<u>**Optical and Photonic Glasses**</u>

Lecture 27:

Integrated Optics

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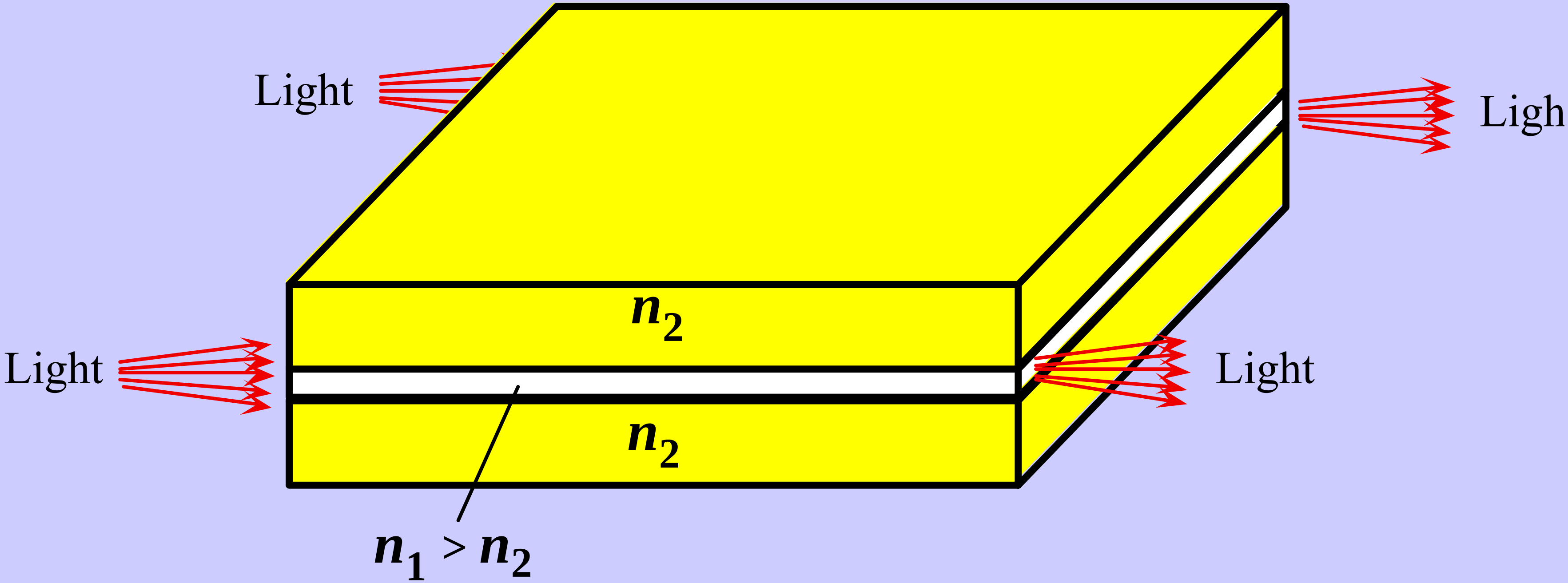
Integrated optics

The so-called "Moore's law" states that the speed of the electronic microprocessors fabricated with the current technology doubles every 18 months (speed $\alpha \sim 2^{t/18\ \mathrm{mos}}$).

The fiberoptic bit rate capacity doubles every ~ 10 months. However, the electronic memory access speed $\alpha \sim 1.05^{t/12\ \mathrm{mos}}$ only. Therefore, very soon, the capacity to send information over optical fibers will exceed the ability to switch, modulate or otherwise process and control that information. That is why *integrated optics* is becoming increasingly important.

Integrated optical circuits (IOC's) are the direct optical analogues of the electronic integrated circuits now in use. In a IOC, lasers, lenses, beam splitters, modulators, etc., should be produced in compact, low power consuming, easily connectable packages. Although nowadays one is still a long way from truly monolithic integrated optics, some devices are already available and the fabrication of hybrid circuits is possible, combining some discrete optical components with integrated devices.

The basis of integrated optic devices is the *optical planar* (or slab) *waveguide*.



A planar dielectric waveguide has a central rectangular region of higher refractive index n_1 than the surrounding region which has a refractive index n_2. It is assumed that the waveguide is infinitely wide and the central region is of thickness $2a$. It is illuminated at one end by a monochromatic light source.

Challenges of IOC's

Some of the outstanding challenges at present are:

- High propagation losses, ~ 1 dB/cm for a planar waveguide, compared with less than 1 dB/km for silica glass-based optical fibers, although the small path lengths involved in IOC's make optical losses a lesser problem.

- Coupling losses between optical fibers and integrated optic waveguides.

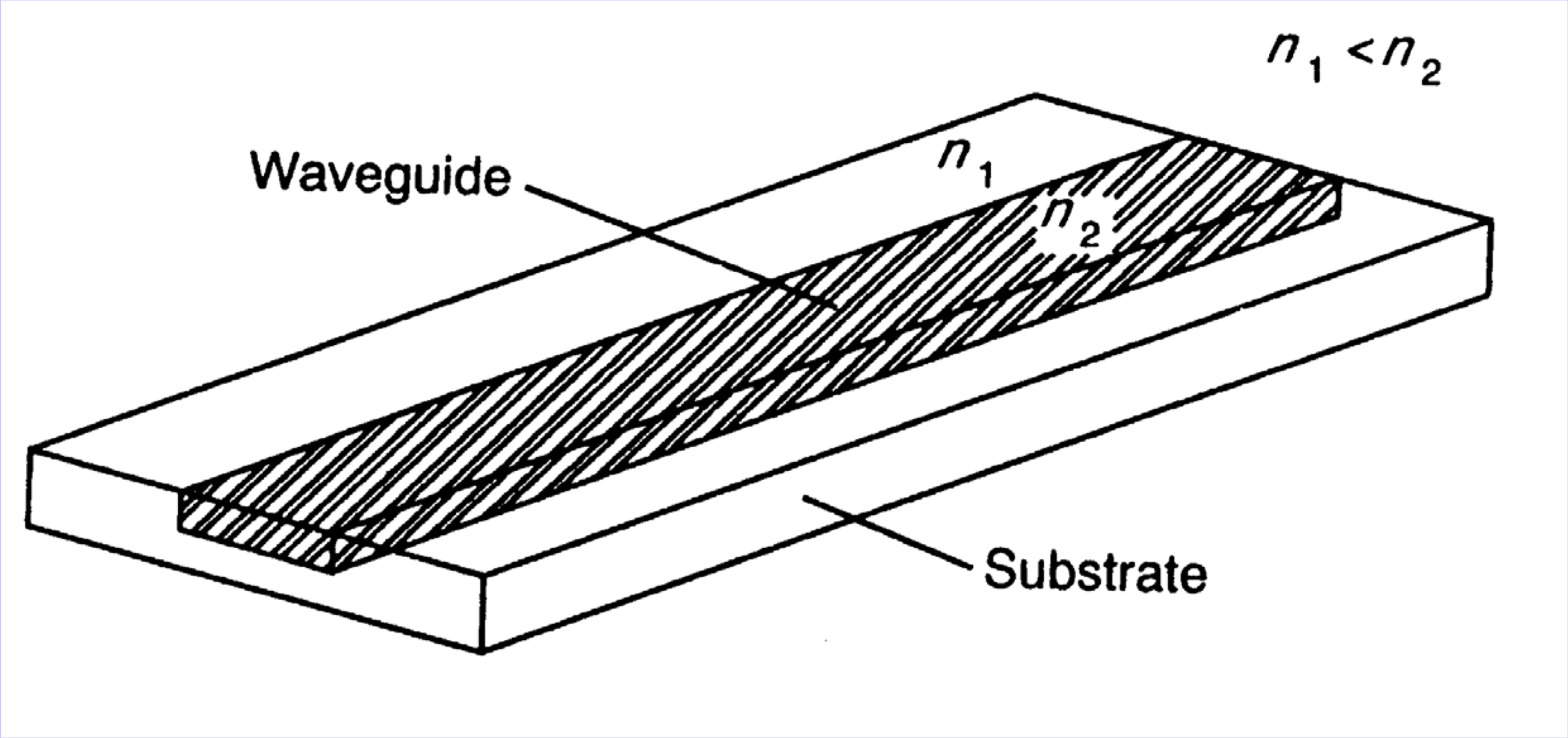
- Difficulty in directing light around the sharp bends of miniature (i.e., *nanophotonic*) IOC's, using conventional waveguiding methods. Here, planar photonic bandgap structures may be of help in the future.

