Glass Processing

Lecture 19 # **Introduction to Dielectric Waveguide**

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Introduction to Dielectric Waveguide

OUTLINE

Day One (Introduction to Dielectric Waveguide)

1 – Introduction & Useful references

2 –Dielectric waveguide
    Representative of Chanel waveguides
    Waveguide condition
    Single and multimode waveguide
    TE and TM modes

3- Waveguides Materials

4-Characterization of Optical Waveguides

5- Waveguide devices

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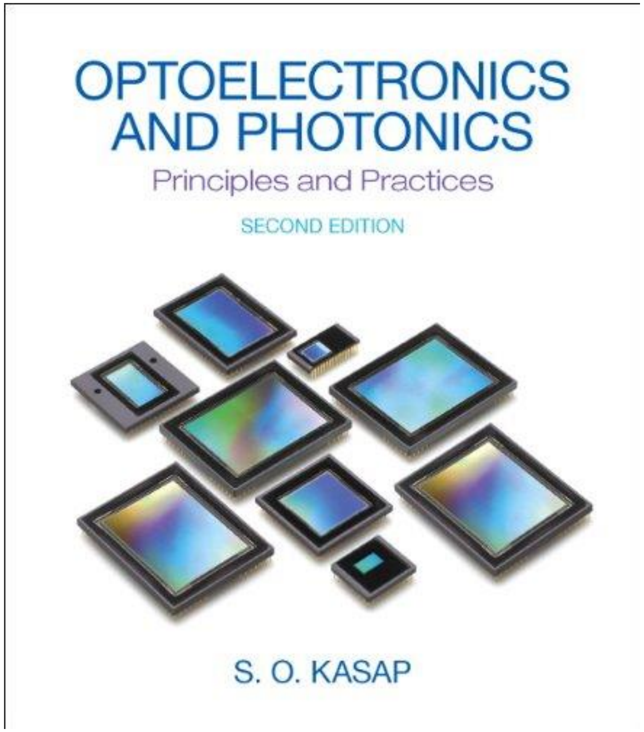
USEFUL REFERENCE

Optoelectronics & Photonics: Principles & Practices (2nd Edition) Hardcover – October 25, 2012 by Safa O. Kasap (Author)



OPTOELECTRONICS AND PHOTONICS
Principles and Practices
SECOND EDITION
S. O. KASAP

ISBN-10: 0133081753
Second Edition Version 1.056

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Introduction to Dielectric Waveguide

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Optical Waveguides (OPT568)

Govind P. Agrawal
Institute of Optics
University of Rochester
Rochester, NY 14627

http://www.optics.rochester.edu/users/gpa/opt468a.pdf

Photonics devices

Jia-Ming Liu
Electrical Engineering Department
University of California
Los Angeles, CA 90095-1594

http://course.ee.ust.hk/elec509/notes/Lect4-Optical%20waveguides.pdf

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Introduction

The basic element of **any optical circuit** is the **optical waveguide** which permits to connect optically different devices.

To build **integrated optical circuits** that substitute micro-electronic circuits, **integrated optical waveguides** with light confinement in a size of the order of the wavelength are **mandatory**.

Optical waveguides can be classified according to their :

a) **Geometry:** Planar, Strip, Fiber waveguides
b) **Mode Structure**: Single mode, multimode
c) **Rectractive index distribution:** Step, Gradient index
d) **Material:** Glass, Polymer, Semicomducteur.

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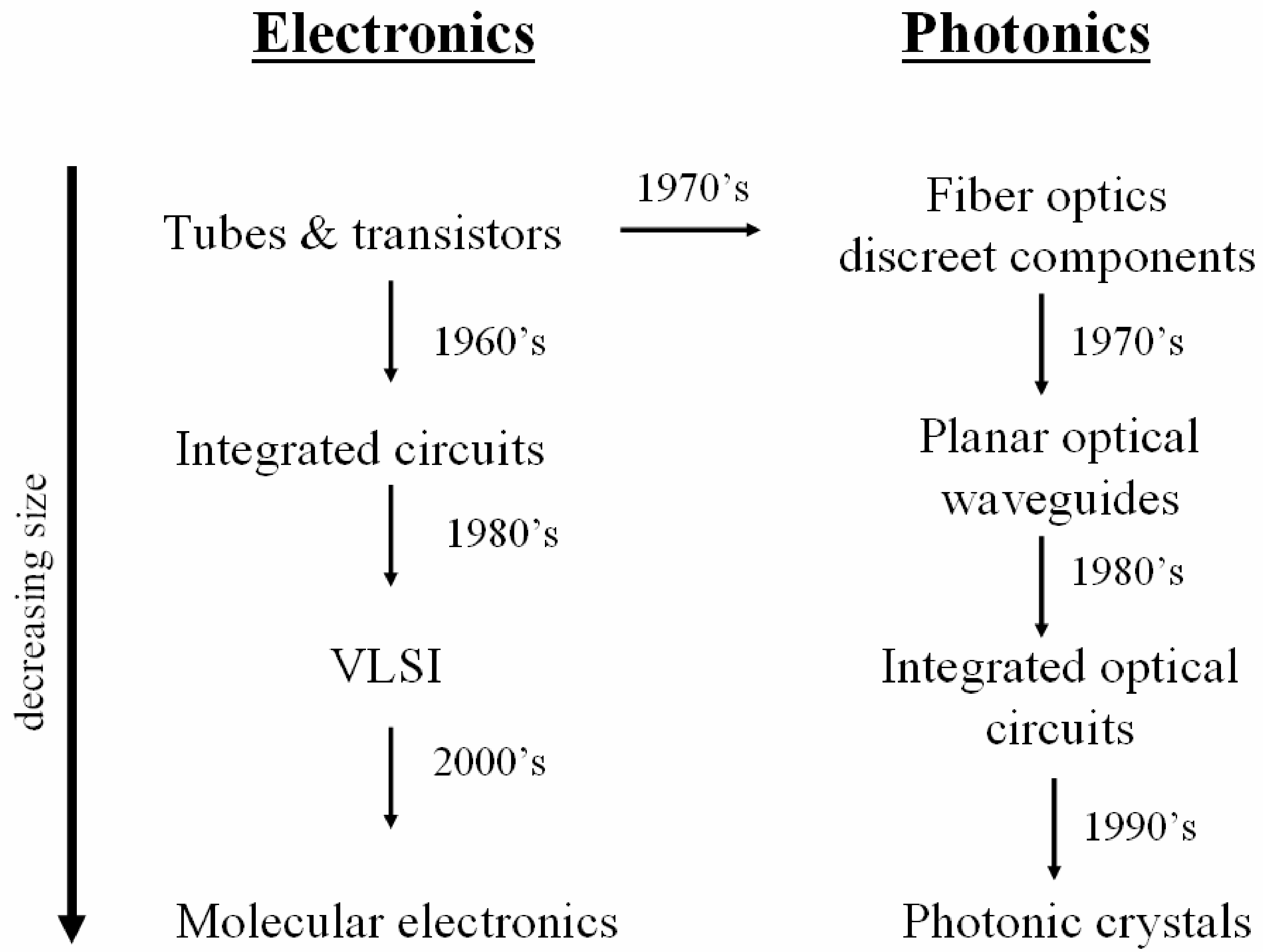
Introduction



