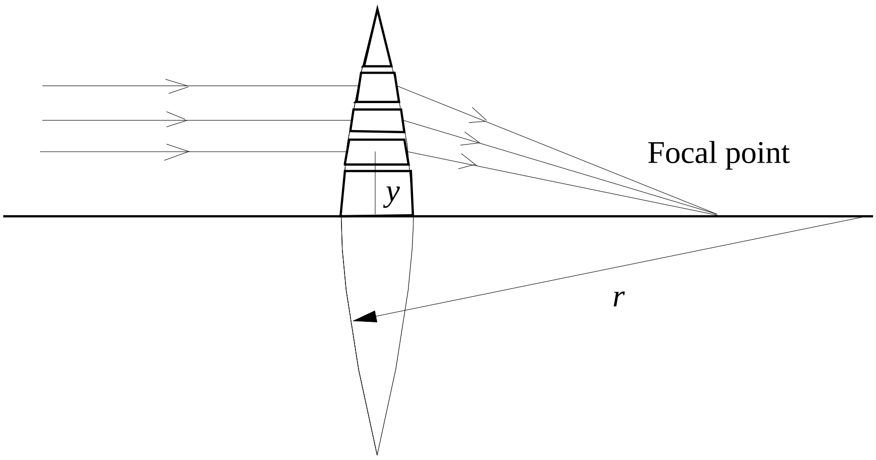
And the total deflection of the ray through the prism is θ such that.

$$\theta = \beta_1 - \beta_2 - \beta_3 + \beta_4 = \beta_1 + \beta_4 - \alpha$$

If we have a thin prism such that α is small and a small angle of incidence such that $\sin \beta \approx \beta$ then the total deflected angle can be approximated to:

$$\theta = (n-1)\alpha$$

This is the basic principle used in all most geometric ray problems. Deviation from small values of α and β lead to aberration in the optical system, hence these values form a solid basis for good lens design and minimisation or potential aberrations and is know and the first order or paraxial approximation. They do, however limit what can be done in an optical system, especially if size is a constraint. A good example of how this property can be used is shown below, where a thin lens is made from a series of thin prism sections.



Each prism section is at a height y from the optical axis of the thin lens. Hence as they are thin lenses, the apex angle can be expressed as $\alpha = 2y/r$ where r is the radius of curvature of both surfaces, hence the deflected angle of a ray passing through each prism section will be:

$$\theta = (n-1)\frac{2y}{r}$$

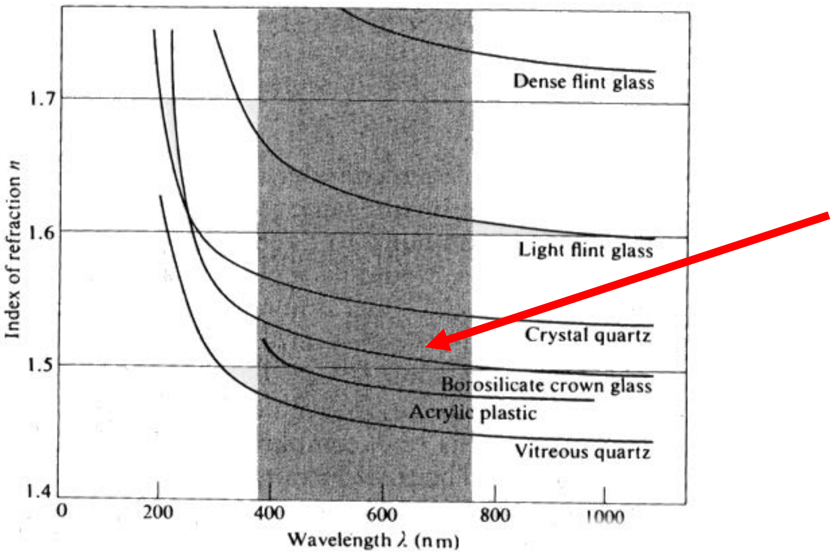
This deviation of each ray means that if parallel rays are incident on the lens, then they will all converge to the same point called the focal point or focal length of the lens. We can represent this as $f = y/\theta = r/2(n-1)$. Moreover, parallel rays incident at an angle to the lens will converge to a different point on the *optical axis*. The basic paraxial equation for the focal length of a lens gives two main control parameters. The refractive index n (difficult and rather inflexible) and the curvature r.

