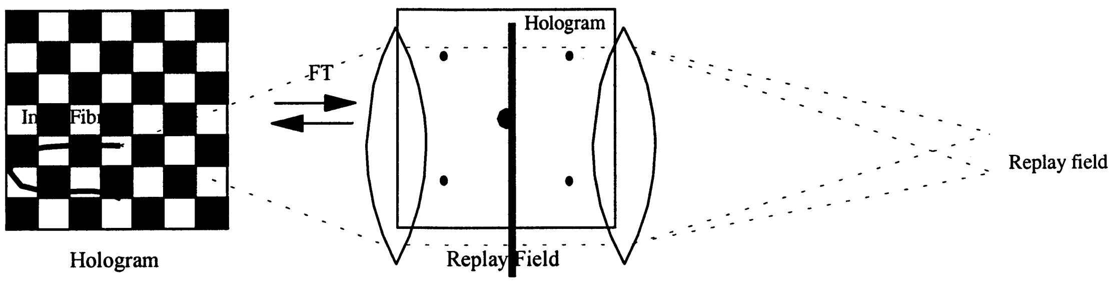
Q1 answer

a) By combining an array of these pixels at various positions on a regular grid, it is possible to generate a complex amplitude function in the far field. Such a 2-D combination of these pixels in various positions is defined as a Hologram and the pattern generated by the hologram if the far field is the Replay Field. The translation between the two is the Fourier transform.



b) The far field of a single square pixel is its Fourier transform: $F(u,v) = A\Delta^2 \text{sinc}(\pi\Delta u)\text{sinc}(\pi\Delta v)$

The original rectangular aperture is defined as a single pixel. By combining an array of these pixels at various positions on a regular grid, it is possible to generate a complex amplitude function in the far field. By altering the value of the amplitude A of each pixel, centred on a grid of interval b (in the example of two pixels above Δ was equal to b, but may not always be so), it is possible to add up the 2-D sinc functions and create an arbitrary 2-D distribution in the far field region. By superimposing all the exponential phase terms due to the shift and varying the amplitude A, it is possible to create useful patterns in the far field. In general terms, the broader the feature or combination of pixels, the smaller or more delta function-like the replay object. The exact structure of this distribution depends on the shape of the 'fundamental' pixel and the number and distribution of these pixels in the hologram. The pattern we generate with this distribution of pixels is repeated in each lobe of the sinc function from the fundamental pixel. The lobes can be considered as spatial harmonics of the central lobe which contains the desired 2-D pattern.

The spatial coordinates (u,v) are related to the original absolute coordinates used earlier in the diffracted aperture (α,β) by the relation.

$$u = \frac{k\alpha}{2\pi f} \qquad v = \frac{k\beta}{2\pi f}$$

This function is common for all the apertures which make up the hologram, only the phase changes as they get shifted about. Hence it forms the envelope function for the replay field of the hologram. The useful information of the replay field is contained in the central first lobe of the sinc function, so we can calculate the width of the replay field as where the first zero of the sinc function occurs ($\pi\Delta u = \pi$, $\pi\Delta v = \pi$). We want the coordinates in terms of $[\alpha,\beta]$, so we use the above transformation to get.

$$\alpha_M = \frac{f\lambda}{\Delta} \quad \beta_M = \frac{f\lambda}{\Delta}$$

α_M and β_M tell us the width of the central lobe of the sinc envelope, due to the pixel pitch Δ. From this we can assume that an NxN pixel hologram will generate NxN spatial frequency 'pixels' in the replay field. This is an approximation, as the FT actually generates a continuous function in the replay field. Hence, the replay field will have a spatial frequency pixel of pitch.

$$\alpha_0 = \frac{f\lambda}{N\Delta} \qquad \beta_0 = \frac{f\lambda}{N\Delta}$$

Note that as shown before, there are other orders appearing in the replay field due to the orders of the first suppressed zero in the sinc envelope. This effectively limits the useable area in the replay field to $[\alpha_M/2, \beta_M/2]$ if overlapping hologram replay patterns are to be avoided.

