INTERNATIONAL ATOMIC ENERGY AGENCY
UNITED NATIONS EDUCATIONAL, SCIENTIFIC AND CULTURAL ORGANIZATION

INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS
34100 TRIESTE (ITALY) - P.O.B. 586 - MIRAMARE - STRADA COSTIERA 11 - TELEPHONE: 2240-1
CABLE: CENTRATOM - TELEX 460392-I

H4.SMR/285 - 25

WINTER COLLEGE ON
LASER PHYSICS: SEMICONDUCTOR LASERS
AND INTEGRATED OPTICS

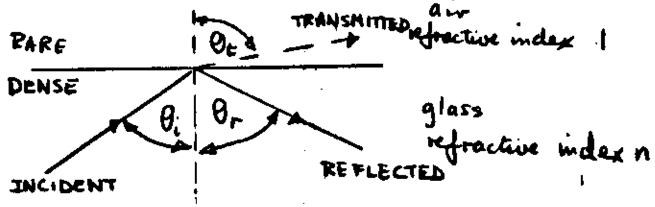
(22 February - 11 March 1988)

# INTEGRATED OPTICS

R.M. De La Rue
Glasgow University
Glasgow, U.K.

INTEGRATED OPTICS R.M. De La Rue

## Introductory talk (slide show)




## First slide

Consider a beam of light incident at an angle on the boundary (plane) between the two media, from the optically more dense medium - i.e. the medium in which the phase velocity of the optical waves is slower.

Two basic rules tell us what happens to the light. (We are neglecting the possibility of any losses or the kind of reflective behaviour which occurs at the boundary between air and a mirror-like metallic surface). We are using dielectrics.

Snells law tells us that:

$$\frac{\sin\,\theta_t}{\sin\,\theta_i} = \frac{n_{\text{incident medium}}}{n_{\text{transmitting medium}}}$$

While phase-matching along the boundaries leads to:

$$\theta_i = \theta_r$$

From Snell's law it turns out that light coming from glass to air (dense-to less-dense) is bent away from the normal - For the given diagram, $\theta_t$ should be larger than $\theta_i$. If we increase $\theta_i$, $\theta_t$ eventually increases to the maximum possible value of $\pi/_2$ and we have the critical condition

$$\theta_i = \theta_c = \sin^{-1}\left(\frac{1}{n_g}\right) \qquad \text{(for our glass-air example)}$$

Beyond this angle of incidence we get TOTAL INTERNAL REFLECTION (T.I.R.). This is the situation of particular interest for integrated optics.

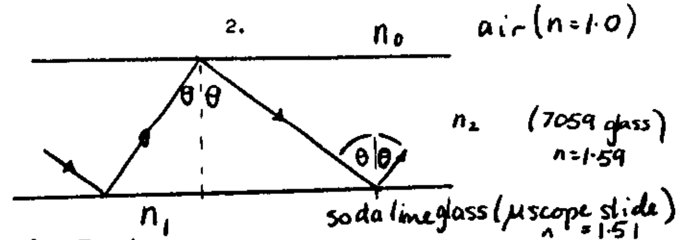
Note the error on the slide - it should say $\theta > \sin^{-1}\left(\frac{1}{n}\right)$

## Second slide

If we can get the light into a finite thickness flat sheet region with two boundaries, it is possible to form a SLAB WAVEGUIDE.








We need total internal reflection at both boundaries, which means the light must be at angle $\theta$ such that both

$$\sin\,\theta > \frac{1}{n_2} \qquad \text{(A)}$$

$$\text{and} \quad \sin\,\theta > \frac{n_1}{n_2} \qquad \text{(B)}$$

Criterion (B) is more demanding than criterion (A). It means typically that $\theta$ is quite close to $90^\circ$.

e.g. $\frac{n_1}{n_2} = \frac{1.51}{1.59}$ $\quad\theta_c = 71.74^\circ$

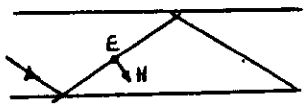
$\frac{n_1}{n_2} = 0.99$ ($\sim$ 1% difference) $\theta_c = 81.9^\circ$

$\frac{n_1}{n_2} = 0.999$ ($\sim$ 0.1% difference) $\theta_c = 87.44^\circ$

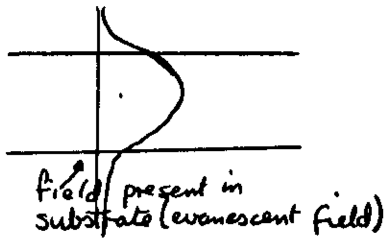
So that, for each case, $\theta$ must be at least as large as the relevant $\theta_c$.