[*Most got this as it was basic bookwork. Some did full derivations (not required) and one candidate had a CNT based variable refractive index lens*]

c) [30%] This interaction is not as simple as it looks, as it is a function of wavelength as well. The change in refractive index with wavelength is called dispersion and is often difficult to derive as it depends on the chemical composition of the medium. Dispersion can arise from many chemical and physical interactions, however a common form of dispersion is due to resonance with the chemical components of the medium which can be expressed in the dispersion equation.

$$n^2(\omega) = 1 + \frac{Nq_e^2}{\varepsilon_0 m_e}\left(\frac{1}{\omega_0^2 - \omega^2}\right)$$

In fact there will be a whole range of different interactions between atoms and components within the medium, which can be represented as a summation of the above equation for different resonant frequencies. This is made even more complicated when considering other electronic interactions such a fixed atomic boundaries. Hence the dispersion is a very complex concept, with many different contributing effects.



From Snell's law we see that the angle of refraction depends on the refractive index. If this varies with wavelength then so does the angle, hence different wavelengths will refract different angles. This is a basis of a dispersive prism which can be used to split up the wavelengths of white light.

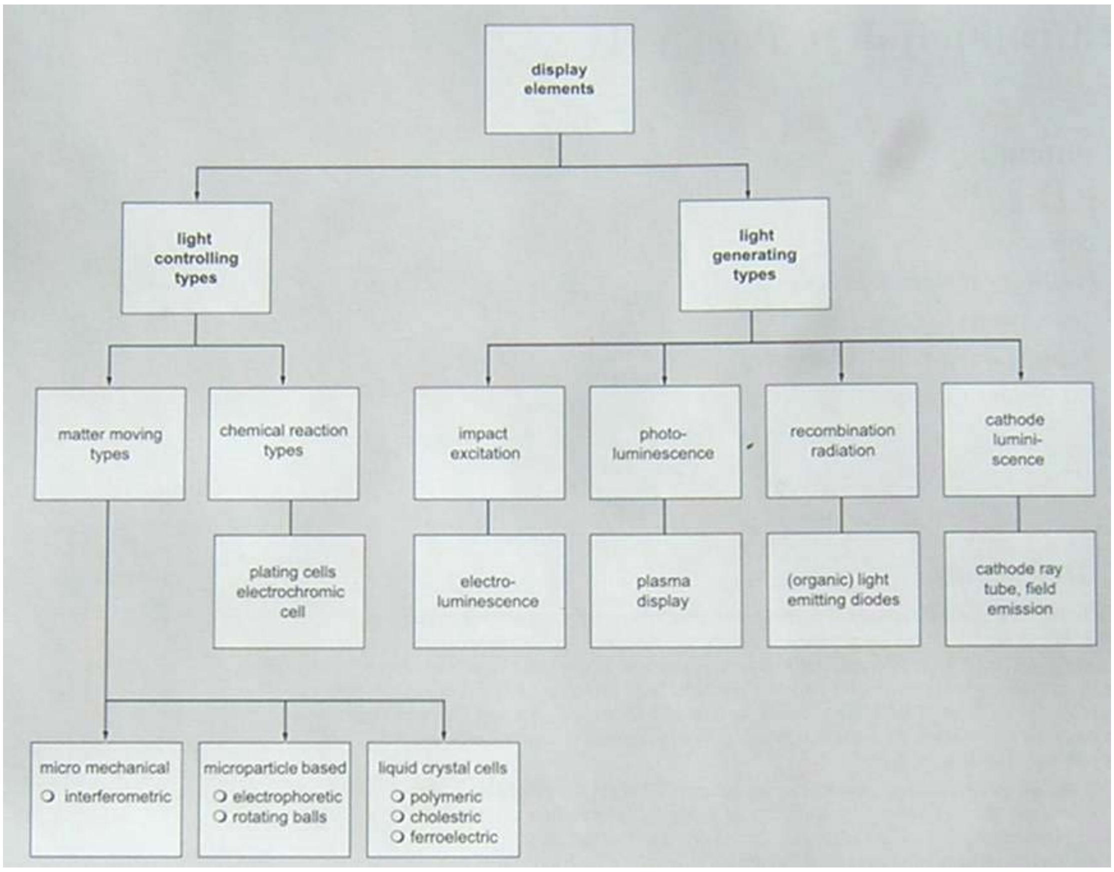
[*Also well answered as it was mostly bookwork.]*

d) [15%] Most lenses operate over range of wavelengths, which means that dispersion will have an effect, as each glass element will have a different refractive index at each wavelength and therefore a different focal length for each wavelength. This is usually referred to as chromatic aberration and means that a singlet lens will never be able to perform in a white light system like a data projector.

This aberration can be corrected for by using multiple glass surfaces, with air gaps between, or by combining two different glass surfaces with different dispersions together to form an achromatic doublet. Varieties of optical glass differ quite widely in the way in which n varies with wavelength, hence it is possible to combine two lenses made from different glasses to compensate for each other over the white light spectrum. The two surfaces may be in contact if they have the same radius of curvature, which is advantageous as it reduces the reflections from each air-glass interface.