At present, planar optical waveguides, as well as channel waveguides of different geometries, are being fabricated on materials like SiO_2 (e.g., silica-on-silicon), Si (e.g., silicon-on-insulator), $LiNbO_3$ and GaAs (or other III-V materials).

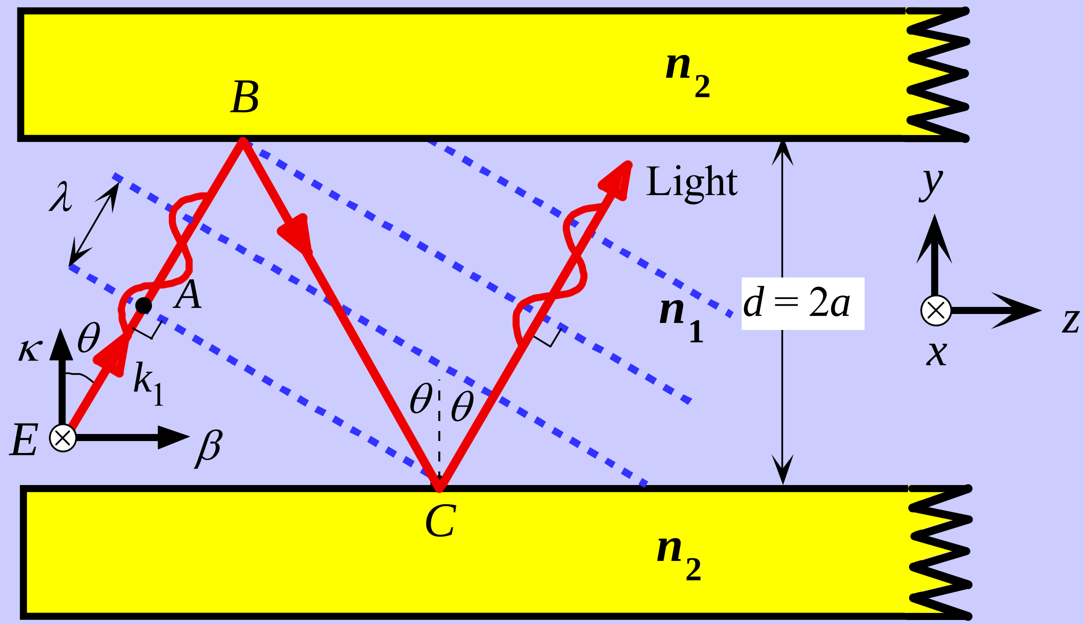
Of particular importance in the field of photonic glasses is the "silica-on-silicon" (SOS) technology, where silica glass-based waveguides are fabricated on silicon substrates, thus allowing the integration between optical devices and the traditional electronic substrate platforms.

SOS integrated optic devices may be processed by thermal oxidation of silicon, sputtering, flame hydrolysis deposition (FHD), CVD and sol-gel deposition.

A *slab* waveguide is similar to an optical fiber, except that it is a planar, rather than cylindrical, waveguide, where a low refractive index substrate contains a slab (or channel) of higher index material, along which light is guided by total internal reflection.



(Adapted from: *The essence of optoelectronics*, K.Booth and S. Hill, Prentice-Hall, 1998))



A light ray travelling in the guide must interfere constructively with itself to propagate successfully. Otherwise destructive interference will destroy the wave.

Mode conditions for planar waveguides

As in the case of the optical fibers, which are cylindrical optical waveguides, the V-number is again defined as:

$$V = \pi \, d \, NA / \lambda$$

Planar waveguides will be single mode when $V < \pi / 2$, a condition which implies that $m = 0$ is the only possible value for m.

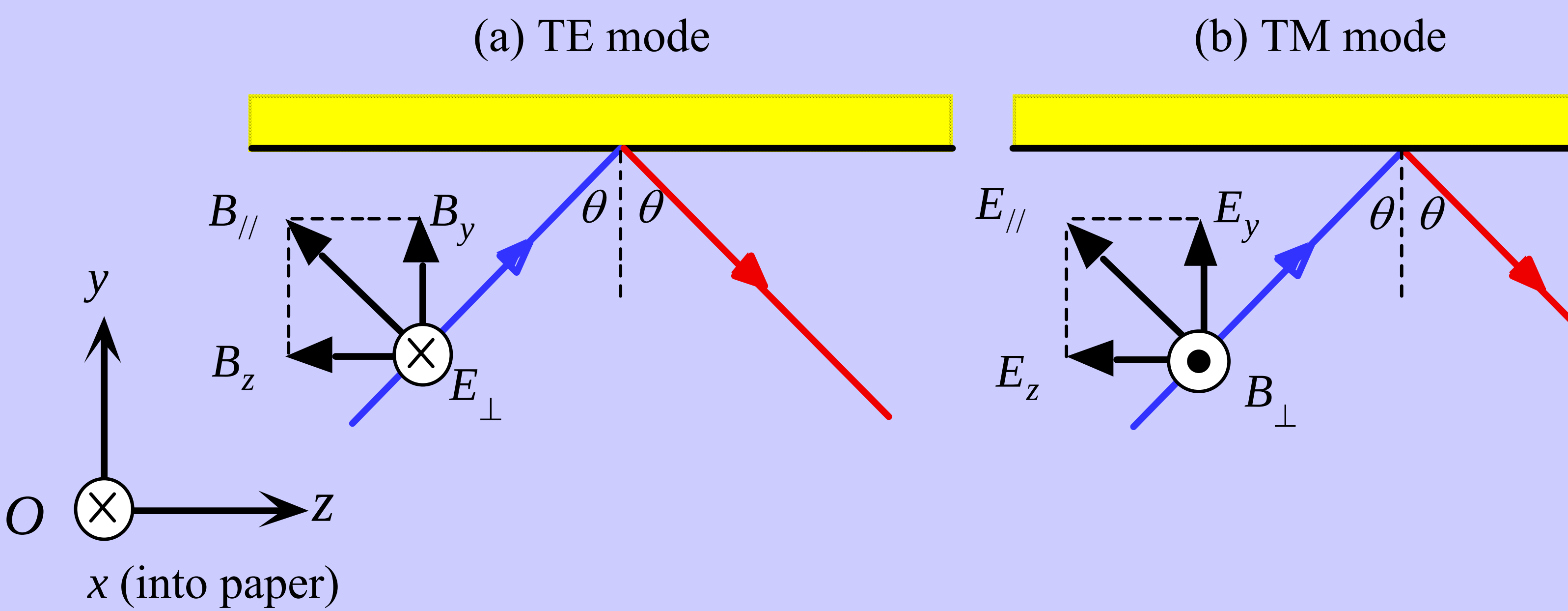
The free space wavelength which makes $V = \pi/2$ is the **cut-off wavelength**, λ_c; above this wavelength, only one mode will propagate (the fundamental mode).

