OPTICIAL WAVEGUIDING (OPTOSCI)

1. INTRODUCTION

The cylindrical dielectric waveguide, in the form of an optical fibre, is now the world's first choice medium for long distance, high data rate telecommunications. The demand for processing the optical signals in such systems has also prompted the development of a large number of waveguide devices and components, such as power splitters and combiners, multiplexers, filters and modulators. Clearly there is a need for optical physicists and engineers to fully appreciate the principles and design rules of optical waveguides. The experiments described in the OptoSCi WAVE module have been designed to demonstrate these principles as taught in an accompanying lecture course.

Conceptually, the simplest optical waveguides are the step index and graded index planner waveguide, and the most straightforward way to introduce students to the basic principles of wave guiding is to examine the ray model of such waveguides. In this approach, students can effectively learn about the principles of modes, mode effective index, mode cut-off thickness, single mode operation and basic wavelength design, all of which are fundamental to the understanding of light propagation in optical fibers, and to the design of waveguide devices, including, integrated optical components. In the experiments detailed below, we are able to investigate the modal properties of step and graded index waveguides formed by thin film deposition and ion exchange processes respectively, and to propose designs of single mode waveguides which can then be confirmed experimentally.

As preparation for these experiments, it may be desirable to have firstly carried out the investigation of reflection and refraction using similar apparatus as detailed in the OptoSci Reflection & Refraction (R&R) module. Those experiments cover Fresnel's laws and total internal reflection which are fundamental to optical wave guiding.

2. THEORY

2.1 Planar step index waveguides

In the ray model of wave guiding, we consider that the light propagates along the guide by a series of total internal reflections (see figure1). Total internal reflection occurs at the interface between a material of high refractive index and one of low index provided that the angle of incidence, relative to the interface normal, is greater than the critical angle. Hence, a planer step index waveguide is simply a thin layer of high index material bound on both sides by material of lower index (Figure 1).

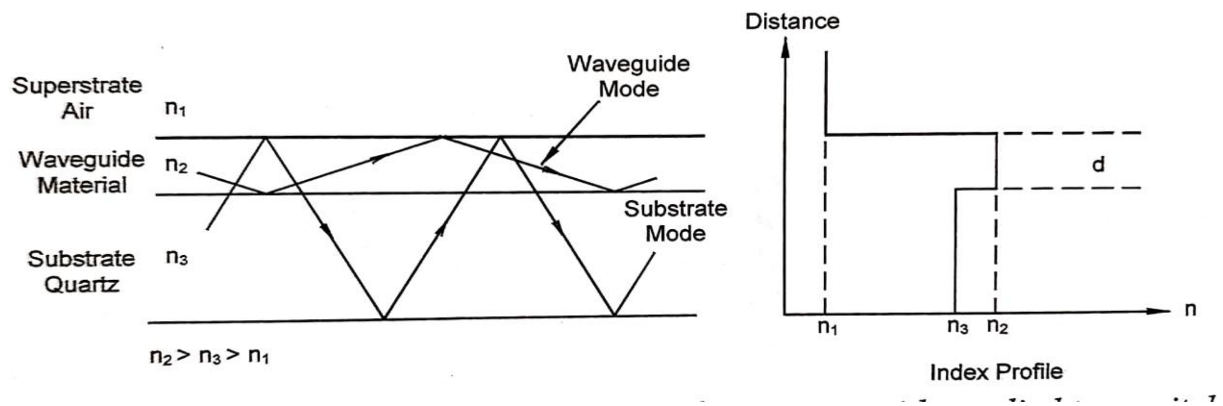


Figure 1: *Schematic diagram of a step index planar waveguide applied to a suitable substrate.*

The condition for light guiding in the plane of the waveguide, with confinement of power in the transverse direction (i.e. perpendicular to the waveguide), is that the counter propagating components of the field in the transverse direction must interfere to form a standing wave. This is necessary to ensure that there is no net transfer of power in the transverse direction. If this condition was not satisfied then the only other possibility of having a travelling wave in the transverse direction would result in net power loss out of the waveguide. Applying the standing wave condition to the transverse field components implies that light can only be guided at certain discrete angles of propagation, each angle referred to as a mode. For a planer waveguide of thickness d and refractive index n_2, the allowed angles, θ_m, are given by the following eigenvalue equation:

$$\frac{2\pi d n_2 \ cos\theta_m}{\lambda_0} = m\pi + \phi_1 + \phi_3 \qquad (1)$$

Where λ_0 is the wavelength of the input light, m is an integer (m = 0, 1, 2….) called the mode number and the terms ϕ_1 and ϕ_3 are the evanescent field phase shifts at the wavelength boundaries with the surrounding material.

Each allowed angle of propagation, uniquely defined by the integer m in equation 1, is referred at as a mode of the waveguide and each mode propagates with a particular phase velocity characterized by a mode effective index, n_e (where $n_e = n_2 \sin\theta_m$). Equation 1 can be re-written in terms of the mode effective indices as:

$$\frac{2\pi d\left(n_2^2 - n_e^2\right)^{1/2}}{\lambda_0} = m\pi + \phi_1 + \phi_3 \qquad (2)$$

Where ϕ_1 and ϕ_3 are given by

$$\phi_i = \tan^{-1} \xi \sqrt{\frac{n_e^2 - n_1^2}{n_2^2 - n_e^2}} \qquad (3)$$

where n_i (i = 1, 3 – see Figure 1) are the refractive indices of the surrounding materials and $\boldsymbol{\xi}$, which depends on the polarization state of the guided light, is equal to 1 for the TE modes and n_2^2/n_i^2 for TM modes. For n_1=n_3 (i.e. $\phi_1 = \phi_3$) we have a symmetrical waveguide, otherwise the waveguide is said to be asymmetrical. Note from equation 2 that as the mode number m increases the n_e value decreases. This is useful for assigning your measured n_e values to their respective m numbers in 6.1.1.4.

As we have decrease the design thickness of a waveguide we can predict what will happen to the modes by examination of equations 1 or 2. With the input wavelength and all other waveguide design variables fixed, decreasing d leads to changes in the propagation angle of each of the guided modes such that $\cos\theta_m$ increases to ensure that equation 1 remains satisfied. This means that the mode angles, θ_m, decrease with decreasing thickness. Eventually, θ_m, for a particular mode, m, becomes equal to and then less than the critical angle, θ_c, for the boundary with the higher index surrounding material, total internal reflection is lost at this boundary and the mode is said to be cut-off (i.e. it is no longer guided). For the waveguide dealt with here, the modes are cut-off at the n_3 boundary (Figure 1). Of course, in a symmetrical waveguide the modes are cut-off at both boundaries simultaneously. As the mode propagation angles decrease with thickness, their effective indices, given by $n_e = n_2 \sin\theta_m$, also decrease. At the cut-off point $n_e = n_2 \sin\theta_c = n_3$, since $\sin\theta_c = n_3/n_2$ for the n_3 boundary. Hence, the mode cut-off condition may be started as $\theta_m = \theta_c$ (for the higher index boundary), if we are using equation 2. The precise thickness at which a mode is cut-off is referred to as the cut-off thickness, d_c, which can be found by substituting the cut-off condition (n_e=n_3) into equation 2 to give:

$$d_c = \frac{(m\pi + \phi_1)\lambda_0}{2\pi\left(n_2^2 - n_3^2\right)^{1/2}} \qquad (4)$$

Equation 4 gives the cut-off thickness of both TE and the TM modes of an asymmetrical waveguide for which the modes cut-off into the surrounding material of higher refractive index, n_3. At the precise point of cut-off, the evanescent field phase shift at the n_3 boundary, ϕ_3, (see equation 3) goes to zero leaving only the ϕ_1 term in equation 4. The presence of ϕ_1 in equation 4 implies that in asymmetrical waveguides the m = 0 mode has a non-zero cut-off thickness (in contrast to symmetrical waveguides for which both phase shift terms go to zero at the mode cut-off point and the cut-off thickness of the m=0 mode is zero).

Step index planar waveguides are fabricated by the application of a thin layer of high index material onto the surface of a lower index substrate. This is often done by a vacuum deposition process. However, the waveguides used here were fabricated by the spin deposition of a sol-gel solution onto a quartz slide. The thickness is determined by the solution viscosity for a given spin speed, with the thickness of the waveguide being proportional to the viscosity. Thus higher viscosities yield thicker waveguides which correspondingly allow more modes to propagate. For many applications a single mode waveguide is required. A waveguide supports only a single mode when its thickness is below the cut-off thickness of the m=1 mode but above that of the m=0 modes. Equation 4 can be used to calculate the cut-off thickness of the m=0 and m=1 modes for both the TE and TM polarization state. These values are then used to used to decide the design thickness to maximize the probability of achieving the required mode operation from a manufacturing process.