[*quite a few got his right, with some mentioning classical aberrations as well]*

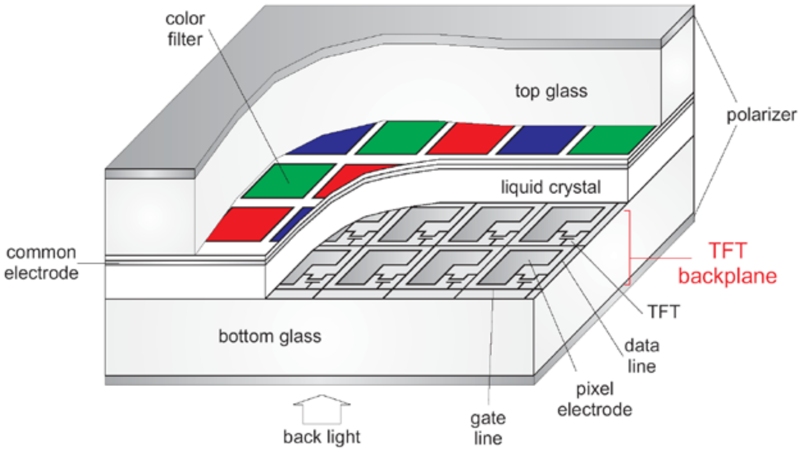
Q2 (a) [20%] The differences between light controlling and light generating displays can be classified by their physical mechanisms used to convert the electronic to optical signal as shown below:



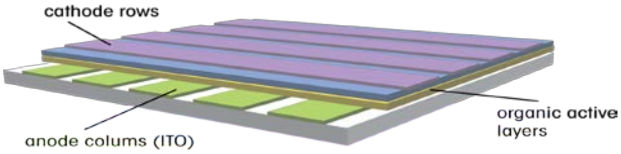
Light generating displays (e.g. CRTs, OLEDs, plasmas) generate photons while light controlling displays (e.g. LCDs, electrophoretic, interferometric) interact (diffuse, polarize, absorb, or depolarize) with ambient or other light.

[Generally well answered with a few producing the above figure. Most got the different types, but several just listed 3 different types of LCD]

(b) [30%] A display consists of a matrix of picture elements or pixels. Each pixel can be addressed by a passive or active matrix architecture. In a passive matrix display, the entire row and column of the matrix is switched, in which the overlapping electrode areas define the pixel. This can result in smearing of the picture, which serves to undermine the resolution. In an active matrix, each pixel is uniquely turned on and off by a transistor. Active matrix displays are essential for high information content

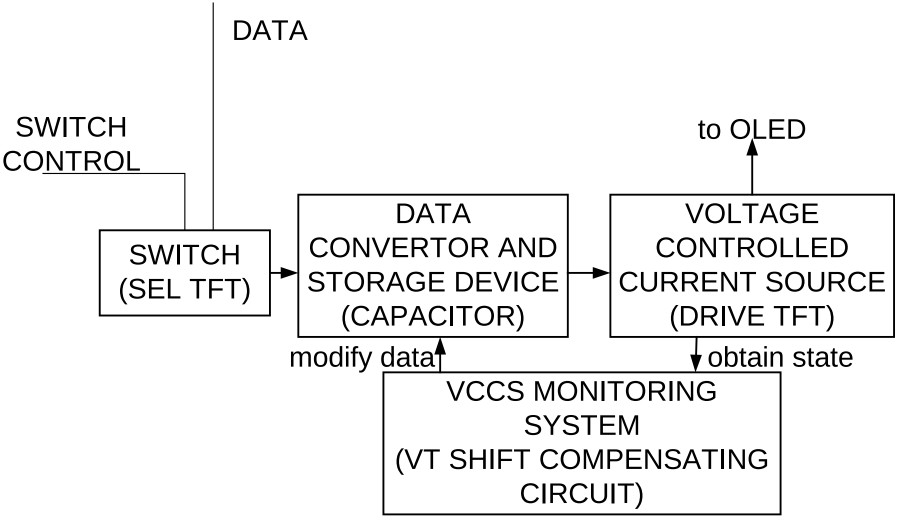


Active matrix illustrated with the liquid crystal display



Passive matrix illustrated with organic light emitting diode) display

In addition to the switching transistor used in the AMLCD pixel, the AMOLED pixel requires a current driving stage (since the OLED is a current-driven device) and a stage to compensate for V_T-shift in the TFT.