Electronics

Photonics

decreasing size

Tubes & transistors

1970's

Fiber optics discreet components

1960's

1970's

Integrated circuits

Planar optical waveguides

1980's

1980's

VLSI

Integrated optical circuits

2000's

1990's

Molecular electronics

Photonic crystals

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Introduction

Optical integrated waveguides:

-***Design:*** energy flow only along the waveguiding structure but not perpendicular to it, so radiation losses can be avoided

-***Mechanism:*** usually, optical integrated waveguides rely on the principle of total internal reflection (TIR)

-***Material science:*** use of materials with good optical properties: low absorption loss is fundamental.

-***Integration:*** The waveguide cross-section should be as small as possible to permit high-density integration (physical limit: diffraction, size λ/2)

-***Functionality:*** linking devices or systems (i.e., optical fiber) or implementation of complex functionalities: splitters/combiners, couplers, AWGs, modulators, etc.

-***Technology:*** Importance of the employed materials and related-technology: Silicon/silica, SiN, polymers, III-V compounds, lithium niobate, etc.

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DIELECTRIC WAVEGUIDES

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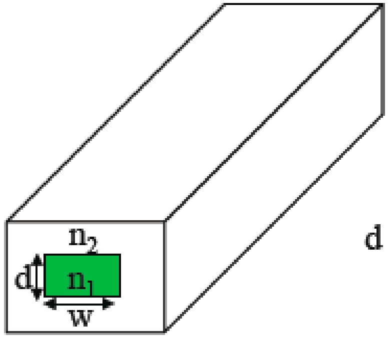
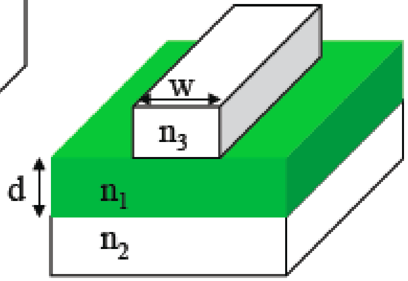
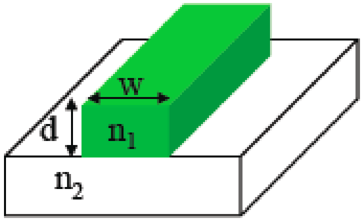
Representative of Chanel Waveguides



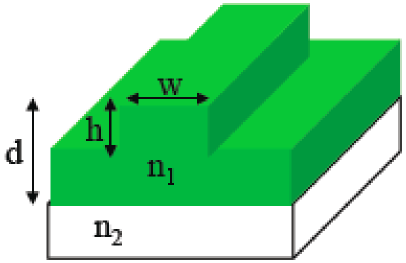
Buried channel waveguide



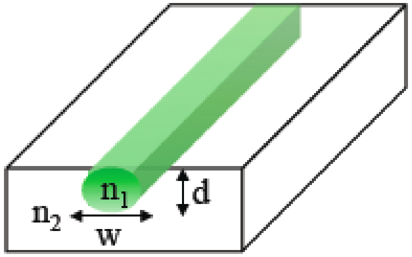
Strip-loaded waveguide



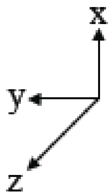
Ridge waveguide



rib waveguide



Diffused waveguide



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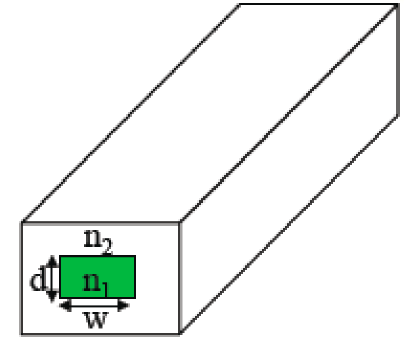
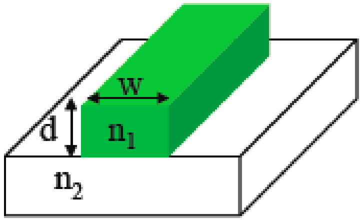
Representative of Chanel Waveguides