In general, for a given asymmetric waveguide (where the overcladding simply consists of air) of thickness d, the number of propagating modes, m+1, is given by the following expression:

$$n_f - n_s = (2m + 1)^2 \lambda^2 / [16 \, d^2 \, (n_f + n_s)]$$

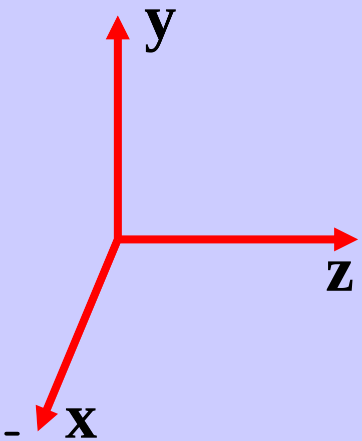
where n_f and n_s are the refractive indices of the guide and the substrate, respectively, λ is the free space wavelength of light and $m = 0, 1, 2, \ldots$. This also shows that, when the wavelength $\lambda > 4 \, d \, NA$, there will be no propagating modes for the asymmetric waveguide. A symmetric waveguide (with an overcladding layer equal to the substrate), however, will always carry at least one guided mode, just like a single mode fiber.

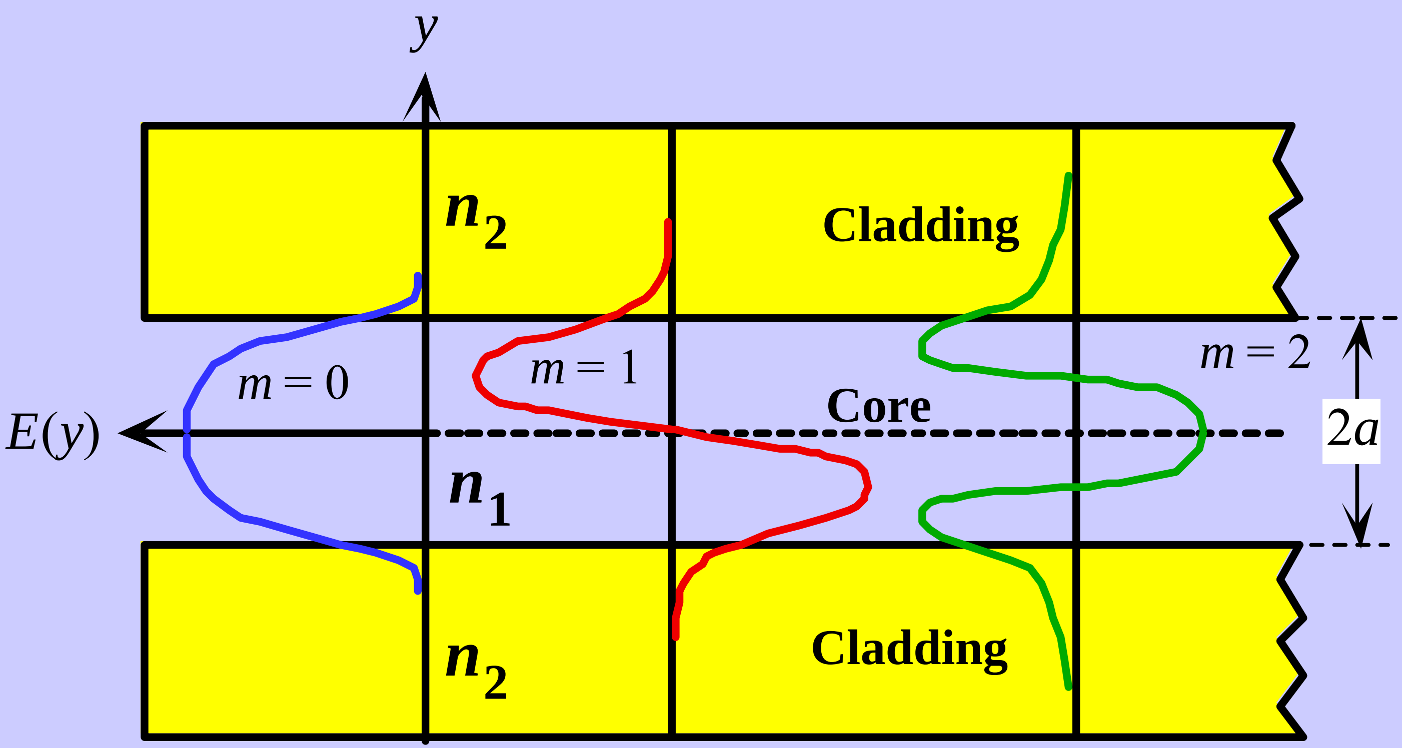
In planar waveguides, allowed modes are always: TE or TM. But for TE modes, H can have longitudinal components along the propagation direction, as shown below; and so can E, in the case of TM modes. This is impossible in free space, but possible in a material guide, due to the interference phenomena.