[Bookwork section well answered. The better answers detailed issues such as the variation of voltage threshold compensation in AMOLEDs]

c) [30%] *General requirements are:*

- *Low processing temperature: ~300˚C glass, ~350˚C metal foils, ~150˚C plastic.*
- *TFTs with low leakage current, high ON/OFF ratio, low voltage operation, and small area.*
- *High uniformity/ device matching, high stability and lifetime.*

Summary of key performance attributes:

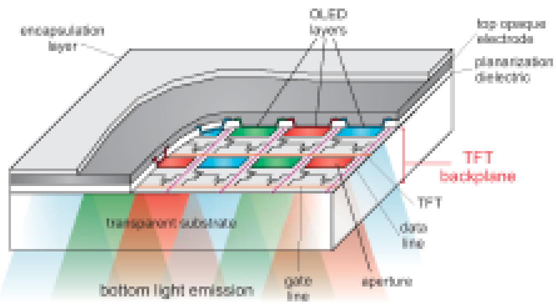
Attribute	a-Si:H	poly-Si	uc/nc-Si:H	organic	oxides
TFT type	*n-type*	*n-type/p-type*	*n-type/p-type*	*p-type*	*n-type*
Process Temp (°C)	*150-300*	*>250*	*150-300*	*100*	*<100*
Mobility *(cm^2/Vs)*	*< 1*	*10~100*	*1~100*	*~ 1*	*1~100*
Temporal Stability (ΔV_T)	*can be managed*	*more stable than a-Si:H*	*more stable than a-Si:H*	*improving*	*research*
Initial Uniformity	*high*	*low*	*potentially high*	*low*	*research*
Scalability	*promising*	*issue*	*research*	*promising*	*promising*
Cost	*low*	*high*	*low*	*low*	*low*

Students should elaborate on the entries they provide for each technology.

[relatively poorly answered, with several candidates only listing a few attributes and several producing bogus tables. Few mentioned process temperature]

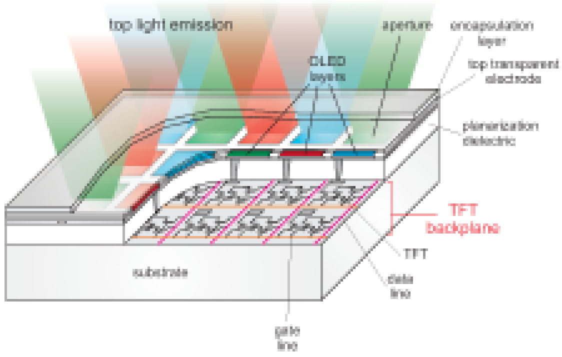
(d) [20%]

Bottom Emission



- Aperture ratio poor for small displays (~30%).
- Simpler OLED-backplane integration process and standard encapsulation.

Top Emission

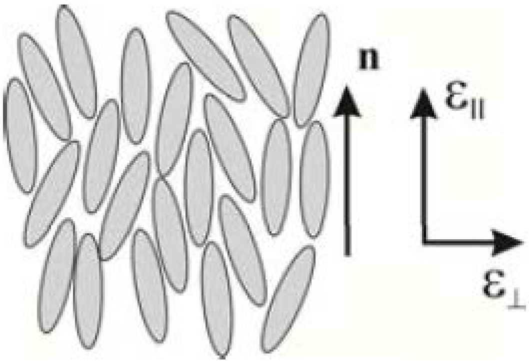


- Aperture ratio high – good for a-Si backplanes
- High process complexity – planarization critical.
- Needs thin film encapsulation.

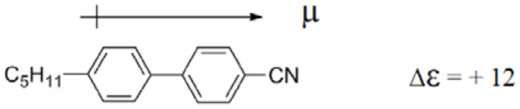
[Overall well answered section]

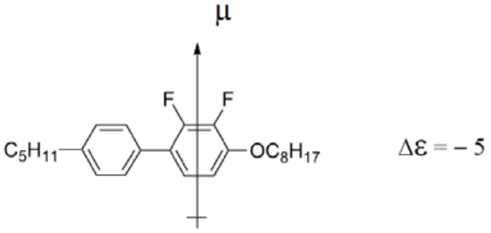
Q3 a) [30%] Any material that is polarisable, but non-conducting is referred to as dielectric. Non-polar molecules may acquire an induced dipole moment in an electric field as the field causes a distortion in their electronic distributions and nuclear positions. In a polar molecule a permanent dipole moment is present, this is due to the partial charges on the atoms in the molecule, which arises from differences in electronegativity. Any existing dipole moments are modified by an applied electric field. Since uniaxial liquid crystals are anisotropic in nature, such a medium will have two dielectric permittivity. It is usual to discuss the dielectric anisotropy of a liquid-crystalline material as defined as shown in equation 1.3, here $\varepsilon||$ is the permittivity along the long molecular axis, parallel to the director, and $\varepsilon^{\perp}$ is the permittivity perpendicular to the long molecular axis and to the director.