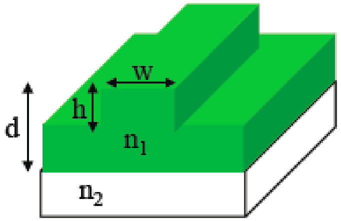
Buried channel waveguide

A ***buried channel waveguide*** is formed with a high-index waveguiding core buried in a low-index surrounding medium.



Ridge waveguide

A ***ridge waveguide*** has a structure that looks like a strip waveguide, but the strip, or the ridge, on top of its planar structure has a high index and is actually the waveguiding core. A ridge waveguide has strong optical confinement because it is surrounded on three sides by low-index air (or cladding material).



rib waveguide

A ***rib waveguide*** has a structure similar to that of a strip or ridge waveguide, but the strip has the same index as the high index planar layer beneath it and is part of the waveguiding core.

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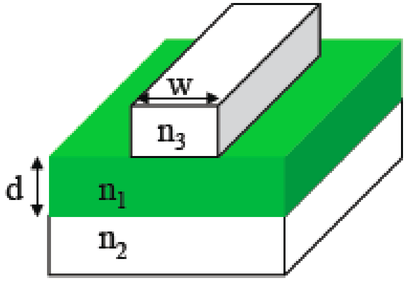
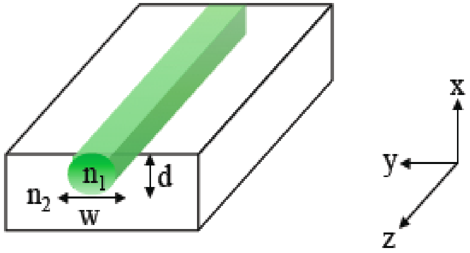
Representative of Chanel Waveguides



Strip-loaded waveguide

A ***strip-loaded waveguide*** is formed by loading a planar waveguide, which already provides optical confinement in the x direction, with a dielectric strip of index n3<n1 or a metal strip to facilitate optical confinement in the y direction. The waveguiding core of a strip waveguide is the n1 region under the loading strip, with its thickness d determined by the thickness of the n1 layer and its width w defined by the width of the loading strip.



Diffused waveguide

A ***diffused waveguide*** is formed by creating a high-index region in a substrate through diffusion of dopants, such as $LiNbO_3$ waveguide with a core formed by Ti diffusion.

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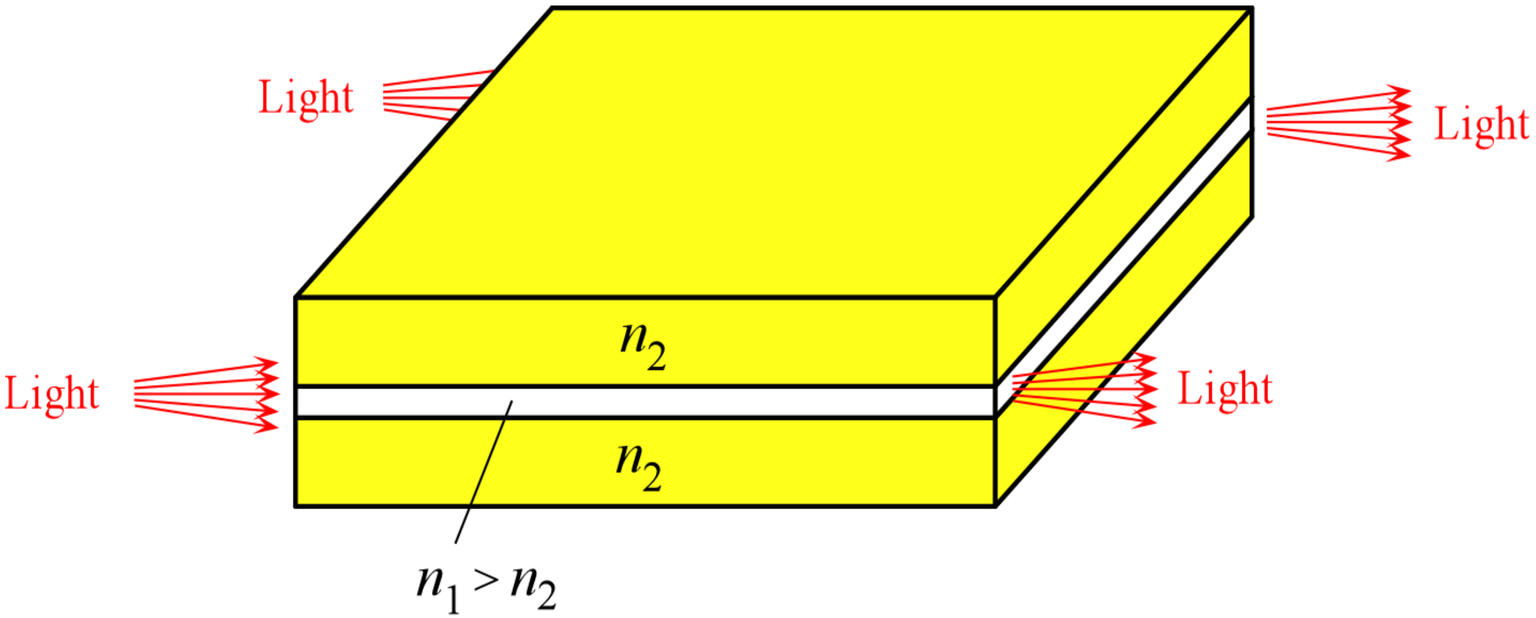
Planar Optical Waveguide