2.2 Graded index waveguides

Thin film deposition is the primary approach to the production of step index waveguides. Alternative fabrication techniques, which result in graded index waveguides, include the use of diffusion and ion exchange processes. In the diffusion process a layer of material, usually a metal, is vacuum deposited onto a suitable substrate. The structure is then heated in a furnace at a sufficiently high temperature to allow the metal to diffuse into the substrate. The presence of the metal locally increases the refractive index of the material resulting in the creation of the waveguide. The refractive index is greatest at the surface, falling off as we go deeper into the material until it is equal to the index of the substrate (Figure 2). The refractive index thus varies across the waveguide which is then referred to as a graded index waveguide. The surface index is determined by the metal thickness, and the waveguide thickness is determined by the diffusion temperature and the diffusion time at that temperature. This is the approach used to fabricate lithium niobate integrated optic devices in which titanium is diffused into the lithium niobate substrates at temperatures up to 1000^0C.

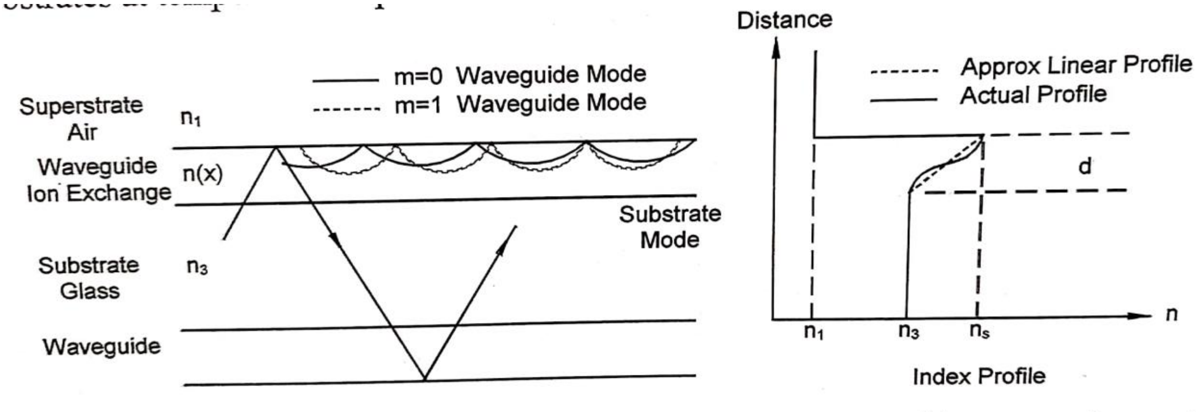


Figure 2: *Schematic diagram of graded index waveguide formed by ion exchange (or diffusion) with both sides of a glass slide.*

In the ion exchange process a suitable substrate is dipped into a molten salt (Figure 3). At the elevated temperatures of the melt, ions in the substrate become mobile and surface ions may exchange with ions from the melt. For suitable choices of the substrate and melt, this results in a local increase in the surface refractive index to form the waveguide. Many common glasses, sometimes referred to as ‘soda lime glasses’, contain sodium ions in their silicon/oxygen network, and these sodium ions may be exchanged with silver or potassium ions if the glasses are immersed in molten salts of silver nitrate or potassium nitrate respectively. In this way the refractive index of soda lime glasses may be increased to form waveguides of a few µm deep at the glass surface. Ion exchange integrated optic devices such as power splitters and wavelength division multiplexers are fabricated using this technique. In the experiments detailed below we shall investigate the mode structure of ion exchange waveguides which are identical in their principle and behavior to diffused waveguides.

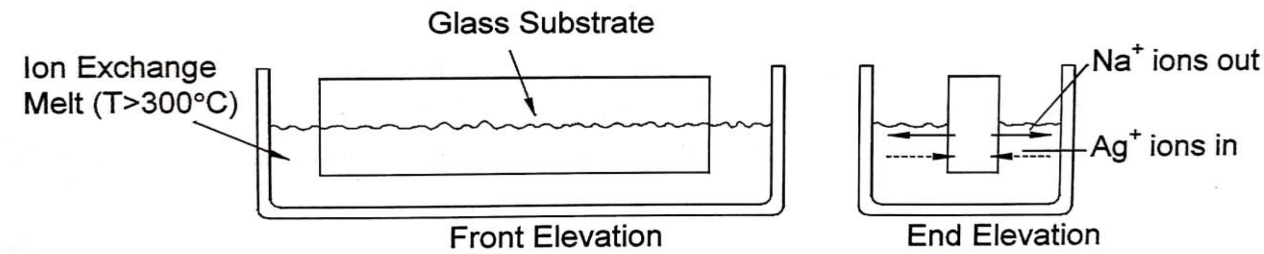


Figure 3: *Fabrication of ion exchange waveguides.*

Figure3: *Fabrication of ion exchange waveguides.*

In ion exchange waveguides, like diffused guides, the refractive index is greatest at the surface falling off as we go into the material until it equals the index of the substrate. Again, the index is not uniform across the thickness of the waveguide and the ion exchange process thus leads to graded index waveguides (Figure 2). The surface index is determined by the concentration of the exchange ions in the melt, and the waveguide thickness is defined by the temperature of the melt and the time of immersion.

In graded index waveguides the models travel in curved ray paths. Like step index waveguides the allowed guided modes must propagate such that the field components in the transverse direction form standing waves. The standing wave condition implies that each mode, m, propagates in a unique path with its own unique effective index, n_e, given by:

$$\frac{2\pi}{\lambda_0} \int_0^{d_m} \sqrt{n^2\,(x) - n_e^2}\; dx = m\pi + \frac{\pi}{4} + \phi_1 \tag{5}$$

Where n(x) is the refractive index profile, d_m is he mode depth and ϕ_1 is given by equation 3.

For many purposes it is a reasonable approximation to assume that the index profile is linear (see Figure 2), in which case equation 5 reduces to the following expression:

$$\frac{2\pi d\left(n_s^2 - n_e^2\right)^{3/2}}{3n_s(n_s - n_3)\lambda_0} = m\pi + \frac{\pi}{4} + \phi_1 \tag{6}$$

Where n_s is the surface index of the waveguide, d is its full thickness (see Figure2) and π/4 is the evanescent field phase shift term at the boundary with the n_3 material.

As for step index waveguides, the mode effective indices decrease with reducing waveguide thickness and successive modes of order m are cut-off when their effective indices become equal to and then less than n_3. Substitution of $n_e=n_3$ into equation 6 and letting the π/4 term go to zero gives the mode cut-off thickness as:

$$d_c = \frac{(m\pi + \phi_1) 3 n_s (n_s - n_3)\lambda_0}{2\pi\left(n_s^2 - n_3^2\right)^{3/2}} \qquad (7)$$

Equation 6 may be used to analyse the mode structure of graded index waveguides and equation 7 can then be used to determine the cut-off thickness of the m=0 and m=1 modes in order to select a design thickness for single mode operation.

Once the design thickness has been chosen, the waveguide designer must then select the fabrication parameters to achieve this thickness. The waveguide thickness is determined by the temperature, T, of the ion exchange melt and the immersion time, t, in the melt, in accordance with the following relationship:

$$d = \sqrt{Dt} \qquad (8)$$

where D is the temperature dependent effective diffusion coefficient given by $D = D_o \exp(\Delta H/RT)$; D_0 being the effective diffusion constant, R the gas constant (R = 8.31 J/mole.K) and ΔH the free energy of diffusion. Thus the depth of the waveguide increases with immersion time in the melt, so that a short immersion time yields a thinner waveguide which correspondingly allows fewer modes to propagate.

2.3 Prism coupling

Light may be coupled from a collimated or focused beam into a waveguide using a high index prism clamped to the waveguide surface (see Figure 4, Figure 5 & Figure 7).