$$\Delta\varepsilon = \varepsilon\| - \varepsilon\perp$$



The magnitudes of $\varepsilon||$ and $\varepsilon\perp$ are dependent upon several factors, namely:
a) The spatial structure of the molecules,
b) The degree of order within the phase which is also dependent upon the temperature and most importantly,
c) The presence of permanent or induced dipole moments (μ) within the structure acting along directions parallel and perpendicular to the long molecular axis. (compounds A and B)

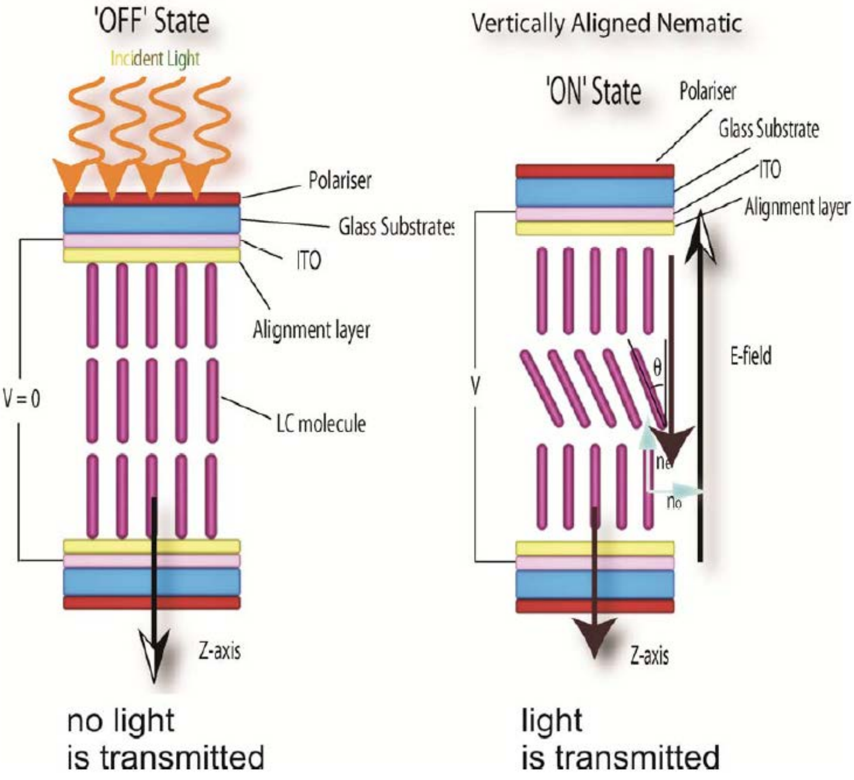




The sign arises from the magnitude of ach component with respect to the long axis of the molecule. Materials with a higher ε on the short axis have negative dielectric anisotropy. Positive materials switch from planar to homeotropic and are slower due to flow effects in the LC. Negative materials are faster due to reduced flow from the reveres switching. They often have lower viscosity as well.

[*Well answered with most getting the molecular relationship, however several candidates linked it to chirality*]

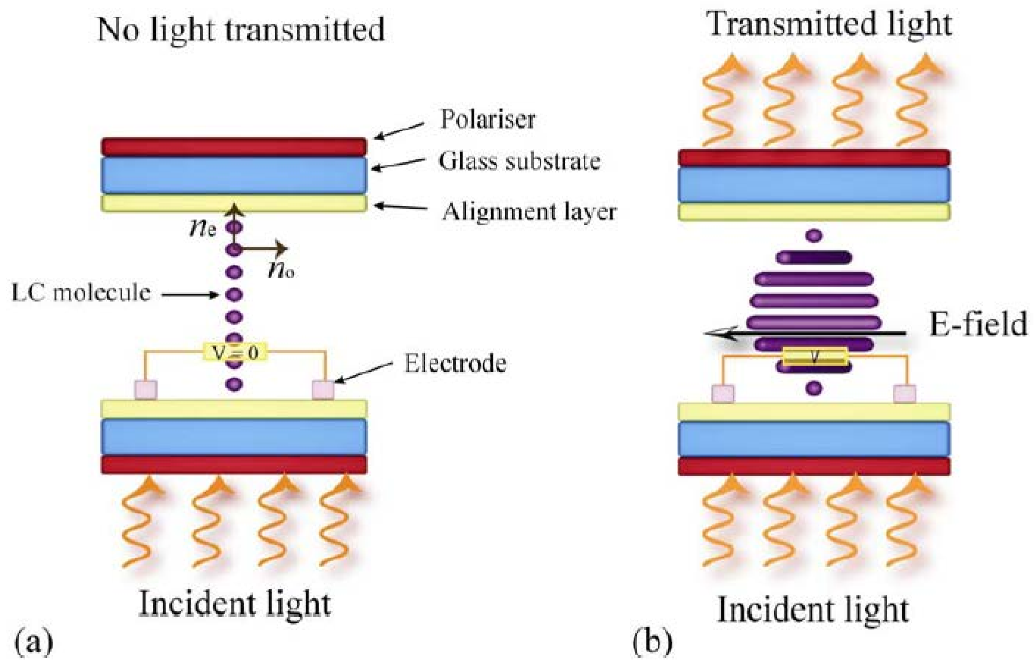
b) [30%]