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 2*a*. It is illuminated at one end by a nearly monochromatic light source.

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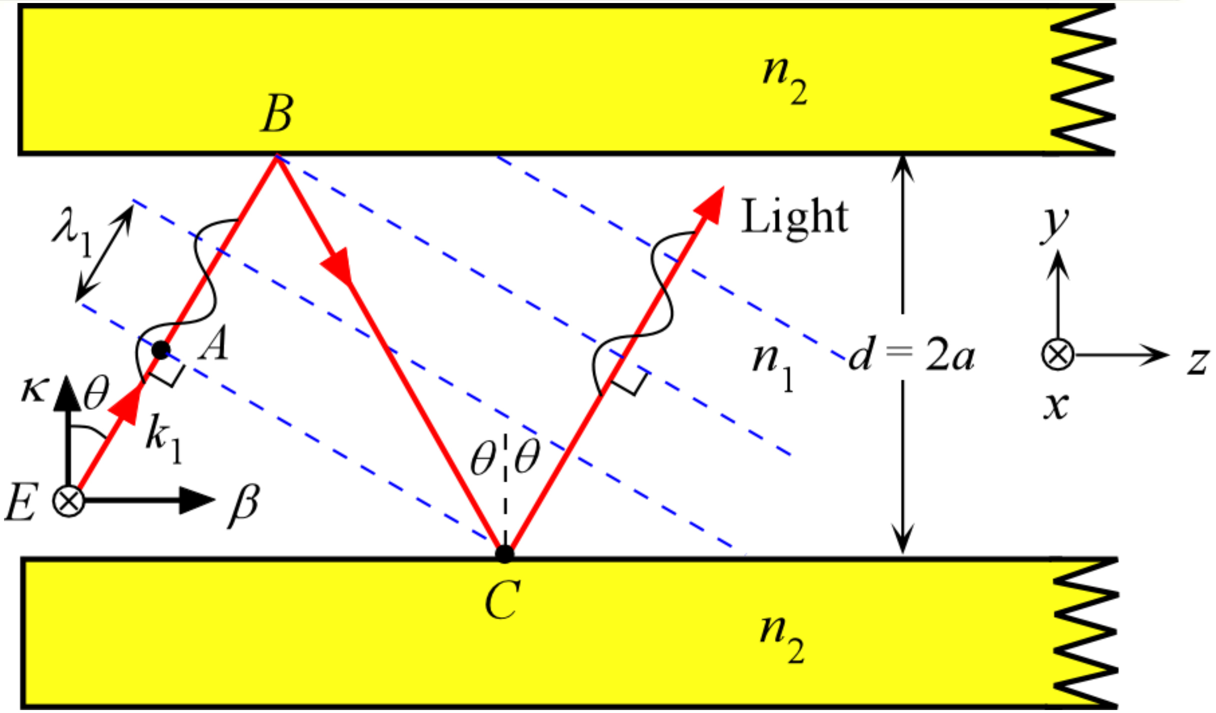
Waves Inside the Core



A light ray traveling in the guide must interfere constructively with itself to propagate successfully. Otherwise destructive interference will destroy the wave. E is parallel to x. (λ_1 and k_1 are the wavelength and the propagation constant inside the core medium n_1 *i.e.* $\lambda_1 = \lambda/n_1$.)

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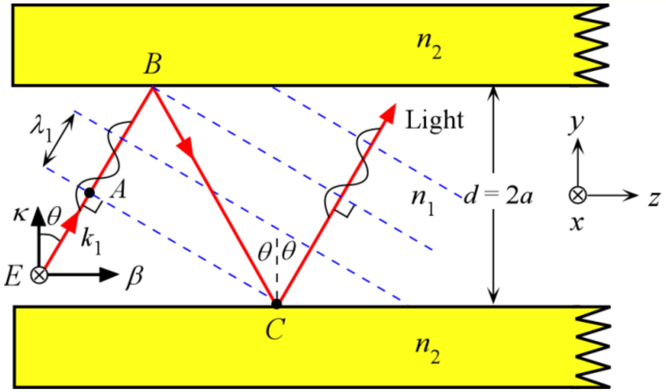
Waveguide Condition And Modes



$$k_1 = kn_1 = 2\pi n_1/\lambda,$$

$$\Delta\phi(AC) = k_1(AB + BC) - 2\phi = m(2\pi)$$

$$BC = d/\cos\theta \text{ and } AB = BC\cos(2\theta)$$

$$AB + BC = BC\cos(2\theta) + BC = BC[(2\cos^2\theta - 1) + 1] = 2d\cos\theta$$

$$\mathbf{k_1[2d\cos\theta] - 2\phi = m(2\pi)}$$

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$$\left[\frac{2\pi n_1(2a)}{\lambda}\right]\cos\theta_m - \phi_m = m\pi$$

m* = 0, 1, 2, 3 *etc
Integer

"Mode number"