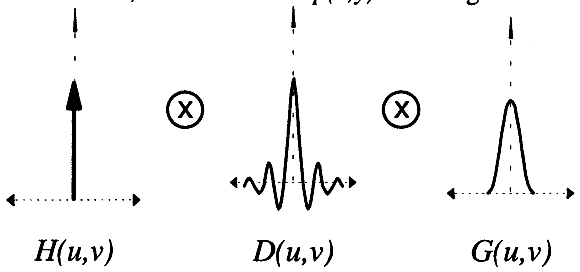
c) In the examples given the illumination of the hologram is uniform and that the hologram and lens extend to infinity. This is not the case in the real world, as there are a finite number of hologram pixels creating a aperture over the hologram and the light used to illuminate it will not be uniformly distributed. In all the examples we are assuming that the illumination source is a collimated monochromatic laser which generates high quality parallel wavefronts with a wider diameter than the hologram or the lenses. Such a source will usually have an intensity distribution which can be expressed as a Gaussian beam profile or function.

$$g(x,y) = A_G e^{l(x^2+y^2)}$$

The entire illumination system (apodisation) can be modeled as a sequence of multiplied functions. The input illumination distribution *g(x,y)* times the hologram aperture *d(x,y)* times the total aperture of the FT lens (if it has a smaller diameter than the hologram) *p(x,y)*. Hence effect of the FT on these functions results in a convolution of their transforms.

$$F(u,v) = G(u,v) \otimes D(u,v) \otimes P(u,v)$$

The ideal hologram replay field *H(u,v)* is designed as an array of delta functions in desired positions. The lens aperture *p(x,y)* is a large circular hole, so the FT *P(u,v)* will be a first order Bessel function (like a circular sinc function). The hologram aperture is a large square of size $N\Delta$ and its FT, *H(u,v)* will be a sharp sinc function. The effect of the FT of the illumination *G(u,v)* is to add a Gaussian profile. Hence, the profile of the spots in the hologram replay field will not be delta functions, they will be delta functions convolved with a Bessel function convolved with a sinc function convolved with a Gaussian function. This means that the replay field will not look exactly as expected, spots which are placed next to one another will interfere due to the tails of the Gaussian, sinc and Bessel functions and the individual desired sharp 'spots' become ringed blobs with finite width. In most cases, the hologram aperture will be smaller than the lens, so the effect of *p(x,y)* can be ignored.

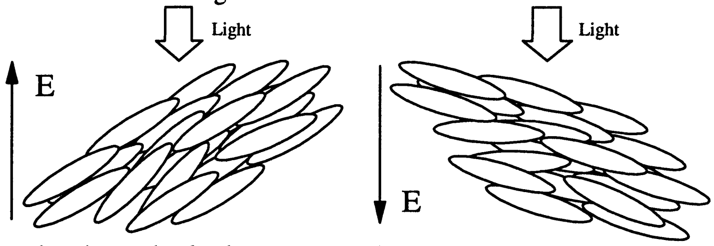


This can be a severe limitation to crosstalk in optical switches as the sidelobes are picked up by the neighbouring channels.

d) All holograms are shift invariant, so when a hologram is replicated, then multiple copies of the replay field are superimposed onto each other with associated phase shifts. This means that the replications interfere wit one another. This can be seen in the pixels of the final replay field as the spacing between then changes. K replications of an NxN pixel hologram will have effectively KN pixels in total which increases the size of the apertures and reduces sidelobes in the replay field which helps reduce the crosstalk. The final replay field appears as if it has been sampled K times which created a sparse distribution of the hologram orders. Hence if the spacings of the fibre channels are carefully chosen, then the fibre cores will appear in the gaps of the sidelobes greatly reducing the crosstalk.