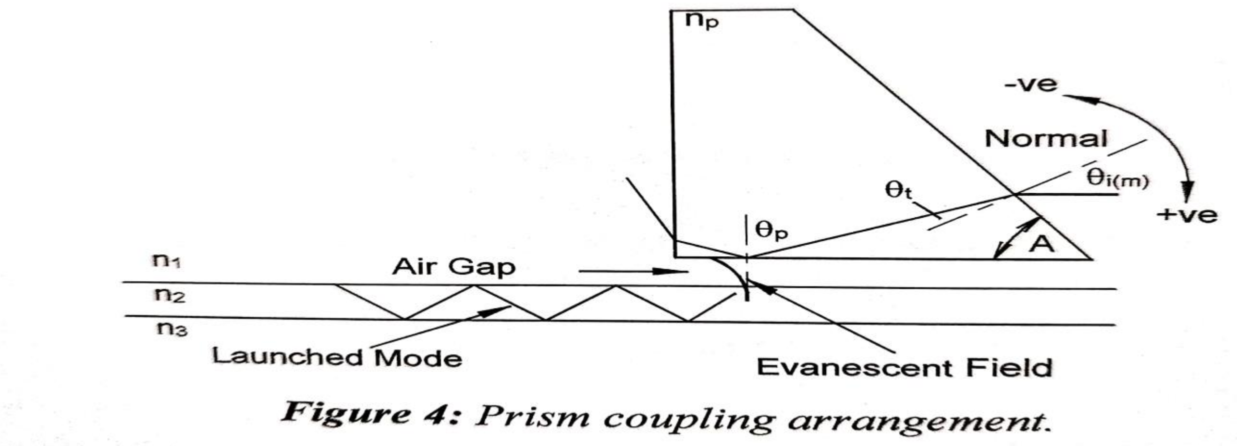


Figure4: *Prism coupling arrangement.*

The conditions for coupling to take place are as follows:

1. The prism refractive index n_ρ, must be greater than that of the waveguide material.
2. The prism and the waveguide must be in good optical contact such that the evanescent field generated by total internal reflection at the bottom surface of the prism penetrates into the waveguide. Since the evanescent field strength decays exponentially within a few µm in air, the contacting surfaces must be clean and dust free, and the assembly must be clamped firmly, but not too tightly as the air gap is necessary.
3. The effective index (and hence the phase velocity) of the light wave along the bottom surface of the prism (i.e. the effective index of the evanescent field in the plane of the waveguide) must be adjusted to match that of a waveguide mode (Figure5). This is achieved by adjusting the angle of incidence at the input face of the prism by rotation of the prism coupling assembly.

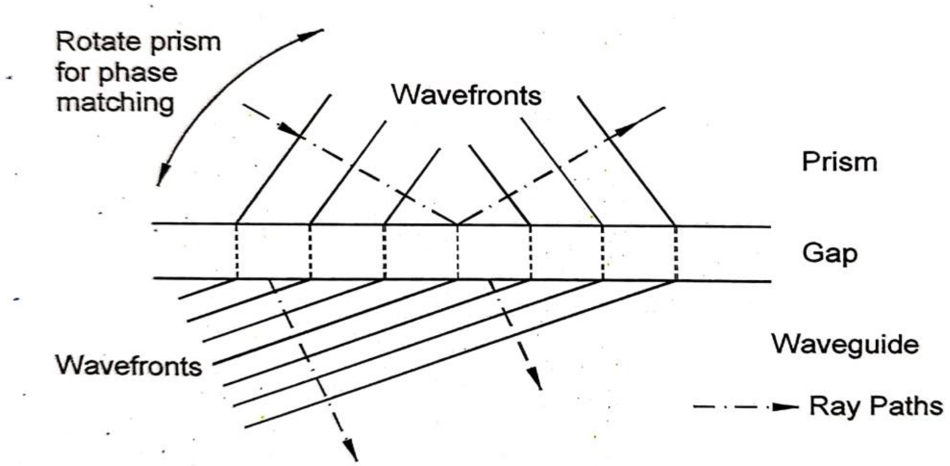


Figure 5: *Phase matching condition at prism - waveguide interface*

With reference to Figure 4 the effective index, n_{ep}, of the advancing field along the prism surface in contact with the waveguide is $n_{ep}=n_p \sin\theta_p$, where $\theta_p=A+\theta_t$ (A being the prism angle and θ_t the transmitted angle at the prism input face). Snell's Law enables θ_t to be expressed as $n_p\sin\theta_t=\sin\theta_i$ i.e. $\theta_t=\sin^{-1}[(\sin\theta_i)/n_p]$. This means that the mode effective indices, n_e, of all of the waveguide mode to which coupling is observed may be found from the following expression:

$$n_e = n_{ep} = n_p \sin\left[A + \sin^{-1}\left(\frac{\sin\theta_i(m)}{n_p}\right)\right] \qquad (9)$$

where $\theta_i(m)$ are the measured angles of incidence, relative to the normal to the prism input surface, which results in excitation of the waveguide modes of number m. Note that for the sign convention in use here and the experimental set-up shown in Figure 7b, measured incident angles which extend clockwise from the normal are positive and those which extend anti-clockwise are negative.

Light within a guided mode may be coupled back out of the waveguide by clamping a second (output) prism to interact with the mode at a distance of about 1-3cm from the input prism (Figure7b). If the output prism is the same as the input prism, then the light coupled out of the guide will emerge at the same angle, relative to the output face normal, as the input angle, $\theta_i(m)$. Most of the power emerges in a beam which is in the incidence plane. However, the output coupling condition as regards angle is satisfied for a section of a cone. Hence, when the emergent light is viewed on a white card, we see an illuminated line with a bright spot at its centre. The line, referred to as a mode line or m-line, is in fact a shallow arc resulting from the intersection of the emergent cone of light with the card. It is interesting to scan the incidence angle to selectively launch successive modes while viewing the m-lines (see later).

3 APPARATUS

The apparatus consists of the following hardware elements:

1. An optical rail bench (Figure 6) fitted with a visible (633nm) semiconductor laser with integral drive electronics plus its mount, a polarizer with a graduated rotational mount, a mounted lens with a 15cm focal length, and a precision graduated rotational table mounted on a translation assembly which can be adjusted vertically and horizontally transverse to the optical axis.

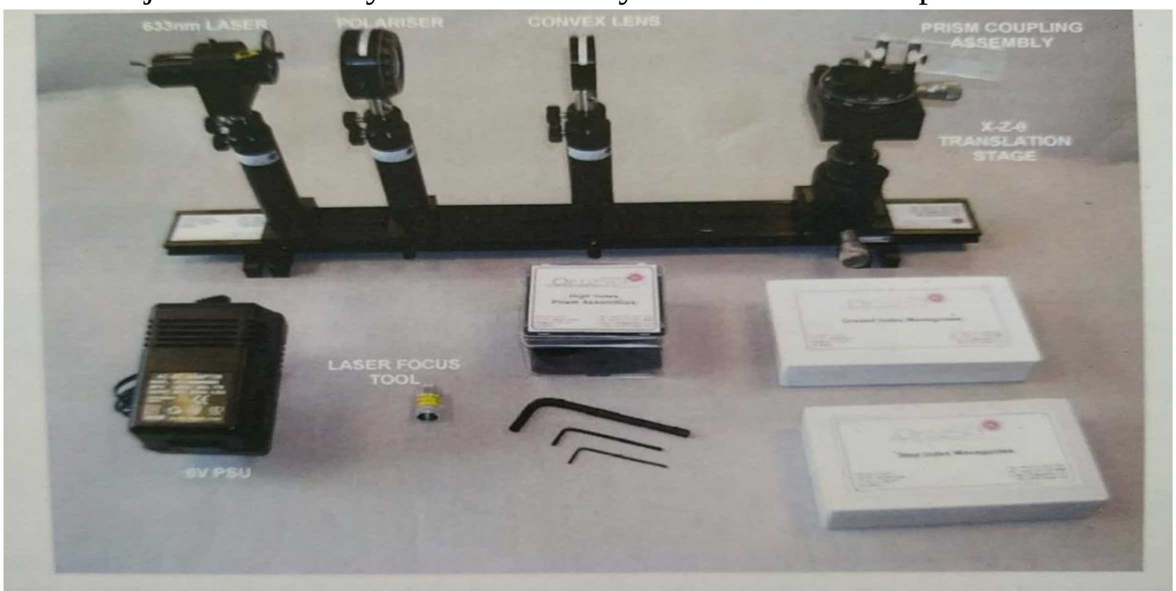


Figure 6: Equipment for Waveguiding experiments

2. A 633nm laser diode module powered by a 6V regulated power supply which is connected at the rear of laser unit (note that the tip of connection lead should be positive). Power to the laser is controlled by the on / off switch and is indicated as on when the green LED, adjacent to the switch, lights up. A moveable shutter at the laser output can be employed to block to emitted laser beam. The laser focus can be adjusted using the tool provided (e.g. to collimate or focus the laser beam) as described in Appendix LA & C).
3. A prism coupling assembly which is mounted on the rotational table and into which the waveguides may be clamped for investigation.
4. A selection of multi mode and single mode step index waveguides fabricated by the spin deposition of a sol-gel onto a quartz slide from solution.
5. A selection of multi mode and single mode graded index waveguides fabricated by the ion exchange process into a soda-lime glass slide.

Once this system is assembled properly (see Section 5), the prism coupling arrangement is addressed by a focused laser beam of selected polarization and can be rotated to vary the angle of incidence in order to effect coupling to the optical waveguides.

4 LASER SAFETY

WARNING: IT IS IMPERATIVE THAT YOU READ AND UNDERSTAND THE FOLLOWING SAFETY INFORMATION BEFORE ATTEMPTING ANY OF THE EXPERIMENTS DETAILED BELOW. IF YOU HAVE ANY QUESTIONS PLEASE CONSULT YOUR LECTURERE OR LABORATORY SUPERVISOR.