A more detailed theoretical analysis tells us that $\theta$ will range ~~from~~ between $\theta_c$ - a condition which corresponds to the cut-off of a particular waveguide mode, and $90^\circ$. $\theta$ approaches $90^\circ$, for the particular mode, as we increase the film thickness d.

## Third slide




← Electric field at right angles to direction of propagation (TE modes)



We have already started using the word 'mode'. Dr. Laybourn has introduced the idea of mode in talking about optical fibres. Often these are labelled as being '<u>multi-mode</u>' or '<u>single mode</u>'. The situation for slab-waveguides is very similar, but significantly simpler physically and mathematically - because plane-waves hitting plane boundaries are easier to handle than curved (?) waves hitting curved boundaries. We are not however going to attempt the proper electromagnetic wave analysis - Maxwell's Equations plus boundary conditions - which tells us in detail about the properties of the guided modes of a slab waveguide. It is important to know that

(a) The number of modes increases approximately in proportion to the guide thickness (d), at a given wavelength.

(b) <u>Shortening</u> the optical wavelength → e.g. going from infra-red to visible, or red to blue, or blue to ultra-violet, also increases the number of modes.

(c) Modes have either purely TE or purely TM polarization. TE means Transverse electric, the electric field is entirely perpendicular to the propagation direction, but in the plane of the SLAB. TM means Transverse Magnetic, the magnetic field is entirely perpendicular to the propagation direction, but in the plane of slab.

(d) as the diagram shows part of the energy is in the slab, but part of the guided mode energy is in the exterior regions - but with exponentially <u>evanescent</u> amplitude (goes to zero at infinite, finite amount of <u>stored</u> energy). Diagram is of distribution for the lowest order mode - sometimes called the zeroth order.

<u>Fourth slide</u> effective index definition $n_e$

$$V = \text{phase velocity} = \frac{c}{n_e}$$

$$n_1 < n_e < n_2$$

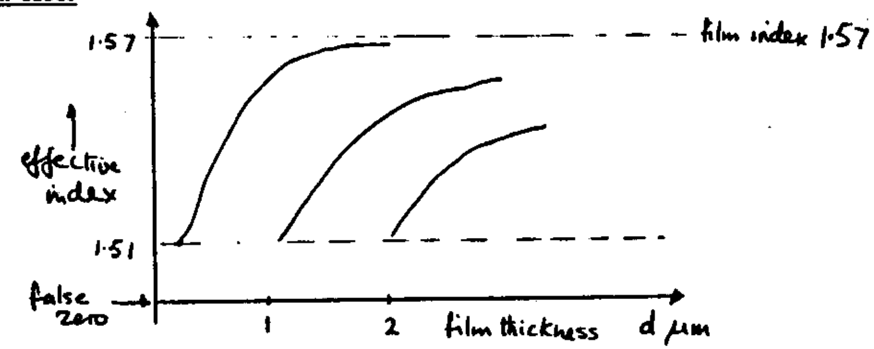
↑ cut-off — all energy in slab region

At cut-off the decay rate of the evanescent field into region (1) tends to zero - much more energy in substrate as we appraoch cut-off. Further away from cut-off, more energy in slab.