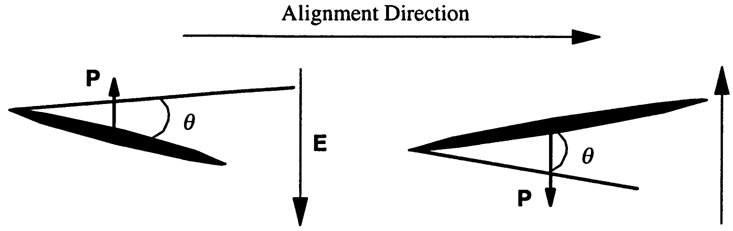
Q2 answer

a) One of the commonest calimatic liquid crystal mesophases is the nematic phase. This is the least ordered mesophase before the isotropic. Here the molecules have only long range order and no longitudinal order. This means that the molecules retain a low viscosity, like a liquid, and are prone to flow. This can greatly effect the speed at which nematic LCs can modulate the light. The existence of dielectric anisotropy means that we can move the molecules around by applying an electric field across them. This combined with the flow properties means that a nematic molecule can be oriented in any direction with the use of an electric field. This is a very desirable feature as it leads to their ability to perform greyscale modulation of the light.



The calimatic molecular shape also leads to an optical anisotropy in nematic LCs, with the two axes of the molecule appearing as the refractive index. The refractive index along the long axis of the molecules is often referred to as the extraordinary n_e (or fast n_s) and the short axis the ordinary n_o (or slow n_s) axis. The difference between the two is the birefringence. $\Delta n = n_e - n_o$. One of the most useful smectic mesophases is the smectic C (SmC) phase as the molecules are highly ordered and form layers with the molecules tilted within each layer. The smectic C structure can be improved by adding chirality to the molecular structure which adds an extra dipole perpendicular to the molecular axis of the LC material. This is often is referred to as chiral smectic C or SmC*.

If the FLC is restricted to a cell thickness of 2-5μm then the helix of along the cell is suppressed and the molecules are bounded into two stable states either side of the director cone. The angle between these two states is defined as the switching angle θ. This is referred to as a surface stabilised FLC geometry an creates a high degree of ferroelectricity and creates a large birefingent electro-optical effect. The penalty for doing this is that the molecules are only stable in the two states an therefore the modulation will only be binary. The up side to this binary modulation is that it can be very fast (~10μsec) and that the stability can lead to the molecules remaining in the two states in what is known as bistable switching.

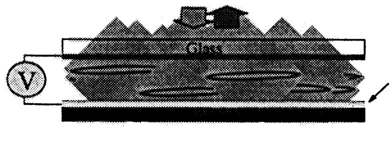


b) i) An optical correlator – must be fast hence FLC is best. Binary phase is ok, but has no asymmetry in the recognised objects. To break symmetry, must use more then binary phase levels. Polarisation sensitivity is not an issue.

ii) A single mode fibre to fibre optical switch – Speed is important, but not as important as loss and crosstalk. Therefore need to use a nematic LC for multi-level phase modulation. But this is polarisation dependent, hence we need an integrated quarter wave plate device.

ii) An optical packet switch – speed is everything. Need to modulate below 1usec, hence an electoclinic modulator is Ok. Optical loss is high, but this is Ok for speed

c)

Reflective  Mirror

LCOS device has integrated circuitry and pixel mirrors on the silicon backplane. This means the device can be very small, compact and high speed as well as possible intelligence. All of the drive electronics can be integrated into the backplane which makes for a very compact microdisplay. The mirror quality can also be optimised using planarisation and cold evaporated aluminium.

A LCOS backplane is designed for a particular type of modulation or material. FLCs are binary materials which require very simple circuitry to drive the pixels. This means that the circuits can implement complex binary logic, memory, registers and counters which makes the implementation very flexible and sophisticated. Allows for DC balancing and bitplane greyscale type operations.