4.1 Operational Hazard – Semiconductor laser diodes

The laser diode source you will be using emits red, visible light at a wavelength of 633nm. It is categorized as a Class 2 source and is thus defined to be eye safe, having a power output below 1mW. However, ***never*** look directly into the beam path or stare at the laser output port when the laser is switched on and the output port is open. In addition, you must ***never*** point the laser beam at yourself or anyone else, either directly, or as reflected off any surface which you are handling.

The semiconductor laser diode is fully compliant with IEC 60825-1:2002. The output power of less than 1mW at 633nm meets Class 2 limits as defined within that standard.

5 THE EXPEPRIMENTAL SYSTEM

5.1 Aims and Objectives

The overall aims of this experimental investigation are to demonstrate the principles of light propagation in optical waveguides via modes, to provide some appreciation of the design of waveguides and to illustrate the prism coupling technique for examining the modal structure of waveguides and determining the waveguide parameters (i.e. refractive index profile and thickness). To achieve these aims the specific objectives of the experiments are:

1. To determine the mode structure of several step index and graded index planar optical waveguides using the prism coupling technique to measure the number of modes guided and their effective indices for both the TE and TM polarization states.
2. To determine the approximate index profile and thickness of the waveguides investigated, using the results of the mode structure measurements.
3. To establish designs for the manufacture of single mode step index and graded index planar waveguides and
4. To confirm that your designs do in fact yield single mode waveguiding using the prism coupling technique and examination of the m-lines.

5.2 Assembly and operating instructions for the experimental system

5.2.1 Assembly of the system

The key aim is to deliver the focused output of the laser onto a point on the rear face of the launch prism which is centred on the rotational axis of the rotation stage. This optimizes the position for the coupling point for all launch angles and facilitates easier measurements.

If it is not already assembled, the optical rail should be set up in accordance with Figure 7 following the set-up procedure as detailed in Appendix WAVE1- Basic Assembly Procedure.

5.2.2 Establishment of the required polarization state

The modes of a planar waveguide are polarization sensitive via the phase shift terms in the eigenvalue equation (see Theory). Hence the polarization of the beam incident on the waveguide must be known and adjusted to that required by the objectives of the experiment. Usually this means that we adjust the linear polarization of the incident beam into one of the two states below:

Polarisation launched	E-field vector	Laser Polarisation Direction
TE	Vertical	In the plane of the waveguide
TM	Horizontal	90^0 to the plane of the waveguide

However, as the laser output is ploarised this would require a separate adjustment of the laser for each desired state. Alternatively, and more simply, the laser orientation may be fixed to provide an output polarisation direction at 45^0 which launches both polariasation conditions simultaneously. Once this has been done, the polarization direction incident on the half cylinder may be adjusted simply by rotating the poloariser until its transmission axis is vertical or horizontal as required. Note that the polarizer has been fixed in its mount such that its transmission axis is vertical when the orientations is set at zero. The penalty for this convenience is that the power available at the interface is about half that available if the laser orientation is adjusted for each desired polarization state, but this should not cause a problem when performing the experiment. Hence, it is recommended to employ the latter method (i.e. with the laser at 45^0 to the incident plane) of adjusting the polarization state of the laser beam when performing the experiments which follow in 6.1 and 6.2. The procedure to follow to achieve this alignment is detailed in Appendix WAVE1.

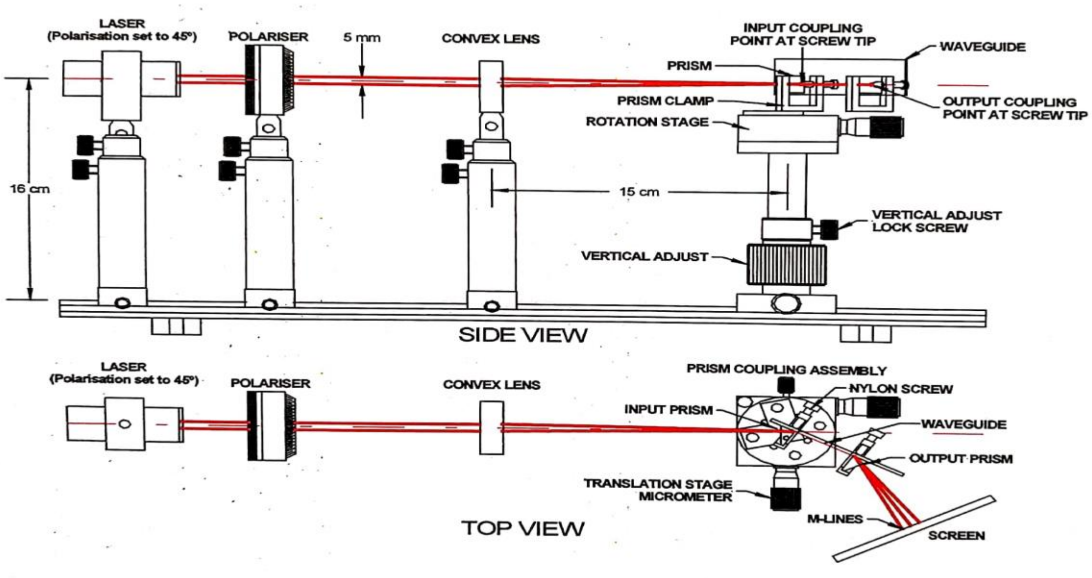


Figure 7: *Prism coupling assembly*

(Recommended settings: Optical axis = 16cm, Laser aligned at 45^0 to polarization axis, Beam collimated Lens-to-Prism distance = 15cm)

5.2.3 Operating of the system

In operation, the incidence angle of the laser beam onto the prism input surface may be varied simply by rotating the prism table, and the precise point of incidence on the rear face of the prism may be adjusted to maximize the coupling efficiency using the horizontal translation stage. Details to help achieve the optimum coupling condition are contained in Appendix WAVE2.

For more precise angular measurements, relative angles can be measured using the micrometer on

the rotation stage which is graduated in degrees and minutes, this technique is described in Appendix WAVE3.

6.EXPERIMENTS AND EXERCISES

Assuming that the system is assembled and aligned as detailed in Section 5 and Appendix WAVE1, the waveguiding experiments may be carried out. The first series of experiments will examine the behavior of the Step Index waveguides. The investigation will then be repeated to characterize the Graded Index waveguides in a similar manner.

> ***Practical Note:*** *Appendix WAVE2 provides a step-by-step guide to assist in achieving waveguiding in the samples and illustrates some typical outcomes of the experimentation detailed below.*

6.1 Investigation of Step Index Waveguide

As outlined in Section 2.1, the step index waveguides are fabricated by the spin deposition of a thin layer of high index sol-gel onto the surface of a quartz substrate. The refractive index of the quartz substrate is 1.456.

Practical Notes:

Care should be taken when handling the quartz slides to protect the waveguide surface from scratches and fingerprints. Ideally you should use protective gloves when handling the waveguides. Alternately always hold the slides by their outer edges and remove or replace them in the slide tray by holding the corner with the information label. However, the sol-gel material used to fabricate the waveguides is 'glassy' in nature which makes the waveguides resistant to damage when cleaned gently with an optical tissue. Hence, if the surface of a step index waveguide appears dirty it is safe to clean it with an optical tissue.

The waveguide area for the step index guides is on the same side of the quartz slide as the information label (i.e. the prism should be clamped to this side of the slide).

6.1.1 Determination of the mode structure of a step index planar waveguide

Determination of the mode structure of a waveguide involves the measurement of the effective indices (n_e) of all of the guided modes of the waveguide for both the TE and TM polarization state. The two orthogonal polarization states should be dealt with separately in accordance with the following procedure.

6.1.1.1 Observation of the substrate modes

Firstly, the polarization state of the incident light should be arranged to be vertical to launch TE modes, as described in Section 5.2.2. The quartz slide supporting the waveguide should then be clamped firmly into the prism coupling assembly as shown in Figure 7, but without the output prism (note the viscosity reading marked on the slide *Medium or High*).

The prism / waveguide assembly should now be rotated and its horizontal position adjusted (using the micrometer stage) to observe, and then to optimize, the coupling to substrate modes which are characterized by the appearance of a series of bright spots on the front and rear faces of the slide. The bright spots appear at the points where the coupled beam undergoes total internal reflection at the slide surfaces (see Figure 1 & Figure 2).

Question 1.

Why do we see the points at which the light is incident on the slide surfaces if we are genuinely in a situation of total internal reflection? To assist in answering this question consider firstly why you cannot see the beam from the laser as it propagates in free space and what you would have to do to enable you to see it.