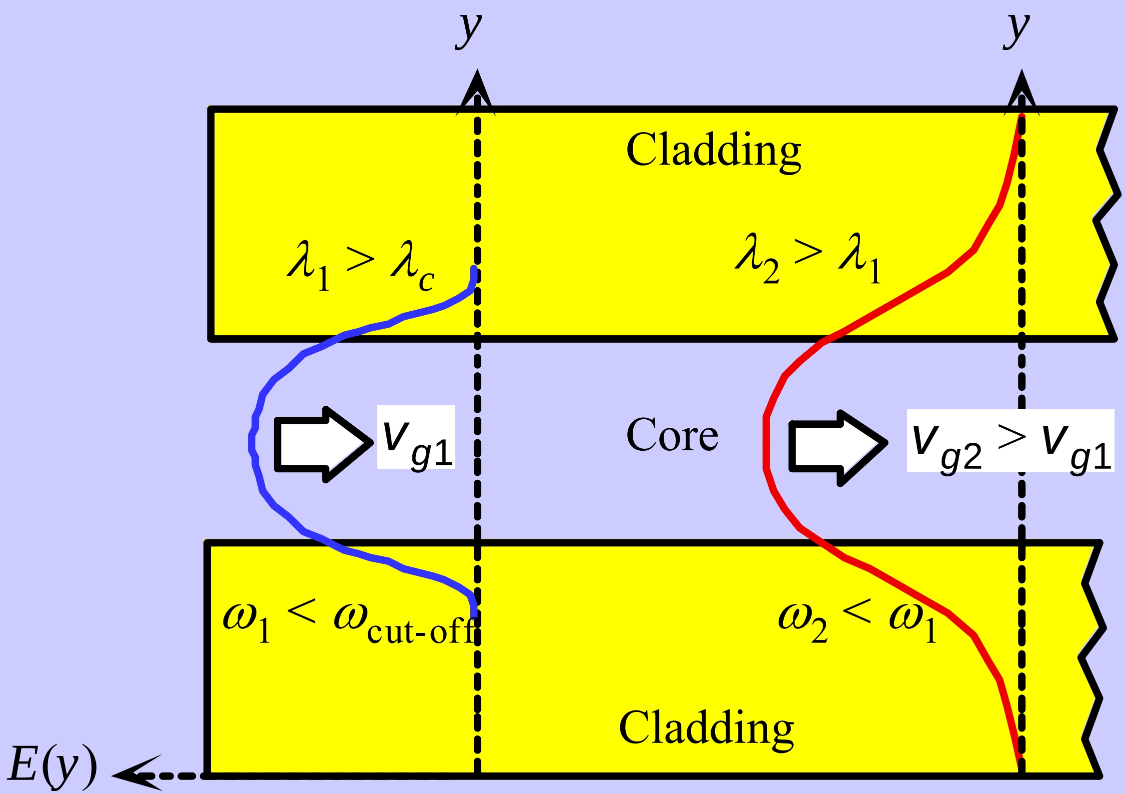
Possible modes can be classified in terms of (a) transelectric field (TE) and (b) transmagnetic field (TM). Plane of incidence is the paper.

Modes in an optical planar waveguide, propagating along the z direction. There is confinement only along the y direction, only.



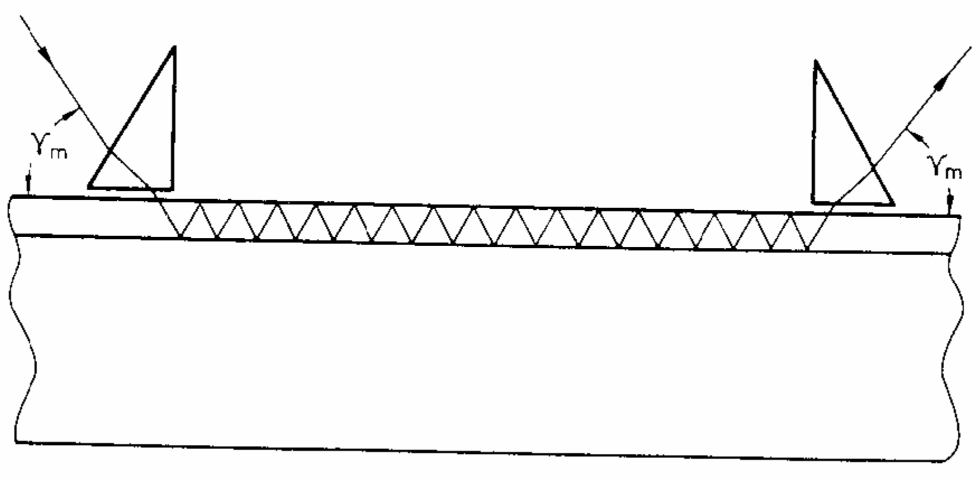


The electric field patterns of the first three modes ($m = 0, 1, 2$) traveling wave along the guide. Notice different extents of field penetration into the cladding. (Evanescent field increases with mode order and λ).



The electric field of TE_0 mode extends more into the cladding as the wavelength increases. As more of the field is carried by the cladding, the group velocity increases.

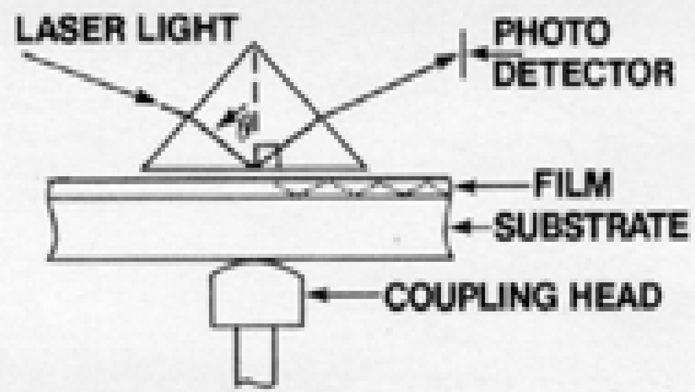
The standard way to achieve modal analysis in a planar optical waveguide is by means of m-line (or dark-line) spectroscopy. This can be done with a *prism coupler*, where light is injected into a waveguide by means of evanescent wave coupling through a high index prism of a material such as Ga-Gd garnet, or GGG, with an index of 1.96 @ 633 nm, or rutile (TiO_2), with an average index of ~ 2.7. The injected light is reflected back to a detector, except when there is coupling to one of the propagating modes of the waveguide; in this case, no light reaches the detector and a downward peak is registered, corresponding to the propagating mode. This allows the different TE and TM modes to be identified, together with their effective indices and the waveguide thickness and index to be determined as well.



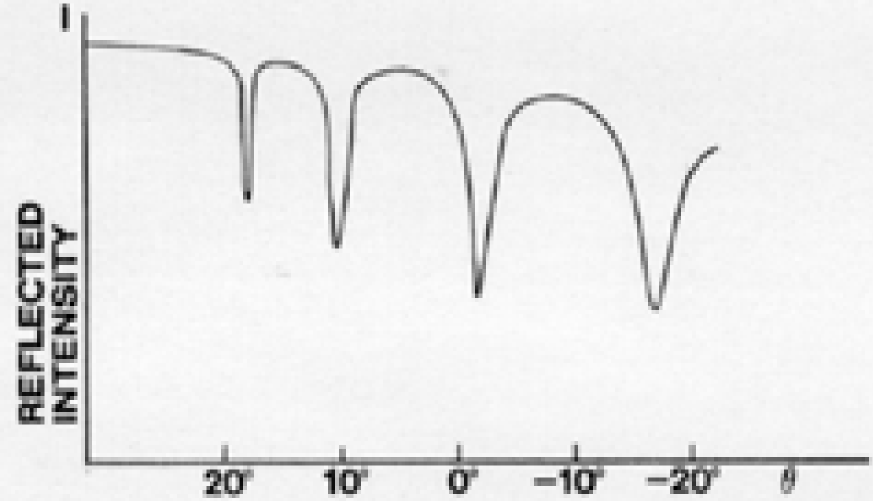
The prism coupler used as a device for modal analysis

(Adapted from: *Integrated optics*, R.G. Hunsperger, Springer-Verlag, 1991)

Typical output of a prism coupler, for a waveguide with four propagating modes. At certain discrete values of the incident angle, called mode angles, the photons can tunnel across the air gap into the film and enter into a guided optical propagating mode (by means of coupling between the evanescent tails of the incident and propagating light beams), causing a sharp drop in the intensity of light reaching the detector.