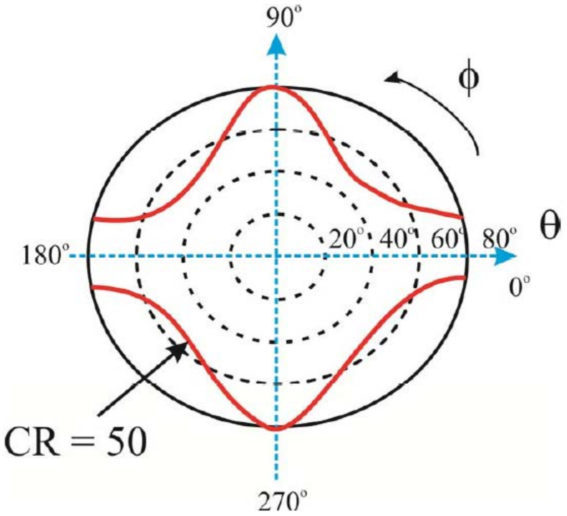
The vertically aligned (VA) or vertically aligned nematic (VAN) technologies consist of a homeotropic alignment of the LC in the absence of an electric field. As a result, there is no optical activity between crossed polarizers. When an electric field is applied the molecules tilt out-of-the plane of the device resulting in a net retardation between crossed polarizers. The advantages of the VA technology are that it requires no rubbing process and it combines a very good contrast ratio with fast response times. For on-axis viewing the dark state is very good and, unlike the IPS mode, is not limited by the quality of the alignment. This device requires crossed polarisers and is used in the NB mode. It also requires a negative dielectric anisotropy LC material.

[*Good overall diagram and most getting the molecular direction correct. Many candidates incorrectly assumed that no alignment layer was required (it requires a homeotric layer*]

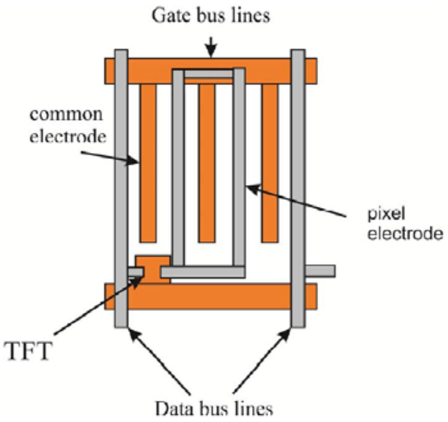
d) [40%] Another device that exploits the wave-guide nature of twisted nematics involves an in-plane switching (IPS) mechanism. In this case the fringing field generated by inter-digitated electrodes causes the LC molecules to rotate in the plane of the cell.



When no electric field is applied the LC molecules adopt a homogenous alignment whereby the nematic director is parallel to the transmission axis of one polariser but perpendicular to it at the other. Since the switching mechanism is in the plane of the device the viewing angle is much wider than for conventional TN cells. The molecules are bounded at the substrates due to strong anchoring conditions and the maximum twist occurs in the centre of the cell.



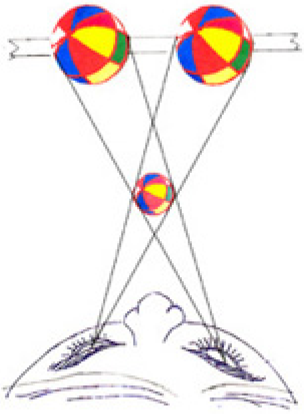
Since the effective birefringence depends upon the polar angle, this means that the transmittance varies with viewing angle. The azimuth angle, on the other hand, is relatively independent of viewing angle. Therefore, in-plane rotation of the molecules inherently has a wide viewing angle compared with out-of-plane technologies. An example of the isocontrast curve of an IPS device is shown above.



One drawback with IPS is that the electric field is not uniform: there are both vertical and horizontal components of the field. As a result, there is some out-of-plane rotation of the molecules. The dimensions of the electrodes and spacing are also important, particularly in terms of the transmission properties. In order to maximise the transmission, the width of the electrodes must be decreased and the separation must be increased. In general, the electrode separation is less than 15 microns to avoid non-uniform transmission across the pixel. IPS devices are not typically used in the NW mode.