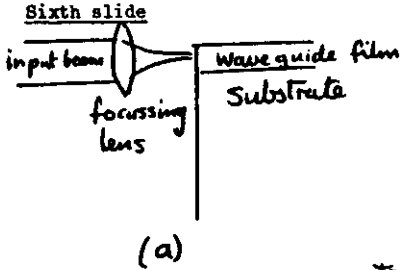


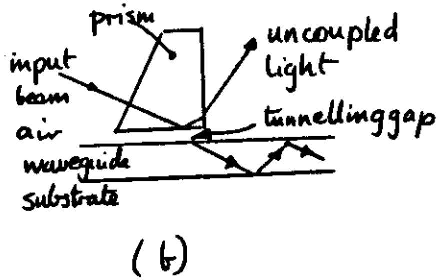
<u>Fifth slide</u>

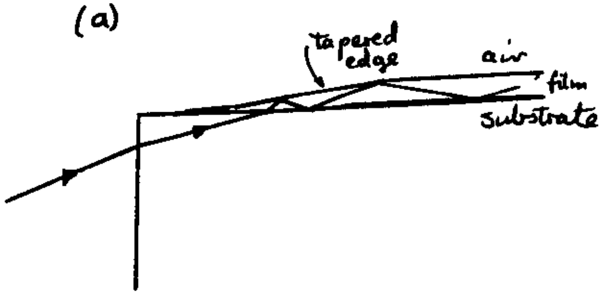



This shows a reasonably typical set of calculated curves for $n_e$ versus guide thickness, d. In fact these are only the TE modes, the TM modes will be very similar, but for each corresponding mode the TM mode occurs slightly to the right of the TE mode. These are essentially dispersion curves - here particularly meaning <u>geometrical</u> dispersion. Since the refractive index is a function of the wavelength (or frequency) of the light, the curves are not quite the same as wavelength dispersion curves for fixed d would be. Note the dimension d in µms. Typically a single mode guide will be on the order of 1 µm thick ∿ i.e. comparable with the optical wavelength.

<u>Sixth slide</u>



There are quite a number of different ways of getting the light into a waveguide. We are usually dealing with light from a laser. The most convenient laser source is a gas laser - most commonly used is the 0.633 μm red emission from a Helium-Neon laser. Gas lasers produce well-collimated, slowly diverging beams which can conveniently be focussed by a simple lens or microscope, or can be expanded by a simple telescope.

In the first diagram we illustrate light from a collimated, moderately large beam, say 1 mm diameter, being focussed down to a small spot for coupling into the end of the waveguide. Using the crude formula:

$$S = \frac{f\lambda}{D} = f.\frac{0.633\ 10^{-6}\ \mathrm{m}}{10^{-3}\ \mathrm{m}}$$

λ is optical wavelength.
f is focal length of lens.
D is diameter of laser beam.

gives $$f = \frac{10^{-6}\ 10^{-3}\mathrm{m}}{0.633\ 10^{-6}} = \underline{1.6\ \mathrm{mm}}$$

(using S ≈ 1 μm).

So a very powerful lens is needed to produce ~~[illegible]~~ efficient coupling into the waveguide end, if the waveguide is about 1 μm thick. Typically a X40 microscope objective is used to get down to this order of smallness in spot size. This end-fire or butt-coupling technique is favoured by many people working in integrated optics. But it requires rather precise alignment both up-and-down and in angle. The depth of focus of a strong lens is also small.

Butt or end-fire coupling can be achieved also with semiconductor lasers and with fibres - and this is definitely an important technique which may well be used in practical systems. For semiconductor lasers, placed directly very close to the waveguide, problems of optically fed-back fluctuation effects are major. The quality of the waveguide end is also crucial. In special cases cleaving may give the required end quality, but generally a special polishing method has to be adopted.

Another problem with butt-coupling is that, in slab guides, the beam, since it starts from a small source, diverges rapidly in the waveguide plane. This can be overcome (but as a major current problem) by using an integrated optical lens to collimate the beam. Alternatively the slab guide is replaced by a finite width (as well as thickness) stripe guide - (to be mentioned in due course).

The second technique shown is the prism coupler technique. This works by optical 'tunnelling' - a direct analogy of the wave-mechanical tunnelling effect of the 'tunnel' diode. The light which enters the prism would be totally internally reflected if it weren't for the fact that the prism is so close to the waveguide (a gap of 1 μm or less is typical) that the evanescent tail of the t.i.r. light (penetrating from glass to air) can couple to a mode of the slab guide. With





prism coupling, in practice, the correct gap is achieved by trial and error, by adjusting, and localising, the clamping pressure. Theoretically very high efficiency is achievable, but getting more than 50% in practice is not easy. Achievement of the required synchronous phase-angle is not too difficult, but the prism must have a higher refractive index than the waveguide for coupling to be at all possible - ~~problem if the waveguide for coupling to be at all possible~~ a problem if the waveguide film and substrate have high refractive indices. e.g. for waveguides on lithium niobate (n ∿ 2.21) prisms of single crystal rutile are commonly used (n ∿ 2.7).

The final diagram shows coupling into a waveguide taper. This is easier to understand in reverse - i.e. as guided light encounters a decrease in the waveguide thickness it tends to become less and less well confined and eventually to leak out of the waveguide into the substrate.