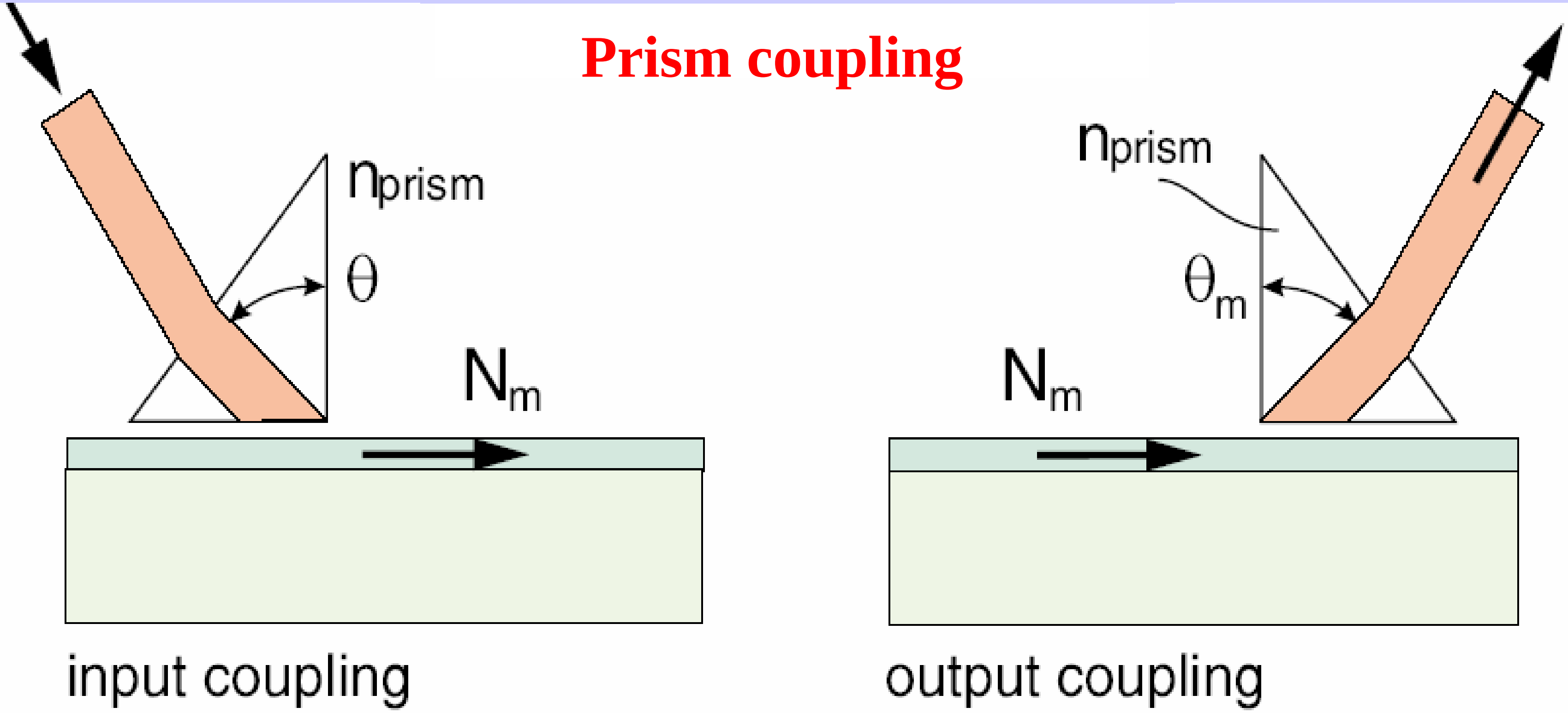
SCHEMATIC OF PRISM COUPLER



INTENSITY (I) OF REFLECTED LIGHT VS. ANGLE OF INCIDENCE (Θ)

(Adapted from: Metricon catalog)

Prism coupling



Distributed coupling of the evanescent fields of prism and guide, requiring synchronism of propagation:

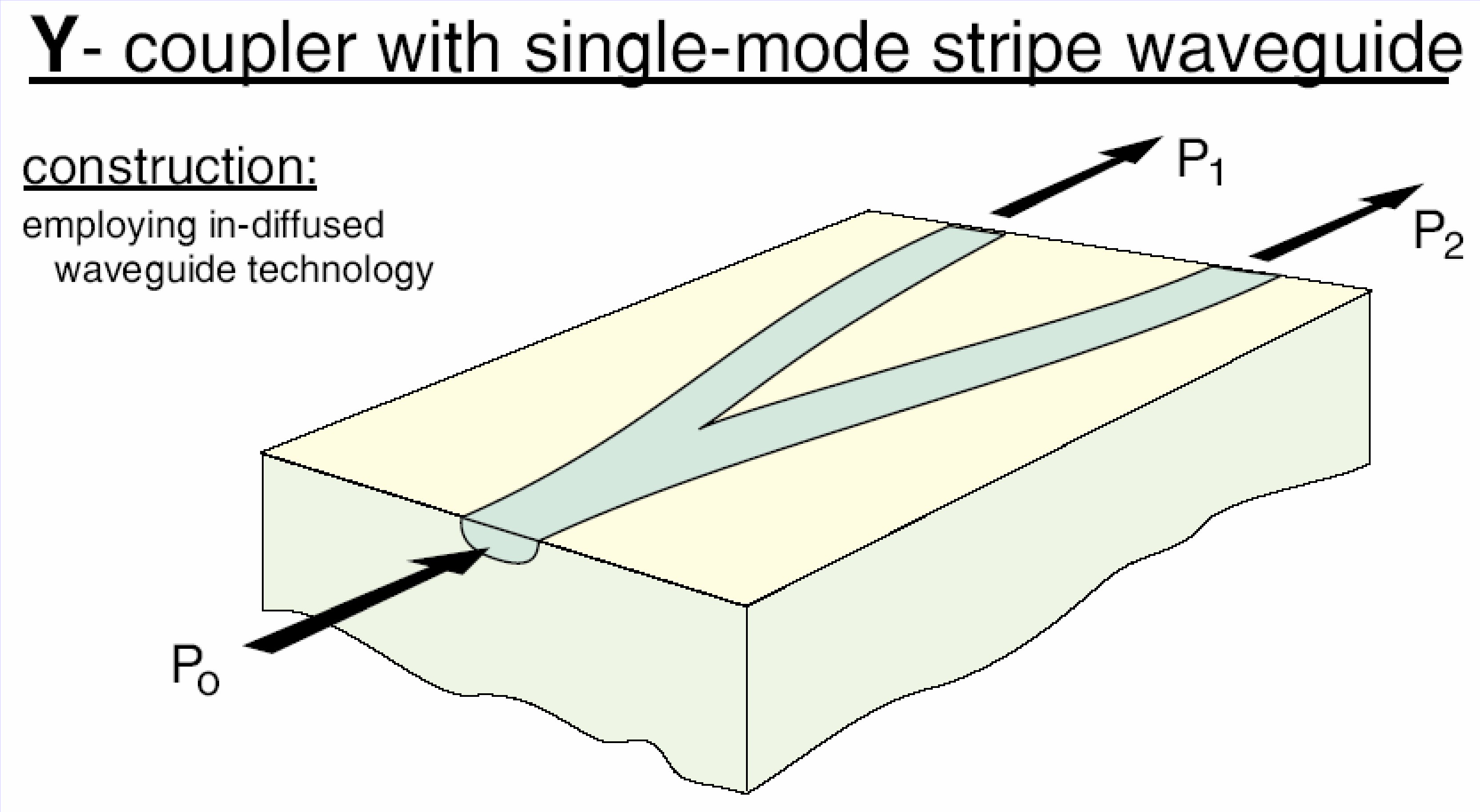
$$n_{prism} \cdot \sin\theta = N_{eff}$$