6.1.1.2 Coupling to the waveguide modes

Following observation of the substrate modes, rotate the prism coupling assembly in an anti-clockwise direction until you observe coupling to a guided mode of the planar waveguide characterized by a continuous illuminated line. As you rotate the prism stage, the coupling to the substrate modes may become-weaker as the optimum coupling position is lost. Hence, as you carry out this exercise, the coupling strength and the brightness of the substrate modes should be re-optimized periodically by adjustment of the horizontal translation stage. This will maximize the probability of observing coupling to the waveguide modes.

Practical Note: *This process can be a little tricky and you must preserve with it until the waveguide modes are identified – refer back to Appendix WAVE2.*

Once you have succeeded in coupling to the waveguide modes rotate the prism assembly to selectively couple to each guided mode in turn and count them to establish the number of modes supported by this waveguide at a wavelength of 633nm.

Question 2.

Why do we observe a bright continuous line when coupling to a waveguide mode?

6.1.1.3 Observation and investigation of the m-lines (mode lines)

To observe the m-lines, clamp the second prism to your waveguide to interact with the guide mode at distance of about 1-3cm from the input prism. If the optical contact is sufficiently good, light will couple out of the guide, and the m-lines may be observed on a white screen (card or paper) held about 20cm from the prism. Rotate the prism assembly and note what happens to the m-lines as power couples selectively to each successive mode.

Question 3.

1. Describe what you observe as you rotate the prism.
2. If you are selectively coupling to only one mode at a time, why do you see more than one m-line simultaneously?
3. How many modes does this waveguide support?

6.1.1.4 Measurement of the coupling angles and mode effective indices for the TE polarization state

> ***Practical Note:*** *For better precision, all relative angles can be measured using the micrometer which is graduated in degrees and minutes. When using this technique the 'Prism Normal' should be set to the midpoint of the micrometer gauge travel and locked in position with the slide screw. The relative angles can then be measured readily by adjusting the micrometer, as is described in more detail in Appendix WAVE3.*

Measure the angles (θ_i (m), see Figure4), relative to the normal to the prism input facet, at which coupling is observed to each of the modes of the waveguide. The orientation of the rotational stage relative to the prism is arbitrary and the reference angle at which the incident beam is normal to the prism face can be found by rotating the prism assembly until the beam reflected from the front face of the prism is in the same vertical plane as the incident beam. The coupling angles (θ_i (m)) are simply the absolute difference between the scale readings at which coupling is observed and the scale reading for the reference angle. Note that angles may be recorded on either side of the reference angle, for which the sign convention used in equation 9 and the experimental set-up of Figure 7 dictates that angles extending clockwise from the prism normal are positive and those extending anti-clockwise are negative (see Figure 4 and equation 9).

Once you have measured all of the coupling angles, calculate the corresponding mode effective indices using equation 9, and draw up a table of mode numbers m, their measured coupling angles and their effective indices. Here n_p is the prism refractive index which is 1.7789, and the prism angle (A) is 60^0. Be sure to assign to correct effective indices to the corresponding mode numbers (see Theory-equation 2).

6.1.1.5 Measurement of the mode structure of the waveguide for the TM polarization state

Rearrange the equipment to launch the TM polarization state and repeat 6.1.1.2 & 6.1.1.4. You now have the full mode spectrum of the waveguide provided for both polarization states.

As an interesting exercise, rearrange the equipment such that the polarization direction of the beam incident on the waveguide is at 45^0 and observe the m-lines.

Question 4.

Describe and explain what you see in the above exercise. What do you think of the m-line technique as a means of confirming the number of modes guided by a waveguide?

6.1.1.6 Determination of the mode structure of the second step index waveguide provided (optional – on instructions from the laboratory supervisor)

Repeat 6.1.1.1-6.1.1.5 for the other step index waveguide you have been given.

6.1.2 Determination of the step index waveguide parameters (i.e. the waveguide refractive index and thickness) from the measured mode spectrum.

From the measurements made in 6.1.1, you should now know the effective indices of all of the TE and TM modes of the waveguides you have been given. The mode effective indices are given by equation 2 in which all of the parameters are known except the waveguide index (n_2) and the thickness (d): λ_0 is the input wavelength which in this case is 633nm; n_1 is the superstrate refractive index which is air (i.e. n_1=1) and n_3 is the refractive index of the quartz substrate which is 1.456. By substituting the measured values of the effective indices and their corresponding mode numbers into equation 2 for two of the modes, we can establish two simultaneous equations with two unknowns. It is difficult to solve for n_2 and d analytically, since n_2 appears on both sides of the equation, and a numerical approach must be adopted. The simplest and most accurate numerical approach is to plot d as calculated using equation 1 against n_2 for the m=0 and m=1 modes over the appropriate range. The true values of d and n_2 may then be read from the crossing point of the two curves. The key to success in this exercise is to use the correct range of n_2. We know that the value of the effective index of the m=0 mode of a multimode waveguide is a little less than the waveguide material index. Hence, for the calculation of d versus n_2, we should choose an initial value of n_2 which is say 0.002 above the measured effective index of the m=0 mode and then increment by 0.002 calculating d each time. This should be continued until the d versus n_2 curves for the m=0 mode and the m=1 mode cross.

Using the approach described above, determine n_2 and d using the m=0 and m=1 modes for the TE polarization and repeat the exercise using the TM mode data. Attempt to explain any differences you may find between the TE and TM results?

Repeat this exercise for your second waveguide (optional – on the instructions of your supervisor).

6.1.3 Establishing the design of a single mode step index waveguide.

For step index waveguides such as the ones investigated here, establishing the design of a single mode guide usually means calculating the appropriate thickness for which only the m=0 mode remains guided. However, in this particular example the magnitude of waveguide birefringence is sufficiently large that there may be issues of polarization to address.

Given that the waveguide index, n_2, is now known, determine your design thickness to ensure that only the m=0 mode is guided for both polarization states and then for only one polarization state. When calculating your design thickness, remember that you will wish to minimize the probability of error in a manufacturing process.

6.1.4 Confirmation of your design of a single mode waveguide.

You will be given a waveguide with a similar thickness to your design thickness for single mode guiding in both polarization states. Confirm that only m=0 modes are guided by establishing prism coupling and observing the m-lines. Describe your observations and how you achieved confirmation.

6.2 Investigation of Graded Index Waveguides

As outlined in Section 2.2, the graded index waveguides are formed by ion exchange into the soda-lime glass substrate. The refractive index of the glass substrate is 1.501.

> ***Practical Note:*** *Remember to follow the handling precautions detailed in 6.1. Note that the waveguiding area for the graded index guides is actually on both sides of the glass slide however for consistency with the step index waveguides it is recommended that the prism should be clamped to the same side as the information label.*
>
> *Since the graded index waveguides are formed into the glass slide, the waveguides are resistant to damage when cleaned with an optical tissue. Hence, if the surface of a graded index waveguide appears dirty it is safe to clean it with an optical tissue.*

6.2.1 Determination of the modes structure of the graded index waveguide

Repeat sections 6.1.1.1 to 6.1.1.4 for the TE modes of the ion exchange graded index waveguides provided, establishing the table of mode numbers, coupling angles and effective indices. Before beginning your measurements, you should take note of the fabrication parameters (i.e. melt temperature and immersion time used in the manufacturing process) for your waveguides. These details are inscribed on the label in the corner of the glass slide containing the waveguide.

The degree of waveguide birefringence in the graded index waveguides is much lower than that in the step index waveguides. Hence, it is not necessary to carry out the mode spectrum measurements for the TM modes. However, it is worthwhile establishing a 45^{o} incident polarization state in an effort to observe the polarization mode splitting in the m-lines.

6.2.2 Determination of the waveguide parameters of the graded index waveguide (the surface index and thickness) from the measured mode spectrum.

Repeat the procedure in 6.1.2, but this using equation 6, to determine the approximate surfaces index and the thickness of the graded index waveguide.

6.2.3 Establishing the design of a single mode graded index waveguide

Given that the surface index, n_s, is now known, calculate your design thickness to ensure the best chance of achieving single mode operation from a manufacturing process. Note that, since waveguide birefringence is small in the graded index waveguide, calculation of the single mode design thickness for either polarization state will ensure single mode operation for both.

For ion exchange waveguides, knowledge of the waveguide thickness to ensure single mode operation does not complete the design and the designer must also specify the fabrication parameters which are the temperature of the ion exchange melt and the time of immersion in the melt. Equation 8 relates the waveguide thickness to the immersion time and the temperature. Using the information from the waveguide that you have investigated, determine the value of the effective diffusion coefficient, D, in equation 8. Finally, determine the time of immersion required to fabricate a single mode guide, assuming the same melt temperature as used to fabricate the multi-mode guide you measured.