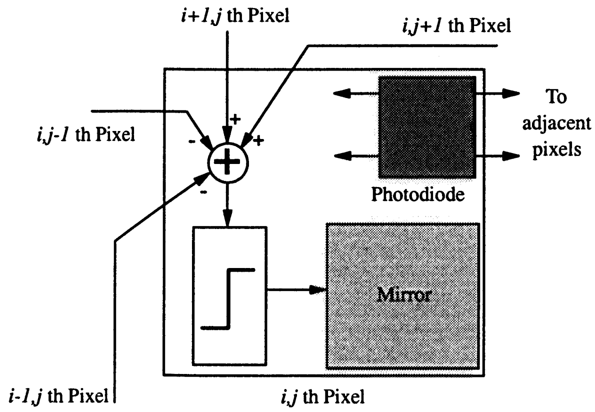
An LCOS backplane used with nematics is more complicated as it must maintain an analogue RMS voltage across the pixels. This needs bulky analogue/mixed circuitry and also includes circuits such as D to A converters and analogue multiplexers.

d) A logical advance in the design of a SLM is to combine the optical properties of the SLM with the processing ability of electronics. This is especially important when VLSI silicon backplane SLMs are used as the VLSI processes are identical to those used to create a standard silicon chip. For this reason, electronics is combined with the SLM to create smart pixels capable of processing information presented optically and then modulating light for further processing. Such pixels are very useful for both image processing and for optical neural networks hence they combine the modulating qualities of the LC material with the electronics and the use of silicon photodetectors at the pixel level.

One type of smart pixel is the isophote or intelligent camera, which performs spatial image processing. In this case, the pixel is fed by the four adjacent pixels to the left, right, above and below. The photodiodes from the adjacent pixels are connected to the central pixel in the fashion shown. The functionality of the summation of these signal is set such that we have the left pixel subtracted from the right added to the top subtracted from the bottom.

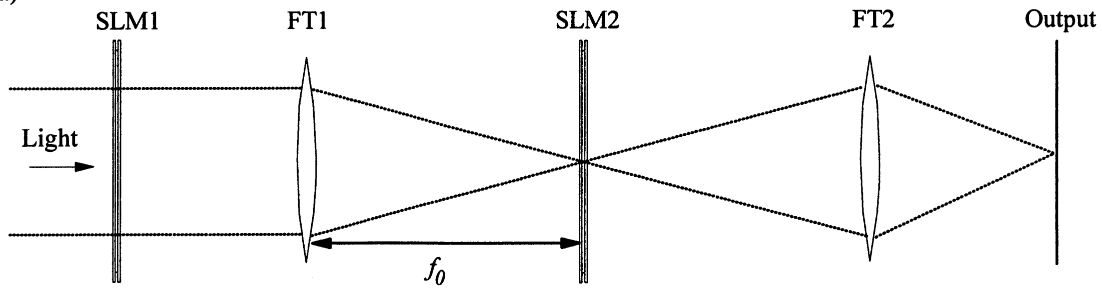
$$P'_{i,j} = \left|P_{i,j+1} - P_{i,j-1}\right| + \left|P_{i-1,j} - P_{i+1,j}\right|$$

This performs the function of a Roberts Cross filter which is a means of achieving edge enhancement. More complex processes such as Sobel filtering (a combination of all eight nearest neighbours) could also be implemented.



Q3 answer

a)



The basic optical layout for a BPOMF follows directly from the theoretical expectations. The input light illuminates SLM1 which is used to display the input image. SLM1 is also a FLC SLM, but it is used in intensity mode (black and white). The SLM is an N_1xN_1 array of square pixels, with a pitch of Δ_1, we are assuming that there is no pixel deadspace. The modulated light then passes through lens f_0 which performs the FT of the input image. The FT is formed in the focal plane of the lens and will have a finite resolution. Once the FT of the input (matched in size to SLM2) has passed through SLM2, the product of the input FT and the BPOMF has been formed. This is then FT'ed again by the final lens and the output is imaged by a CCD camera.

- Light source is collimated coherent laser illumination
- FT1 and FT2 are positive focal length lenses
- SLM1 and SLM2 are FLC transmissive SLMs. SLM1 is amplitude, SLM2 is phase.