(The higher order modes correspond to < θ, n_{eff} values)

Coupling strength adjustable by gap width between prism and guide.

For input coupling: mode m can be selected by adjustment of angle θ

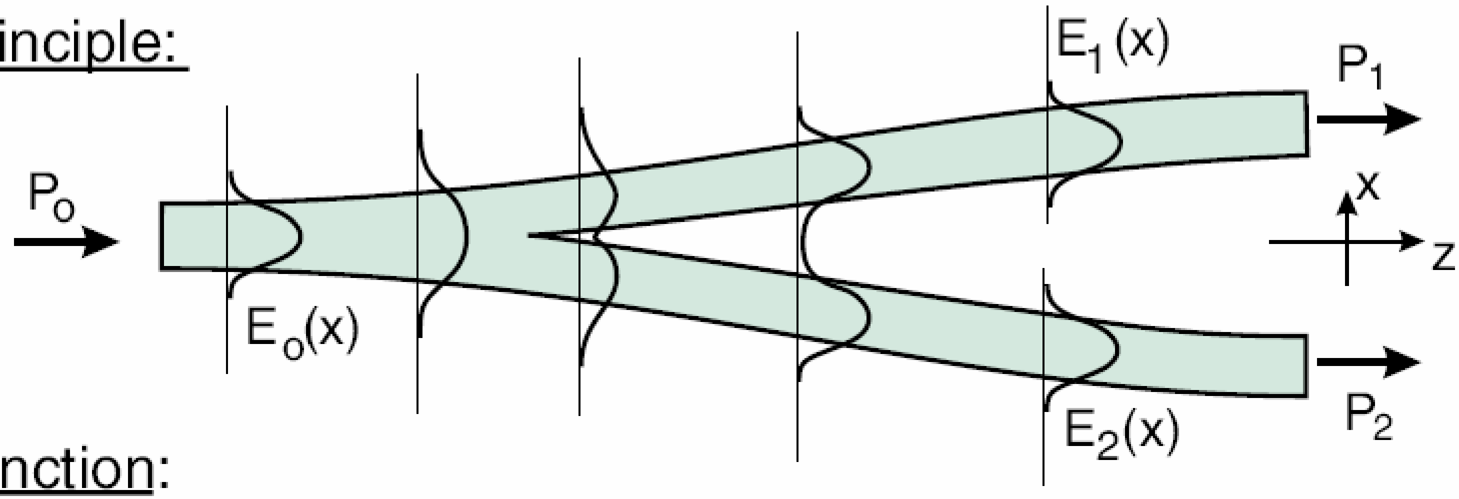
An example of one of the basic IO components is the Y-coupler (also called Y-junction), whose main application is in beamsplitters or interferometric modulators.



(Adapted from: www.om.tu-harburg.de/FIBERS AND INTEGRATED OPTICS/Online)

Principle of the Y - coupler

principle:



function:

Adiabatic transformation of the input wave function $E_o(x)$ to the two output functions $E_1(x)$ and $E_2(x)$.

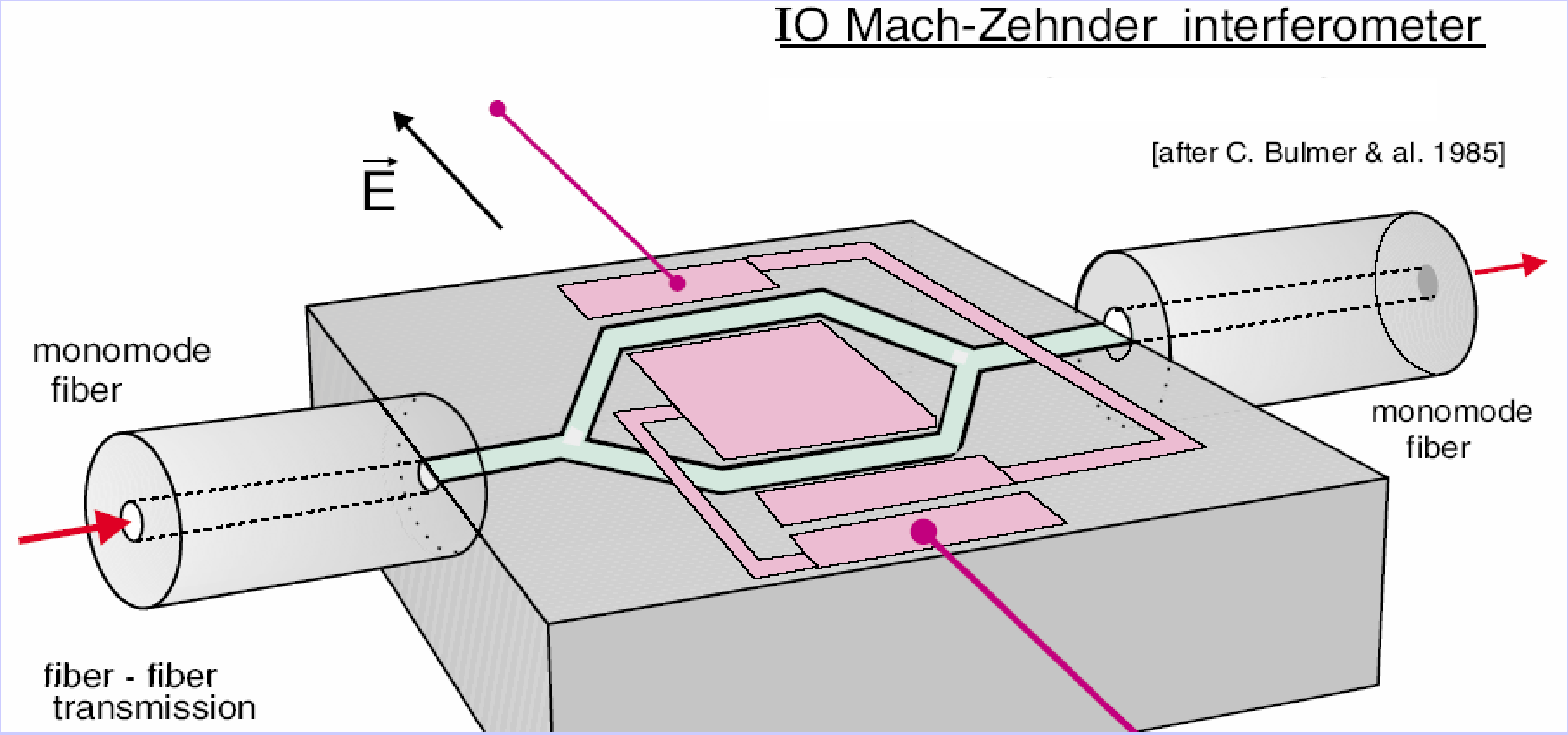
For efficient conversion (low coupling to radiative modes):