6.2.4 Confirmation of single mode operation

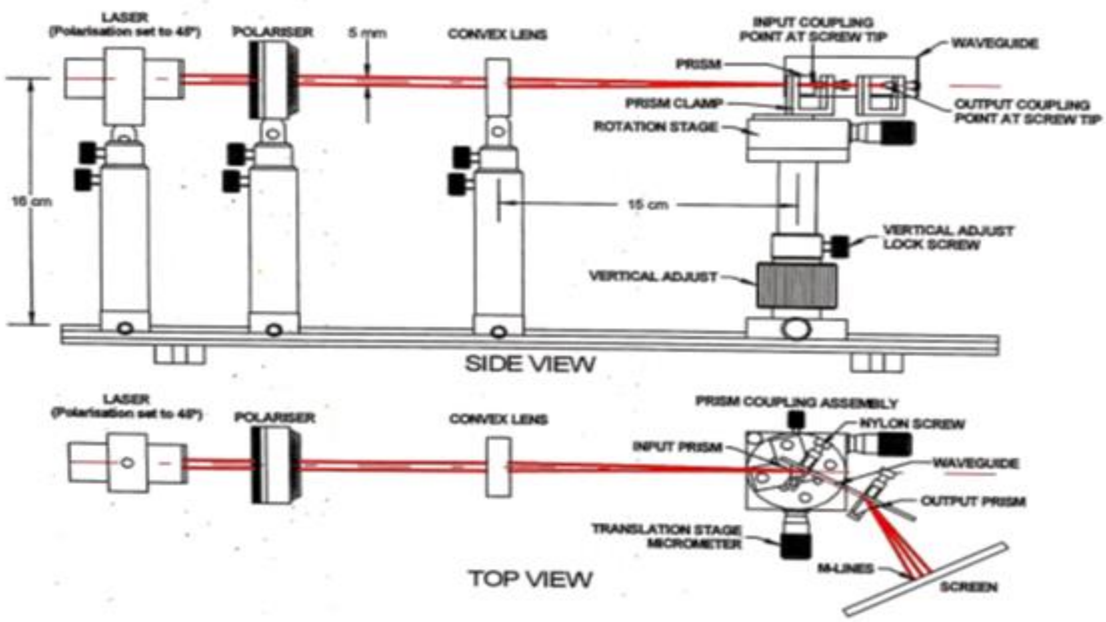
You will be given an ion exchange waveguide fabricated approximately in accordance with your design and manufacturing specifications. Establish prism coupling for this waveguide and investigate the m-lines to confirm single mode operation.

APPENDIX WAVE: OPTICAL WAVEGUIDING SET-UP

WAVE1: Basic Assembly Procedure:

1. Check that the components are set up on the optical rail as shown in Figure WAVE1 and Figure WAVE2.

Figure WAVE1:*Apparatus for waveguiding experiments*



FigureWAVE2: *Set up for waveguiding experiments*

2. Place the laser in its post holder and set the laser beam height to 16cm above the top of the rail. This will set the height of the optical axis. Roughly, centralize the laser beam along the centre of the rail.
3. Since the laser output is polarized, it is recommended than the laser should be rotated around its horizontal axis to be at 45^0 to the incident plane to equalize the laser launch power for 0^0 (vertical polarization) and 90^0 (horizontal polarization).

3.1 Check the orientation of the laser by using the set-up shown Figure WAVE3. Rotate the polarizer and check the angle which yields the minimum output power. This should be around 135^0, if not follow the procedure in 3.2.

3.2 Set the polarize to 135^0, loosen the laser holding screw and rotate the laser within it mount to achieved the minimum output power. This aligns the laser at 45^0 to the incident plane and should ensure that the laser launch powers at 0^0 and 90^0 are close to being equalized. When the process is completed the polarizer may be removed from the system.

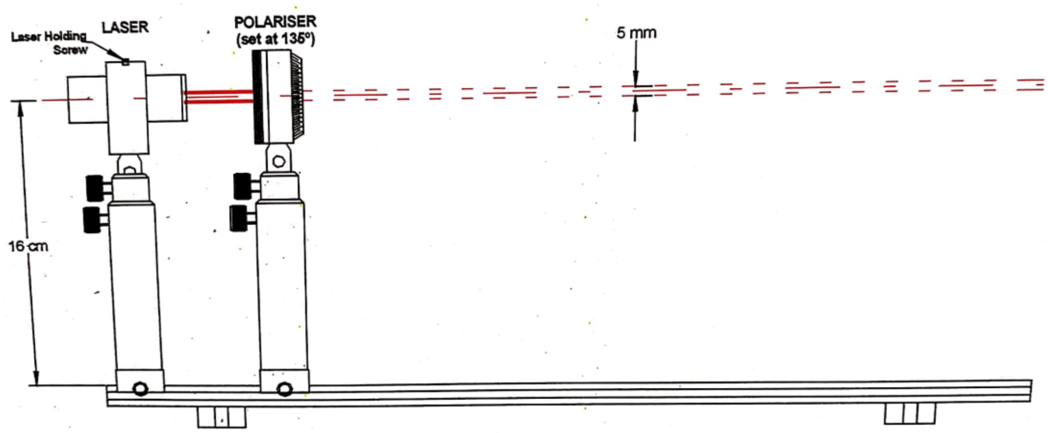


Figure WAVE3: *Set up for establishing the 45° polarisation for waveguiding*

4. To accurately centralize the laser beam and set the optical axis through the centre of the rail follow the procedure outlined in Appendix LA & C.
5. To adjust the collimation of the laser beam follow the procedure outlined in Appendix LA & C. Use the laser focus adjust tool to collimate the laser beam onto the slot at the tip of the M4 screw as is shown in Appendix LA &. Small adjustments can be made to the direction of the laser beam by loosening the laser post lock, screw to ensure that the laser beam remains incident on the slot at the tip of the M4 screw.
6. Assemble the translation stage and set both the vertical and horizontal adjustments to the middle of their ranges. The vertical translation is effected by loosening the locking screw and turning the adjustment knob until the described height is obtained. When the adjustment is complete the locking screw should be tightened again.
7. The prism coupling assembly should now be fixed to the rotational stage in the orientation shown in Figure WAVE2.

8. Mount the completed prism-coupling assembly towards the far end of the rail, as shown in Figure WAVE2.
9. Check the position of the laser as incident on the prism and, if necessary, adjust the translation stage to align the beam onto the tip of the screw on the launch prism.
10. Insert the convex lens 15cm from the translation stage, as shown, and centralize it is vertical position relative to the optical axis (as defined by the laser beam).
11. Replace the system polarizer and centralize its vertical position relative to the optical axis.
12. Examine the components from a vertical position over the rail to ensure they are aligned perpendicularly to the rail.
13. Check that the focused laser beam is incident on the tip of the screw on the launch prism. If necessary, make any minor adjustments using the controls on the translation stage then fix the vertical adjustment with the locking screw provided.
14. As the focal length of the lens is approximately 15cm, slight adjustments to the prism-to-lens distance may also be required to tightly focus the laser onto the screw tip. Check and adjust if necessary.

WAVE2: Practical Guide to Achieving Waveguiding

> ***Note**: In order to achieve prism coupling to either the substrate modes or the guided modes, the prism to waveguide contact must be extremely good since the evanescent field penetration depth is only about 1μm. This means that the prism surface must be dirt free (dust particles are about 5-10μm in diameter). Consequently before attempting to clamp the prism to the waveguide you may require to clean the bottom surface of the prism with a dry optical tissue.*

1. Select the clean glass slide containing the waveguide.
2. Clamp the prism onto the side of the glass slide with the information label.
3. Tighten the nylon screw to clamp the waveguide to the prism assembly. The clamp should not need to be too tight just enough to hold the waveguide firmly.
4. The best way to obtain coupling is to align the input beam/prism coupling assembly (using the various translation stages) so that the focused laser beam is incident on the prism/waveguide interface at the point where the tip of the

screw clamp holds the assembly (i.e. point of closest contact), see Figure WAVE4. Note that vertical translation is effected by loosening the locking screw and turning the adjustment knob until the described height is obtained (Figure WAVE2). When the adjustment is complete the locking screw should be tightened again.