The main limitation of this system is the alignment and scaling of the FT of the input image on SLM1 and the filter in SLM2. They must be matched and aligned to the nearest pixel and maintained by the opto-mechanics of the system. As the SLM shrinks in size, so does the pixel pitch which makes the alignment even more critical.

b) The FT is formed in the focal plane of the lens and will have a finite resolution (or 'pixel' pitch) given by. This comes from the sinc envelope for a pixellated object.

$$\Delta_0 = \frac{f_0 \lambda}{N_1 \Delta_1}$$

There are N_1 'pixels' in the FT of the input image on SLM1, hence the total size of the FT will be $N_1\Delta_0$. The BPOMF is displayed on SLM2 in binary phase mode. SLM2 is also a FLC device with N_2xN_2 pixels of pitch Δ_2. The FT of SLM1 must match pixel for pixel with the BPOMF on SLM2 in order for the correlation to occur. For this reason we must choose f_0 such that.

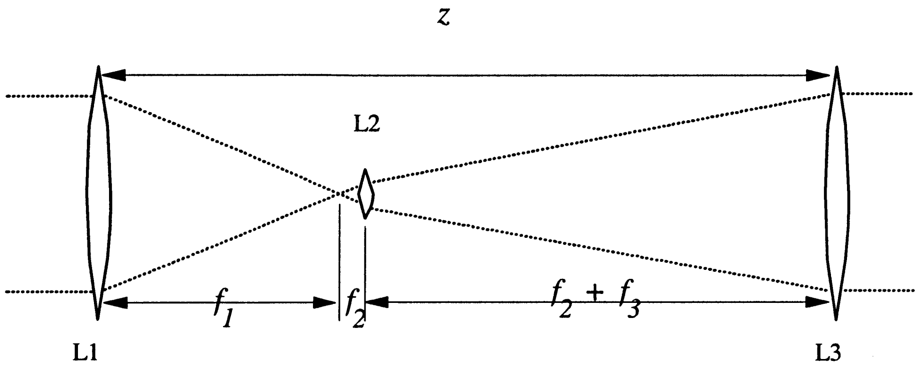
$$N_1 \Delta_0 = N_2 \Delta_2$$

Hence we can say.

$$f_0 = \frac{N_2 \Delta_2 \Delta_1}{\lambda}$$

<u>Example</u> SLM1 and SLM2 are both 128x128 pixel FLC devices, with a 220μm pixel pitch at a wavelength of 633nm. The required focal length to match the input FT to the BPOMF in this case is 9.787m which is clearly impractical as an experimental system. The overall length of the BPOMF would be in excess of 20m!

c) It is possible to shorten the actual length of the optical transform whilst still keeping the effective focal length that is desired by including further lenses in a combination lens. One technique is to combine a positive lens with a negative lens to make a two lens composite. This gives a length compression of around $f_0/5$ which in the example above is still 2m and impractical. Furthermore, the two lenses combine in aberrations which leads to poor correlations due to optical quality.



The three lens combination above provides a much higher length compression of around $f_0/15$. The only drawback is that the more elements you have, the more position errors there will be when the optical system is mounted. The three lens system is an FT lens followed by a two lens telescope to magnify the FT to the size of SLM2. The first lens f_1 generates the FT of the input in its focal plane. The size of this FT will be too small, as f_1 is chosen to be much shorter than f_0. The FT is then magnified by lenses f_2 and f_3 which are configured in a telescope. Lenses f_2 and f_3 are spaced $f_2 + f_3$ apart so that an object placed a distance f_2 in front of lens f_2 will be magnified after lens f_3 by a magnification of f_3/f_2. Hence, if the FT is placed a distance f_2 in front of lens f_2, then it will be magnified after f_3. We can now set the magnification factor so that the input FT matches the size of the BPOMF.

$$Magnification = \frac{f_3}{f_2} = \frac{N_2 \Delta_2 \Delta_1}{f_1 \lambda}$$

If the chosen lenses and SLMs fit this equation, then the FT will be the same size as the BPOMF and the total length of the three lens system will be.

$$z = f_1 + 2f_2 + f_3$$

When choosing the lenses, care must b taken to find good quality low aberration doublets. Choose a suitable f_1 length. Aim to create an FT of the input image which needs scaling by an integer value of magnification to match SLM2. The choose f_2 and f_3 to make this magnification.