Waveguide condition

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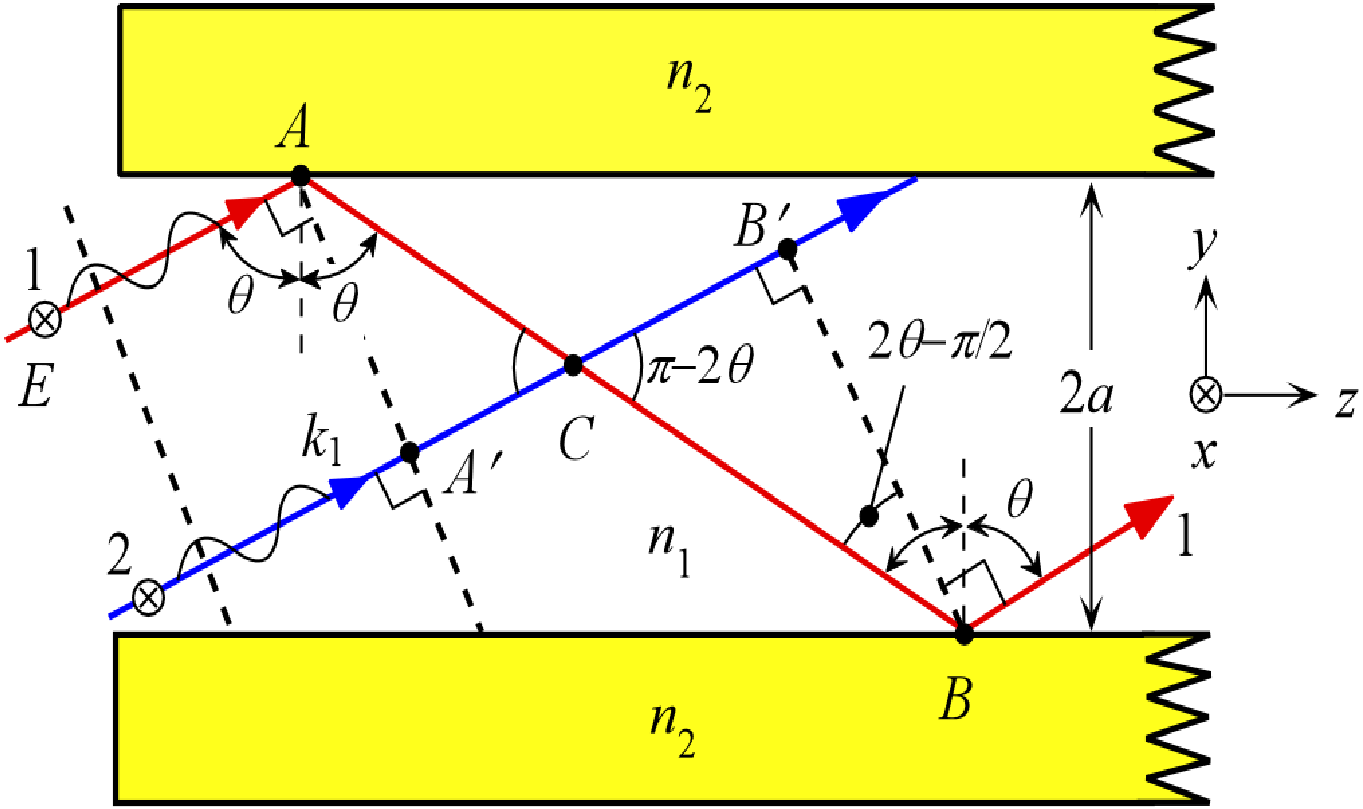
Waves Inside the Core



Two arbitrary waves 1 and 2 that are initially in phase must remain in phase after reflections. Otherwise the two will interfere destructively and cancel each other.

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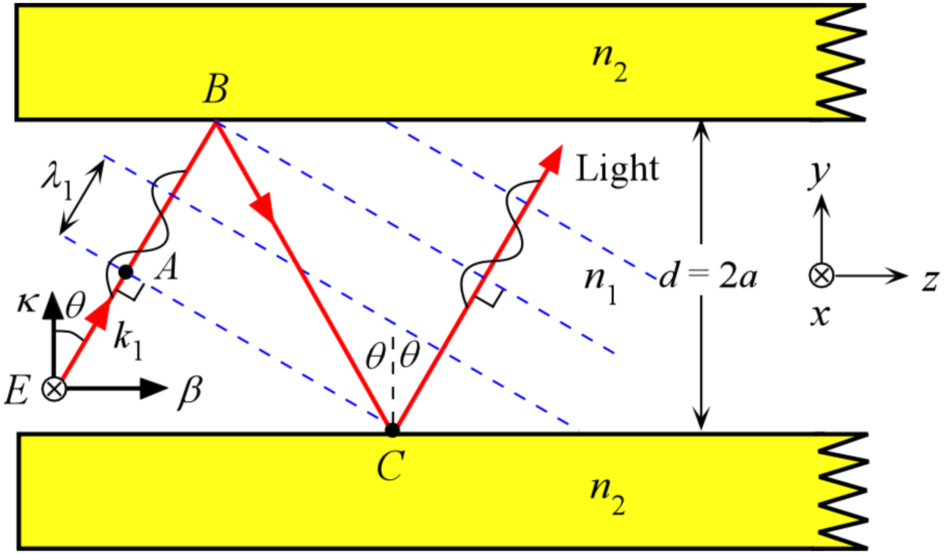

$$\beta_m = k_1 \sin\theta_m = \left(\frac{2\pi n_1}{\lambda}\right)\sin\theta_m$$