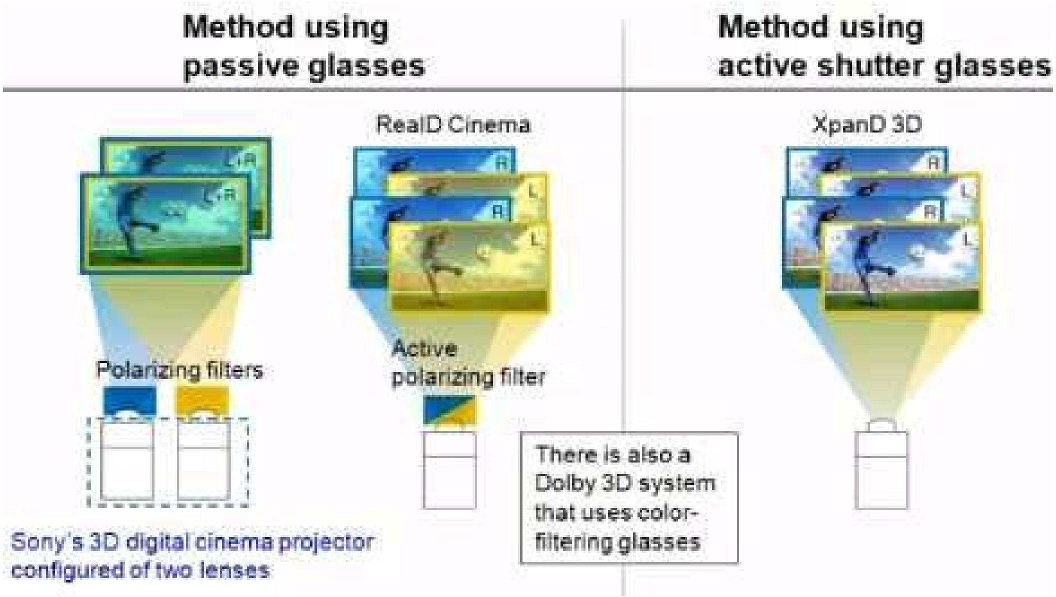
[*Well answered overall with a variety of different comparisons made. Most got the differences, except the complexity of the electrode fabrication with IPS*]

Q4 a) [30%] The autostereoscopic principle assumes that the human brain perceives 3D images as a pair of left and right eye views as we have two spatially separated eyes which we can approximate as cameras.

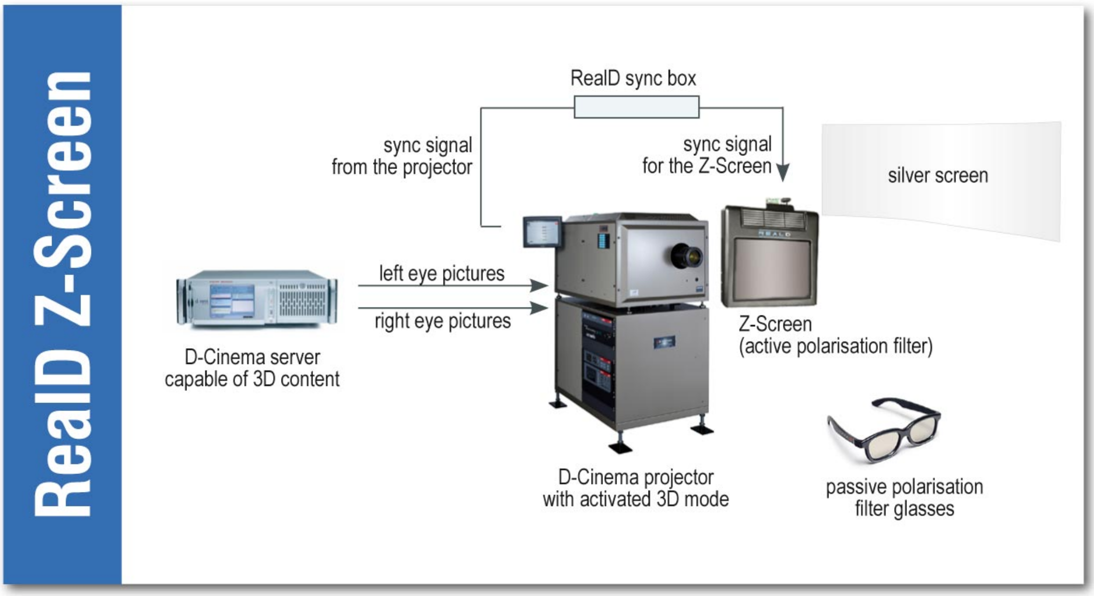


It is relatively simple to create a 3D projection system using a standard 2D projector. Most systems use time multiplexing to project a left and then a right eye view one after another onto a screen. Some form of eyewear is then used to filter each view so that only the correct eye sees the required view. Active glasses use either shutters or filters to switch each view to each eye respectively. Active glasses have better contrast between the views, but are more expensive.