<u>Example</u> For the SLMs in the above example, a first lens f_1 = 250mm was chosen to perform the initial FT. This means a magnification of 39.1 is required for the telescope. From the available catalogue lenses, a combination of f_2 = 10mm and f_3 = 400mm was chosen to give a magnification of 40. A lens of f_3 = 365mm was also available, but was not chosen as the magnification was closer with 400mm. Although the other lens offers a shorter overall optical length, it is best to choose the lens combination which offers the closest magnification to that which is desired. The overall length of the system was z = 670mm, which means that the BPOMF can now be constructed on an optical table.

Q4 answer

a) The job of the component design engineer is to marry together different specifications along with the packaging and environmental specifications in other to create a commercially cost effective component. Two very important considerations are the choice of materials used to make the waveguide and the fabrication methods employed. One of the key aspects to understanding the material properties is to recognise the phenomena which may cause effects at certain wavelengths.

The problem is in finding a unified theory which links together dielectric properties to optical properties such as absorption, dispersion and nonlinearities. A causal relationship linking absorption and the (complex) dielectric properties of all materials has been postulated and is known as the Kramers-Kronig relation.

$$n=\sqrt{\varepsilon_1},$$
$$\varepsilon=\varepsilon_1-i\varepsilon_2,$$
$$a=2\pi.10^6.\varepsilon_2.\log(e)/\lambda,$$
$$\varepsilon_1(\upsilon)-\varepsilon_\infty=\frac{2}{\pi}*\int\frac{\upsilon'\varepsilon_2(\upsilon')}{\upsilon'^2-\upsilon^2}d\upsilon'$$
$$\varepsilon_2(\upsilon)=-\frac{2}{\pi}.\upsilon*\int\frac{\varepsilon_1(\upsilon')-\varepsilon_\infty}{\upsilon'^2-\upsilon^2}d\upsilon'$$

where; n is refractive index; ε's are dielectric constant, 1 is Real, 2 is Imaginary, ∞ at infinite frequency; a is the absorption; ν is frequency; λ is wavelength. This theory can be combined with the materials response to electric fields to create a theory which describes the complex interaction of the material to applied field via the concept of polarisability.

$$n^2=\varepsilon_0+P/E,$$
$$P=\varepsilon_0.(\chi.E+\chi_2.E^2+\chi_3.E^3...),$$
$$n^2=\varepsilon_0.(1+\chi+\chi_2.E+\chi_3.E^2...)$$

Where P represents the interaction between the material and the electric field within the materials and the coefficients represent different non-linear interactions and effects within the materials. They are known as the susceptibilities or hyper-polarizabilities and are directly related to fundamental materials constants.

$$\chi_i\propto\frac{\mu^{i+1}}{(\mathrm{E}_g-\hbar\omega)^i}$$

Here the μ are the dipole moments, the denominator is the energy difference between the band gap (for electronic absorption) and the energy of a photon at the observation frequency. The materials analysis can take us so far in finding the right materials for our waveguide, but other parameters such as purity and the composition of impurities also greatly impact on the performance. In fact, some of the most critical parameters arise from the fabrication processes such as sidewall roughness in planar waveguides and core uniformity in optical fibres.

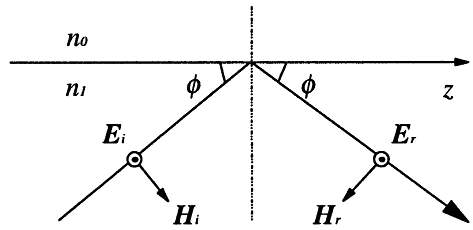
b) Optical fibres are made through a pulling process, where a large preform or boule is created with the relevant core and cladding profile before being heated to melting point and then being drawn down a long fibre pulling tower to create the fibre. The preform or boule is made using two techniques. Both are designed to produce an ultra-pure glass material in order to prevent impurities from increasing the loss per unit length of the drawn fibre. The preforms are made using pure silica glass and the core/cladding refractive index difference is done by doping the glass in the core with materials such as Germanium or Phosphorous. Hence the loss per unit volume must be extremely low in the boule before drawing. This calls for ultra pure glasses with extremely accurately defined refractive indices.