Propagation constant along the guide

$$\kappa_m = k_1 \cos\theta_m = \left(\frac{2\pi n_1}{\lambda}\right)\cos\theta_m$$

Transverse Propagation constant

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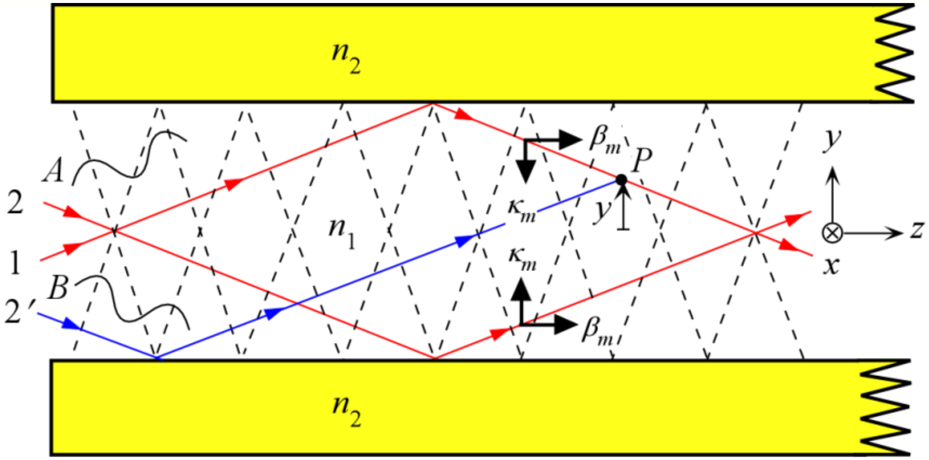
Modes in a Planar Waveguide



We can identify upward (*A*) and downward (*B*) traveling waves in the guide which interfere to set up a standing wave along *y* and a wave that is propagating along *z*. Rays 2 and 2′ belong to the same wave front but 2′ becomes reflected before 2. The interference of 1 and 2′ determines the field at a height *y* from the guide center. The field *E*(*y*, *z*, *t*) at *P* can be written as:

$$E(y,z,t) = \underbrace{E_m(y)}_{\text{Field pattern along } y}\underbrace{\cos(\omega t - \beta_m z)}_{\text{Traveling wave along } z}$$

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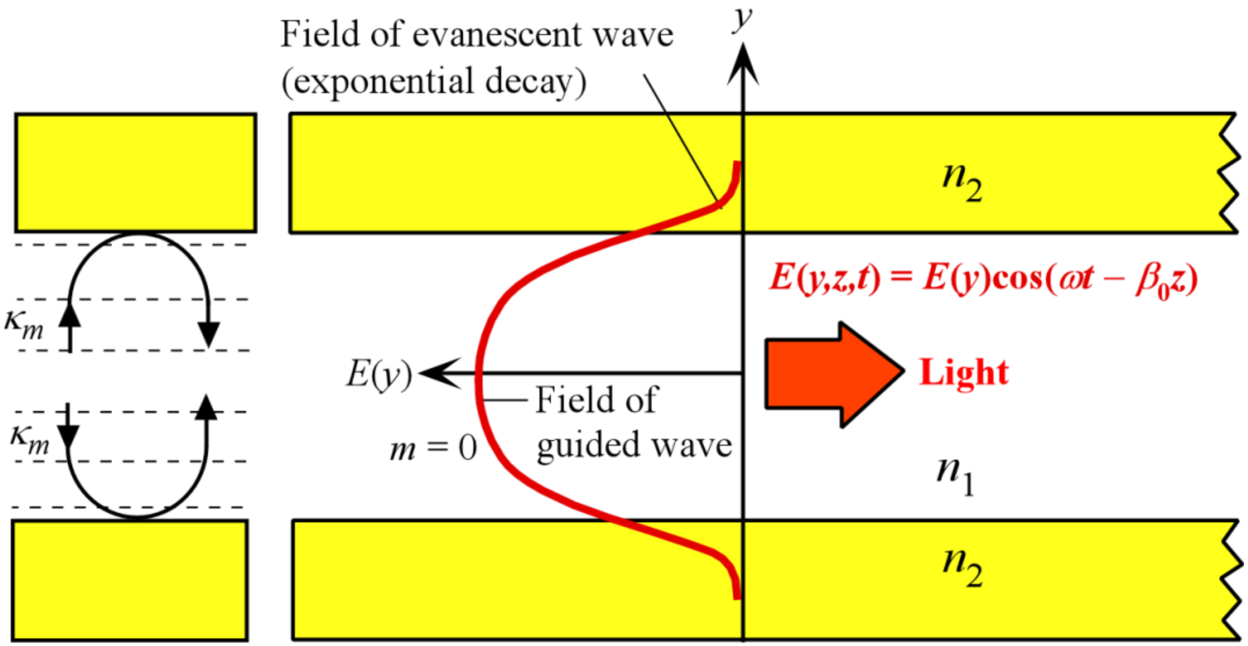
Mode Field Pattern