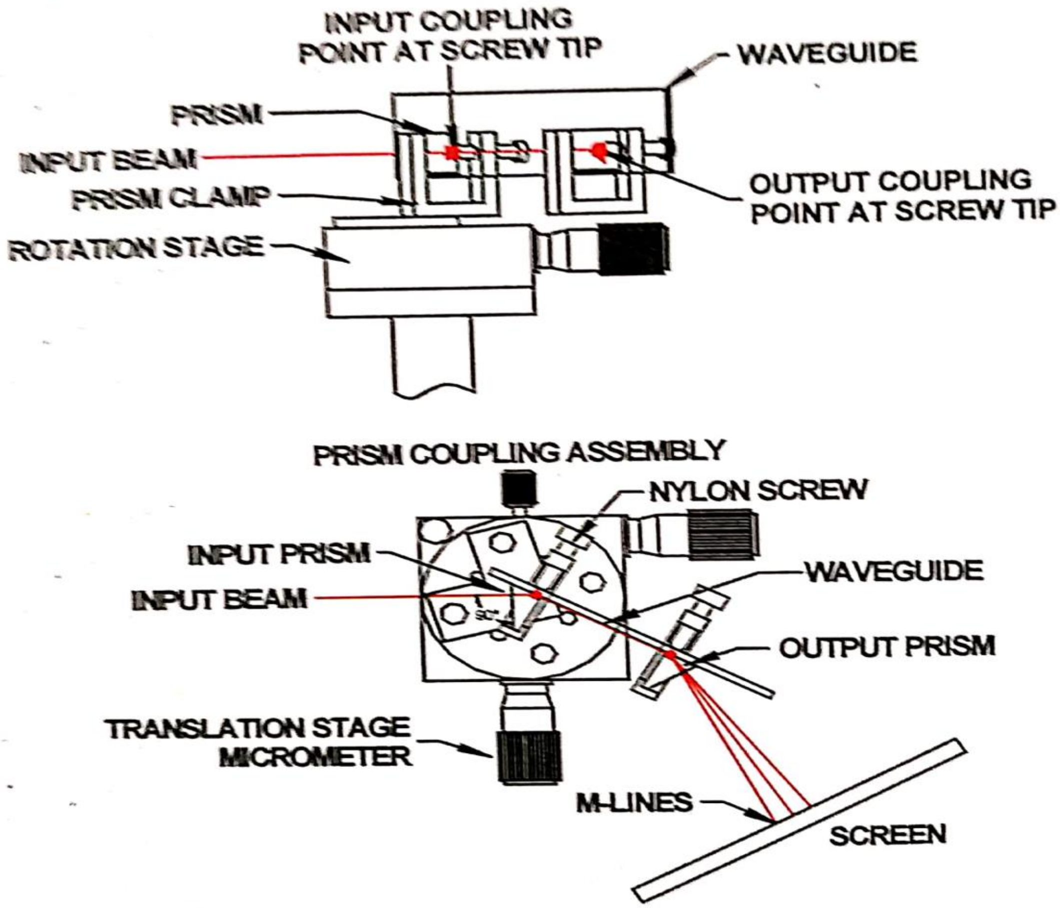
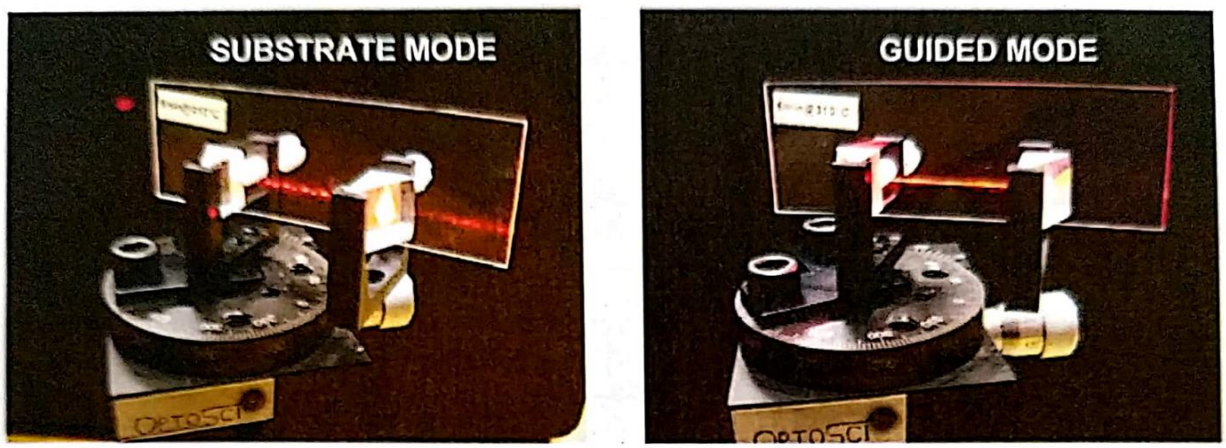


Figure WAVE4: *Detail of the Prism coupling arrangement*

5. Now rotate the prism until the laser beam reflected from the front face of the prism is in the same plane as the incident laser beam (i.e. the beam is reflected straight back to the laser output aperture). Using a white card placed above or below the laser output may assist you in this task. This is the normal to the prism input facet, see Figure WAVE4(b). The waveguide modes will be found very close to this position.
6. Small adjustment of the horizontal translation stage micrometer (Figure WAVE4(b) at the base of the prism coupling mounting system (e.g. transverse to the optical axis) at this point will optimize coupling and should allow you to observe the waveguide modes (see Figure WAVE5(b). At

steeper launch angles substrate modes will be observed, Figure WAVE5(a). These will appear as dotted lines.

7. Clamp the output prism to the waveguide at the same height as the input prism, Figure WAVE4(a). The mode lines (m-lines) will be vertically aligned when they are coupled out of the output prism and viewed on a card, see Figure WAVE6. Once you see the vertical m-lines you can adjust the translation stages to optimize coupling.
8. The birefringence of the STEP index guides can be observed by rotating the polarizer to display both TE & TM modes simultaneously (polarizer at 45^0) or to selectively extinguish either the TE or TM mode, see Figure WAVE7.



(a) (b)

Figure WAVE5: Comparison of (a) substrate mode and (b) guided mode

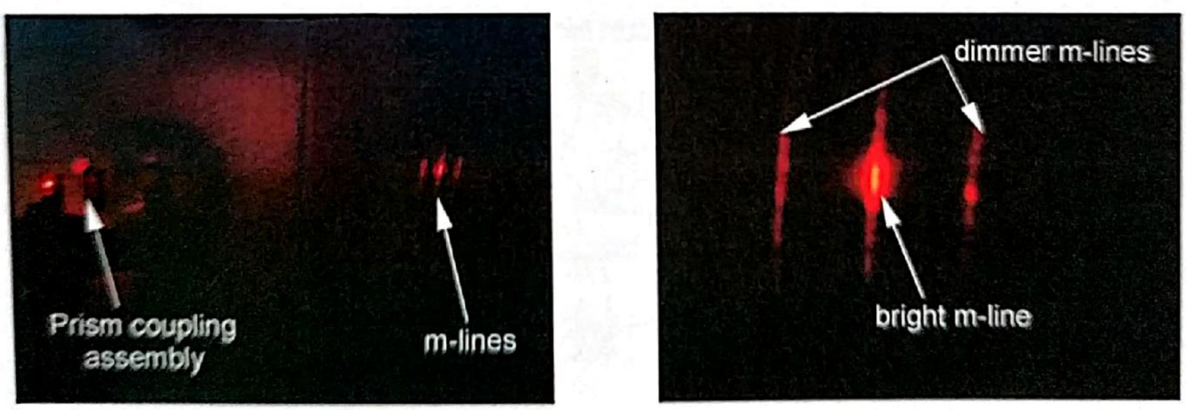


Figure WAVE6: M-Lines

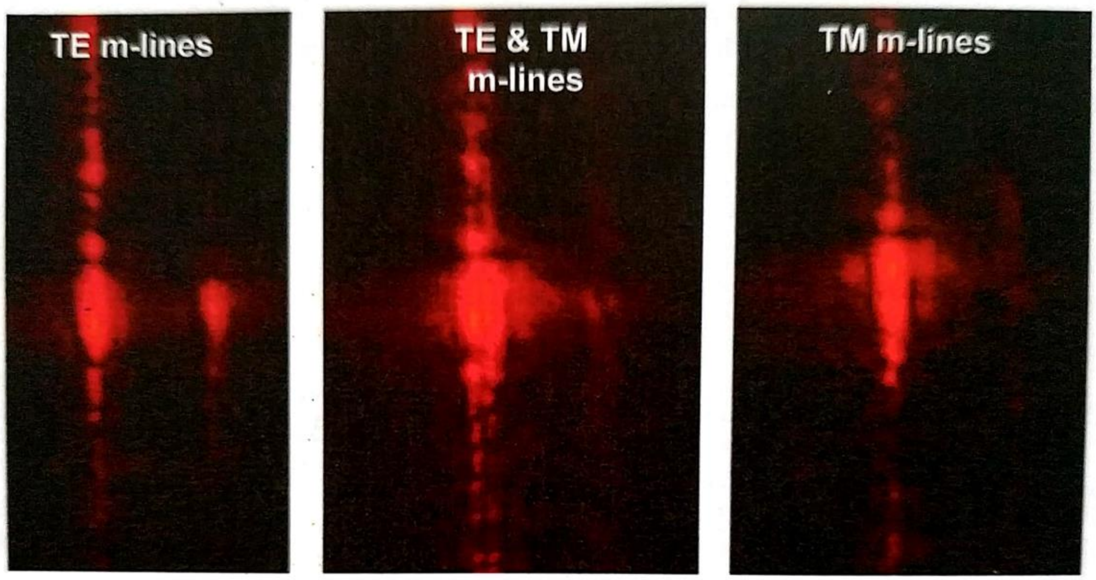
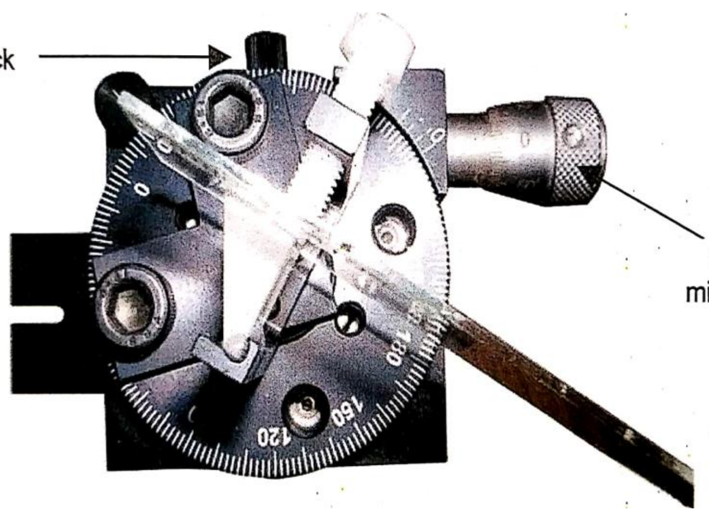