- tapering of the guide width must be gradual
- the notch must be sharp
- the waveguide bends must be smooth

(Adapted from: www.om.tu-harburg.de/FIBERS AND INTEGRATED OPTICS/Online)

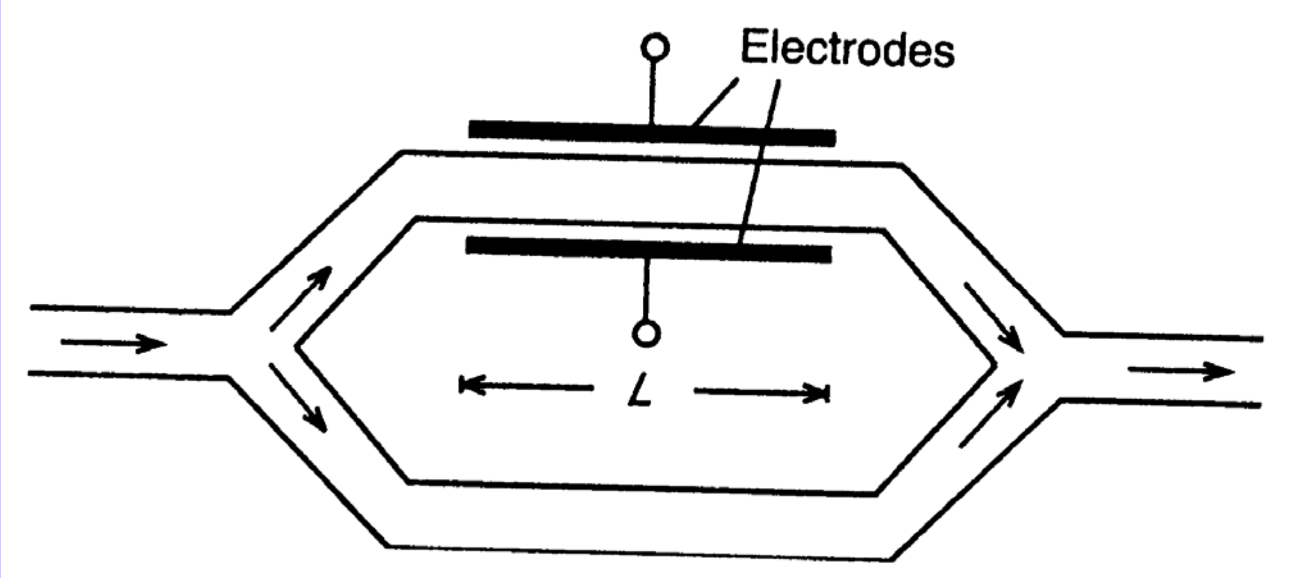
Mach-Zehnder interferometer

Another example is the IO Mach-Zehnder interferometer, which can be used as a light intensity modulator. The input light is split into two coherent waves of the same frequency, which are phase shifted by an applied voltage; the two are combined again and interfere at the output, whose amplitude depends on the phase difference between the two waves. The single mode waveguides are defined in an electro-optic material, such as $LiNbO_3$, or a poled glass, provided it exhibits a significant $\chi^{(2)}$ value. This subject will again be taken up in the non-linear optics section.



Integrated optic ON / OFF switch

This is made on an electro-optic (E-O) material substrate. The light travels down the channel on the left, until this channel splits. Here, half of the light goes down the upper arm and half goes down the lower arm. When a field is applied to the upper arm, the E-O effect causes an increase in its refractive index and, for a field of the correct magnitude, the light in the upper arm travels an optical path length $\lambda/2$ longer than in the lower arm. When the two halves recombine, they interfere destructively and no light leaves the switch. When no voltage is applied, the path lengths are identical and constructive interference occurs, with all the light leaving the switch.

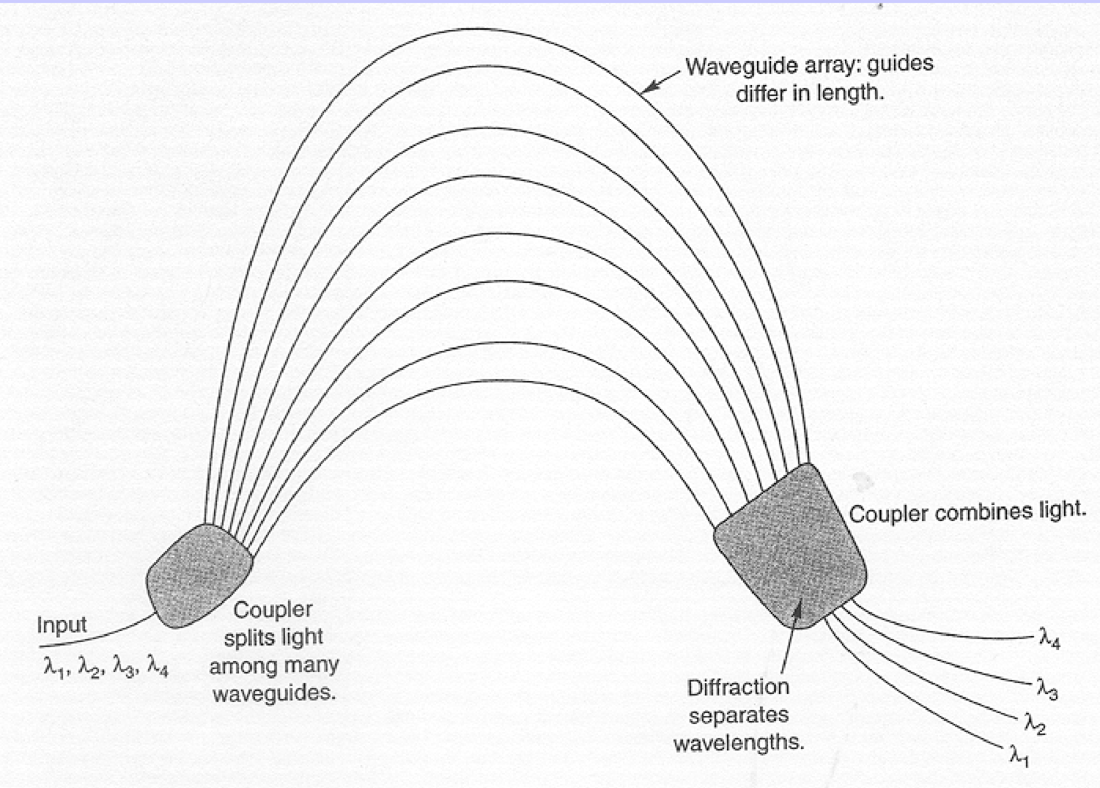


(Adapted from: *The essence of optoelectronics*, K. Booth and S. Hill, Prentice-Hall, 1998)

Yet another example is the arrayed waveguide grating, specially useful as a demultiplexer in WDM systems.