Left: The upward and downward traveling waves have equal but opposite wavevectors κ_m and interfere to set up a standing electric field pattern across the guide. Right: The electric field pattern of the lowest mode traveling wave along the guide. This mode has $m = 0$ and the lowest θ. It is often referred to as the glazing incidence ray. It has the highest phase velocity along the guide

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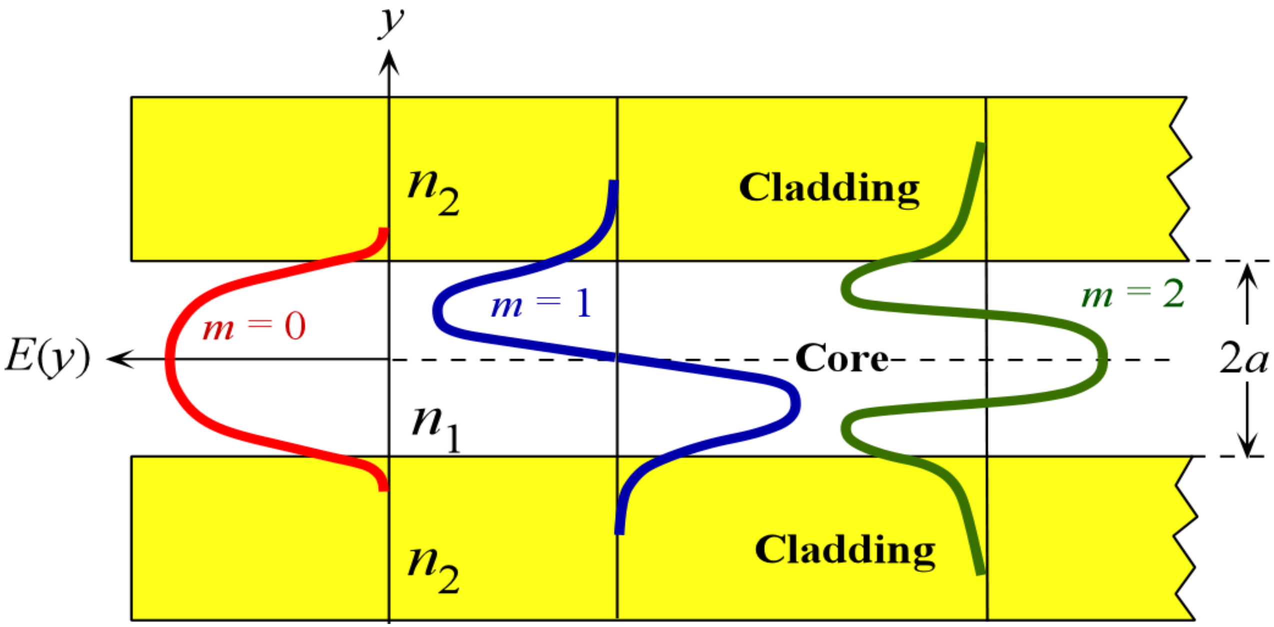
Modes in a Planar Waveguide



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. Each of these traveling wave constitutes a **mode of propagation.**

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Waveguide Condition and Modes

To get a propagating wave along a guide you must have constructive interference. All these rays interfere with each other. Only certain angles are allowed . Each allowed angle represents a **mode** of propagation.

$$\left[\frac{2\pi n_1(2a)}{\lambda}\right]\cos\theta_m - \phi_m = m\pi$$

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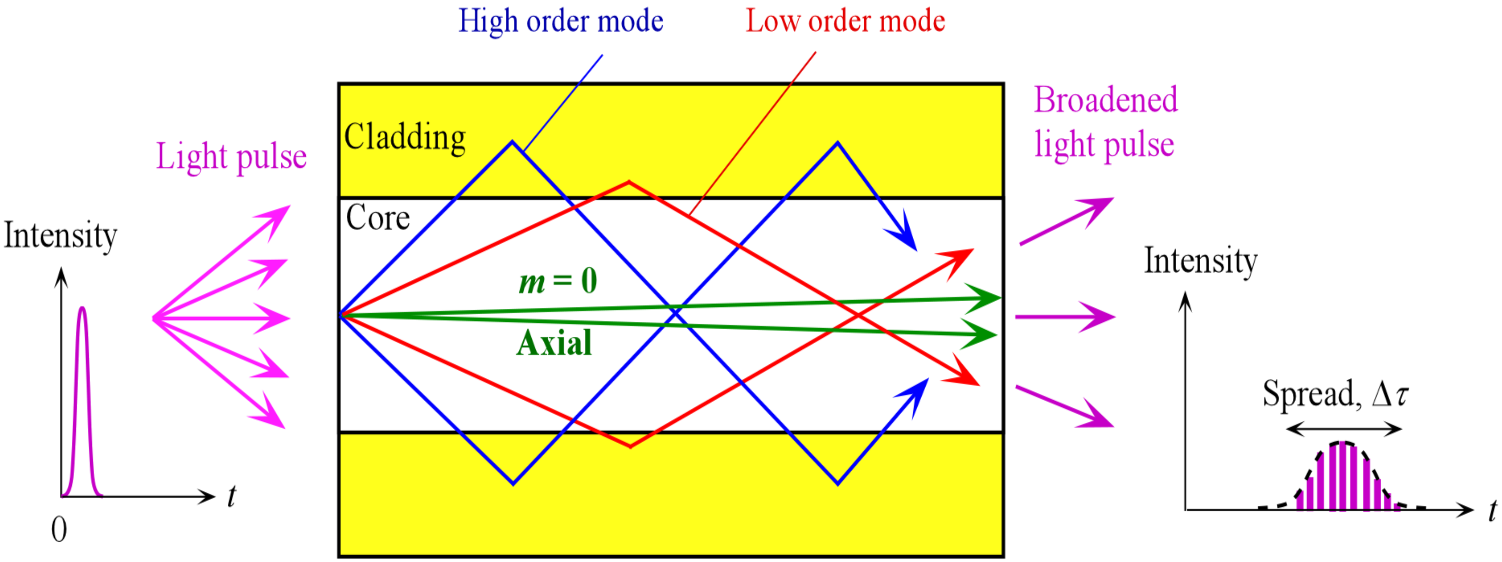