[*Well answered in general, but several candidates listed two types of passive filters rather than active shutters]*



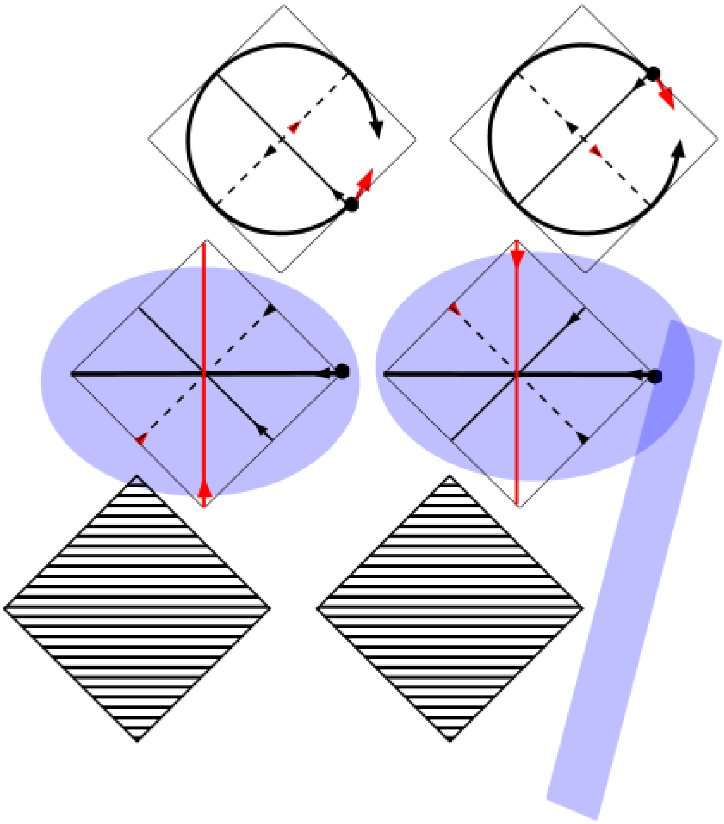
b) [30%] The Real-D system uses passive glasses to filter one orthogonal polarisation into each eye. The shutter switches the polarisation from one state to its orthogonal state. Hence over two frames of the video, each eye sees one view making up an autostereoscopic pair. The main drawback of this technique is that it requires a non-polarized data projector so that the shutter can filter the polarisation and then switch state for each view. As a result of the filter half the light is lost to each view. The eye is only viewing one half of the image pair hence there is a further loss of a half. The shutter must also be synchronized with the projector to switch views at the right time.



Other components required include a 3D video source, a non-polarised data projector (DLP), polarizing glasses and a special polarisation maintaining projections screen.

[Quite well answered, most getting the need for a polarisation screen and the losses]

c) [30%] The Real-D shutter is based on a liquid crystal single pixel cell which rotates the state of the polarsiation of the light incident on the cell. Circular states (left and right) are used for each view to be projected. The light is initially filtered to the horizontal linear state using a wire grid polarisor.



The shutter uses a twisted nematic cell to act like a switchable waveplate and rotate the state of the polarisation circularity of each view. The shutter must be made to very high tolerances in order to maintain a high contrast between the polarisation state of each view. Any crosstalk between views will limit the performance. Hence the orientation and magnitude of the twist in the TN cell must be very well defined ad aligned p the in coming polarisation state.

3D frame rate = 120Hz, therefore the shutter must switch at 240 Hz. This rate that the views must be displayed, hence the actual switching time of the shutter should by approx 10 times faster to avoid effects of fall and rise times of the LC material. This sort of frame rate is not very realistic with a TN material. Other LC effects might be better such as FLC as only two states are required.

[*Not so well answered, several suggested an FLC shutter. Most omitted the need for a waveplate. Most were over complex in the framerate calculation.*]

d) Yes, because the polarisation shutter has a filter to define the incoming state to the LC cell, the output from the data projector should not be polarized as it might be blocked by the filter or change over time/ temperature etc. The best technology for this is the DLP as it has no polarisors in the system and hence the light will be non polarized. The DLP is also a very good choice as it is a frame sequential digital system, hence it is very easy to get access to timing information in order to switch the shutter and also to maintain good synchronization.
[*Well answered overall, a few suggested a LCD as suitable*]