Arrayed Waveguide Grating for WDM

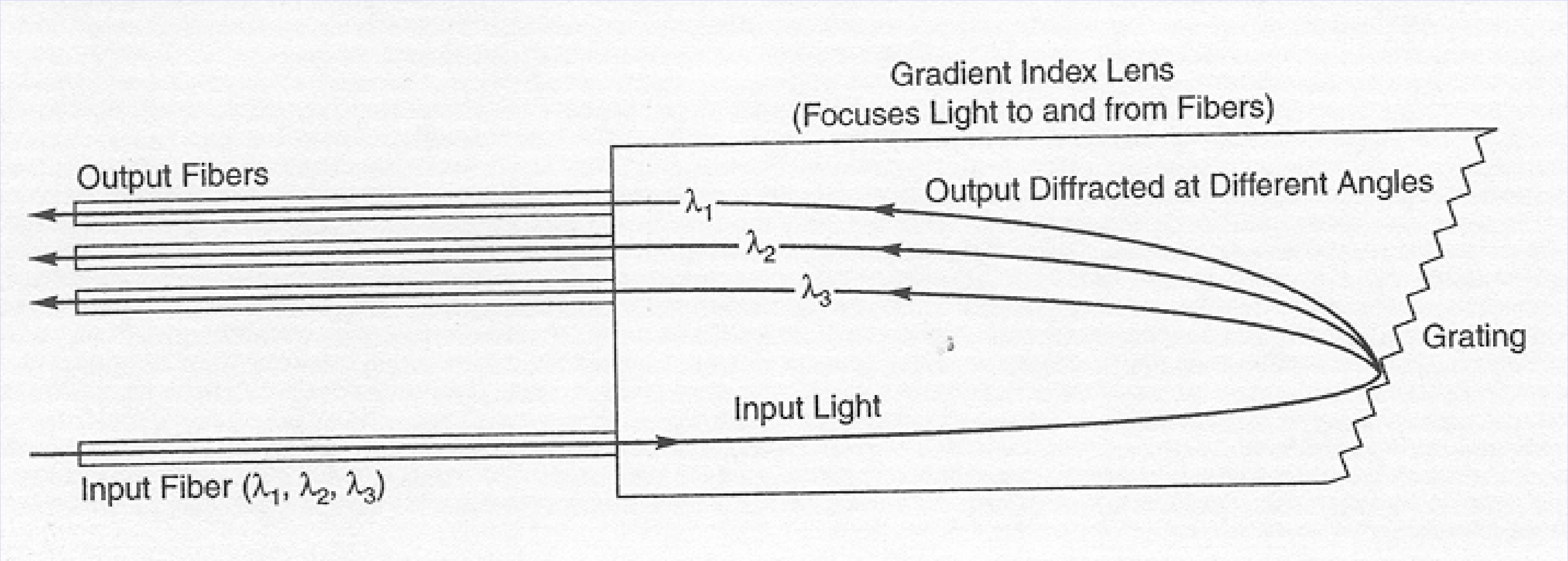
* Optical path length difference depends on wavelength
* silica-on-silicon waveguide platform
* good coupling between silica waveguide and silica fiber



(Adapted from: *Understanding Fiber Optics*, Jeff Hecht, Prentice Hall, 1999)

Echelle gratings as an alternative for WDM

* advances in reactive-ion etching (vertical etched facets)
* use silica-on-silicon platform
* smaller size than arrayed-waveguide grating
* allows more functionality on chip



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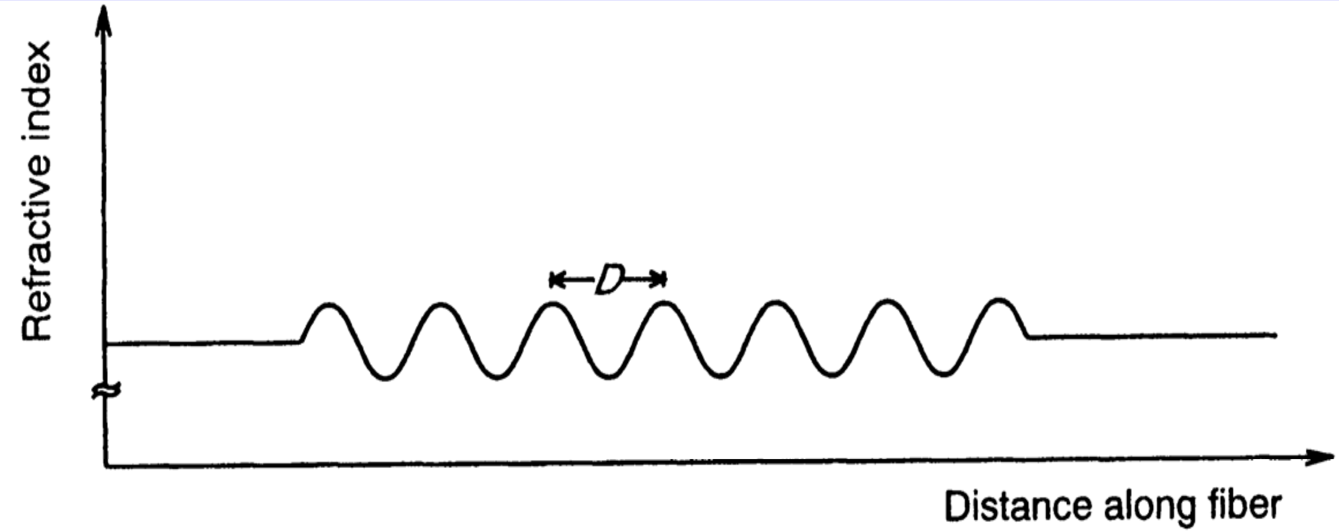
Permanent refractive index gratings can also be written into IO components by etching a corrugated surface into a waveguide.

If the corrugations have a wavelength D, selective reflection of light will occur for wavelengths given by:

$$\lambda = 2\,D\,n\,/\,m$$

where λ is the free space wavelength, n is the waveguide index and m is an integer. Such structures can then be used as optical mechanical sensors, for example to sense flexing in bridges or aircraft wings.



The presence of a grating in a waveguide.

(Adapted from: *The essence of optoelectronics*, K. Booth and S. Hill, Prentice-Hall, 1998)