The fibre is made with a rather remarkable precision. The initial glass fibre is drawn to 125um diameter (for a standard S/M fibre) with a 0.3um tolerance and for extremely high quality fibres that tolerance can be as low as 0.05um. The centricity of the core is also set with a tolerance of 0.1um. The fibre is then protected with two separate plastic coatings. The first is the soft coat which is UV cured to a diameter of 220um and then the final hard coat is added to give the overall diameter of 250um with a tolerance of 5um. The final fibre is either wound onto a drum or further coated with plastic and Kevlar strands.

- refractive index of core is ~ 5e-3 > cladding index, which is typically silica i.e. n(1523 nm @ 20 deg. C) is 1.4463,

- the diameter of the core is ~ 10 μm and cladding 125 μm within a 250 μm jacket (probably dual clad acrylate or nylon),
- the fibre numerical aperture is ~ 0.1,
- the spot-size will be ~ 5.5 μm radii for transmission fibre, circular symmetric

c) If we consider a plane wave propagating along the *z* axis of the waveguide at an angle of inclination ϕ as in Figure1. The actual propagation of the wavefront is perpendicular to it, but the TIR means that propagation is in the *z* direction. The wavelength in the core is λ/n_1 and the wavenumber in the core is kn_1. The propagation constants along the *x* and *z* directions are given by.



$$\beta = kn_1 \cos\phi$$

Incident light A_i Reflected light A_r

$$\kappa = kn_1 \sin\phi$$

Before describing the formation of modes in detail we must understand the phase shift of a light ray which suffers total reflection. The reflection coefficient of the totally reflected light which is polarised perpendicular to the incident plane (the plane formed by the incident and reflected rays) is given by:

$$r = \frac{A_r}{A_i} = \frac{n_1 \sin\phi + j\sqrt{n_1^2\cos^2\phi - n_0^2}}{n_1 \sin\phi - j\sqrt{n_1^2\cos^2\phi - n_0^2}}$$

We then express the complex reflection coefficient *r* as $r = exp(-j\Phi)$, hence the amount of phase shift Φ is given by:

$$\Phi = -2\tan^{-1}\frac{\sqrt{n_1^2\cos^2\phi - n_0^2}}{n_1\sin\phi} = -2\tan^{-1}\sqrt{\frac{2\Delta}{\sin^2\phi} - 1}$$

This is referred to as the Goos-Hanchen shift. Now let us consider the phase difference between two light rays belonging to the same plane wave. Light ray PQ does not suffer a reflection however propagating from R to S will undergo two reflections (top and bottom). Since points P and R are on the same wavefront, points Q and S should also end up on the same wavefront. Hence optical paths PQ an RS (including the Goos-Hanchen shift after two reflections) must have the same path length or be an integral number of 2π different. The distance between Q and R is $2a/\tan\phi - 2a\tan\phi$, the distance between P and Q is expressed by:

$$l_1 = \left(\frac{2a}{\tan\phi} - 2a\tan\phi\right)\cos\phi = 2a\left(\frac{1}{\sin\phi} - 2\sin\phi\right)$$

Also, the distance between points R and S is given by:

$$l_2 = \frac{2a}{\sin\phi}$$

The phase matching condition for the optical paths PQ and RS then becomes:

$$(kn_1 l_2 + 2\Phi) - kn_1 l_1 = 2m\pi$$

Where *m* is an integer. Combining the above relationships gives us the condition for the modal behaviour of the angle ϕ.

$$\tan\left(kn_1 a\sin\phi - \frac{m\pi}{2}\right) = \sqrt{\frac{2\Delta}{\sin^2\phi} - 1}$$

This relationship shows that the propagation angle is discrete and is determined by the waveguide size *a*, the refractive index n_1 and the difference Δ. The optical field which satisfies the phase matching condition above is called a mode. The allowed value of the propagation constant β is also discrete. The mode with the minimum angle ($m = 0$) is referred to as the fundamental mode the others are higher order modes.