Figure WAVE7: Discrimination of TE & TM m-lines for the STEP index waveguide

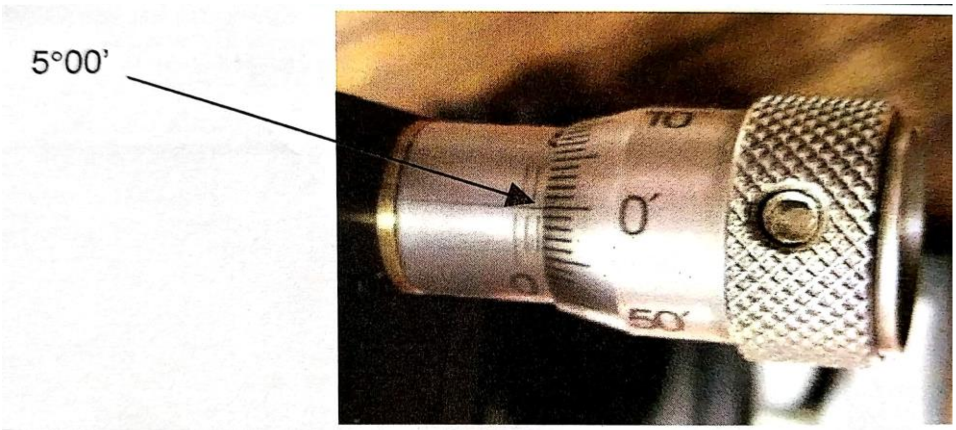
WAVE 3: Angular Measurement Technique Using Micrometer

For better precision when measuring the mode angles, all relative angles should be measured using the micrometer which is graduated in degrees and minutes. The following procedure should be adopted.

1. As noted in WAVE1 waveguide modes are found very close to the prism normal (for the graded index samples the modes are found either side of this normal position).
2. Loosen the rotation stage lock screw and rotate the stage to find the prism normal.



3. Set the micrometer to the midpoint of its travel, as shown below this corresponds to the $5^0$00' position. Check that the prism normal is still aligned correctly (i.e. the reflected beam in the same vertical plane as he incident beam) and retighten the rotation stage lock screw. All rotational adjustments should now be carried out using the micrometer.



4. Now adjust the micrometer to achieved guiding in each of the waveguide modes in turn-the relative angles can then be read directly from the micrometer scale.
5. In this arrangement lower order modes will be found at micrometer settings to the left of the normal position i.e. less than 5^0, with higher order modes found to the right.
6. For the sign convention used in ED-WAVE, the actual mode angles are calculated by subtracting the measured angle from 5^0 reference position. For example if the fundamental mode is found at a micrometer setting of 3^0 which would give a mode angle of $+2^0$ (i.e. $5^0 – 3^0$). Similarly if m = 4 is found at 7^0 then the mode angle is -2^0 (i.e $5^0 – 7^0$).

APPENDIX LA & C: LASER ALIGNMENT & COLLIMATION

LA & C1: Centralising the Laser Beam

An alignment post is provided to assist in aligning the laser beam with the centre of the optical rail. Insert the alignment post into a post holder and secure the holder to the opposite end of the rail from the laser. Adjust the post height so that the M4 screw in the top of the alignment post intersects the laser beam level and lock its post collar to maintain this height. Now loosen the lase post locking screw and adjust the position of the laser so that the laser beam coincides with the centre of the tip of the M4 screw in the alignment post (with a collimated beam the silhouette of the tip of the M4 screw can be viewed on a white card placed behind the alignment post (see Figure LA & C1). This will centralize the laser beam and set the optical axis through the centre of the rail. This procedure can be repeated at any point during the set-up to check that the laser beam is centralized.

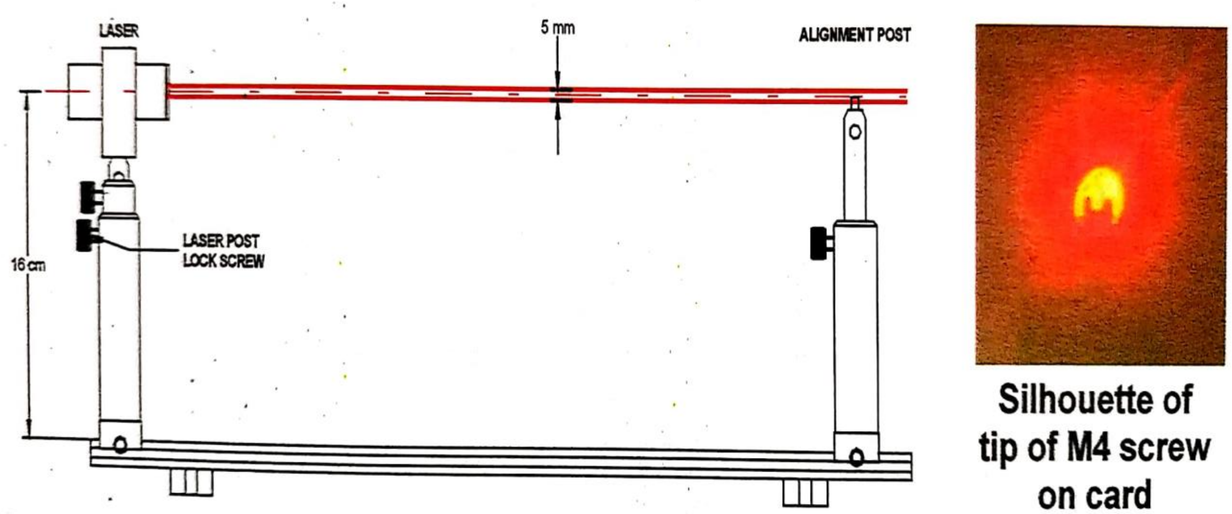


Figure LA&C1: Centralising the Laser Beam for the waveguiding experiments

LA & C2: Collimating or Focusing The Laser Beam

Use the laser focus adjust tool to collimate or focus the laser beam. Insert the notched tool into the corresponding notches at the output of the laser module and turn it in either direction to collimate (or focus) the beam (see Figure LA & C2). If the beam is being focused onto the active area of a photodetector it should be focused down to ~2mm diameter spot on the active area. If the laser beam is being collimated its diameter should be maintained at around 5mm (check using a white card) as you go from the near (~ 3cm from the laser) to the far (~ 3cm from the laser) field of view.

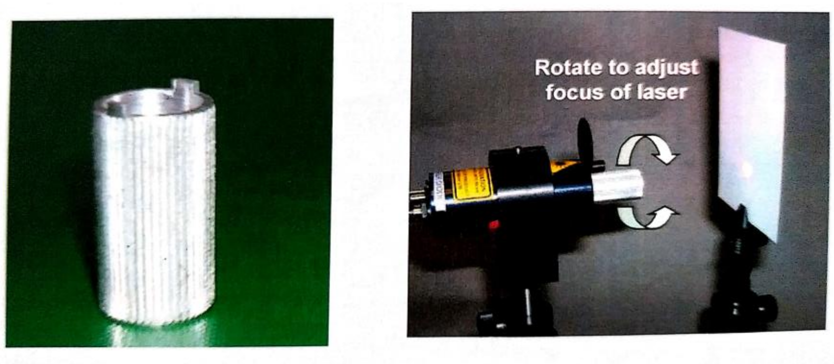


Figure LA&C2: Use of the Laser Focus Adjust Tool