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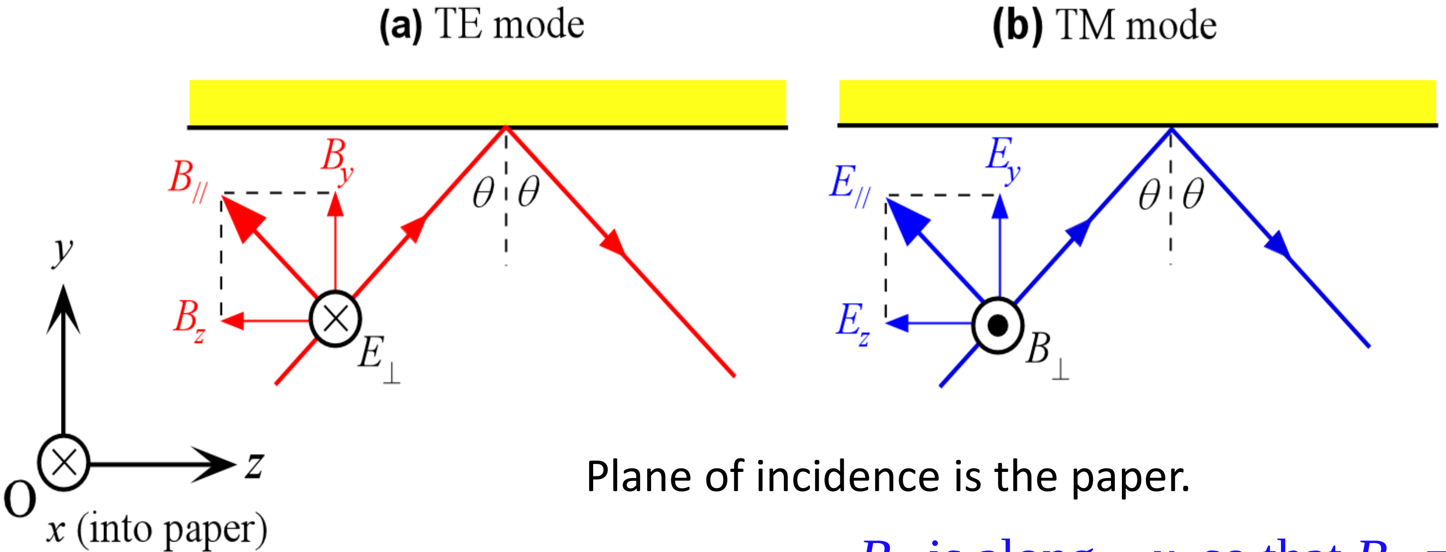
TE and TM Modes

Two of the possibilities for the electric field direction of a wave Traveling toward the core-cladding boundary.



Plane of incidence is the paper.

$B_\perp$ is along $-x$, so that $B_\perp = -B_x$

$E_\perp$ is along x, so that $E_\perp = E_x$

Possible modes can be classified in terms of :

(a) transverse electric field (TE)

(b) transverse magnetic field (TM).

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V-Number

All waveguides are characterized by a parameter called the ***V*-number** or **normalized frequency**

$$V = \frac{2\pi a}{\lambda}\left(n_1^2 - n_2^2\right)^{1/2}$$

$V < \pi/2$, $m = 0$ is the only possibility and only the fundamental mode ($m = 0$) propagates along the dielectric slab waveguide: a **single mode** planar waveguide.

$\lambda = \lambda_c$ for $V = \pi/2$ is the **cut-off wavelength**, and above this wavelength, only one-mode, the fundamental mode will propagate.

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Example on Waveguide Modes

Consider a planar dielectric guide with a core thickness 20 µm, n_1 = 1.455, n_2 = 1.440, light wavelength of 900 nm. Find the modes?

TIR phase change ϕ_m for TE mode

$$\tan\left(\tfrac{1}{2}\phi_m\right) = \frac{\left[\sin^2\theta_m - \left(\frac{n_2}{n_1}\right)^2\right]^{1/2}}{\cos\theta_m}$$

TE mode

Waveguide condition

$$\left[\frac{2\pi n_1(2a)}{\lambda}\right]\cos\theta_m - \phi_m = m\pi$$

Waveguide condition

$$\phi_m = 2ak_1\cos\theta_m - m\pi$$

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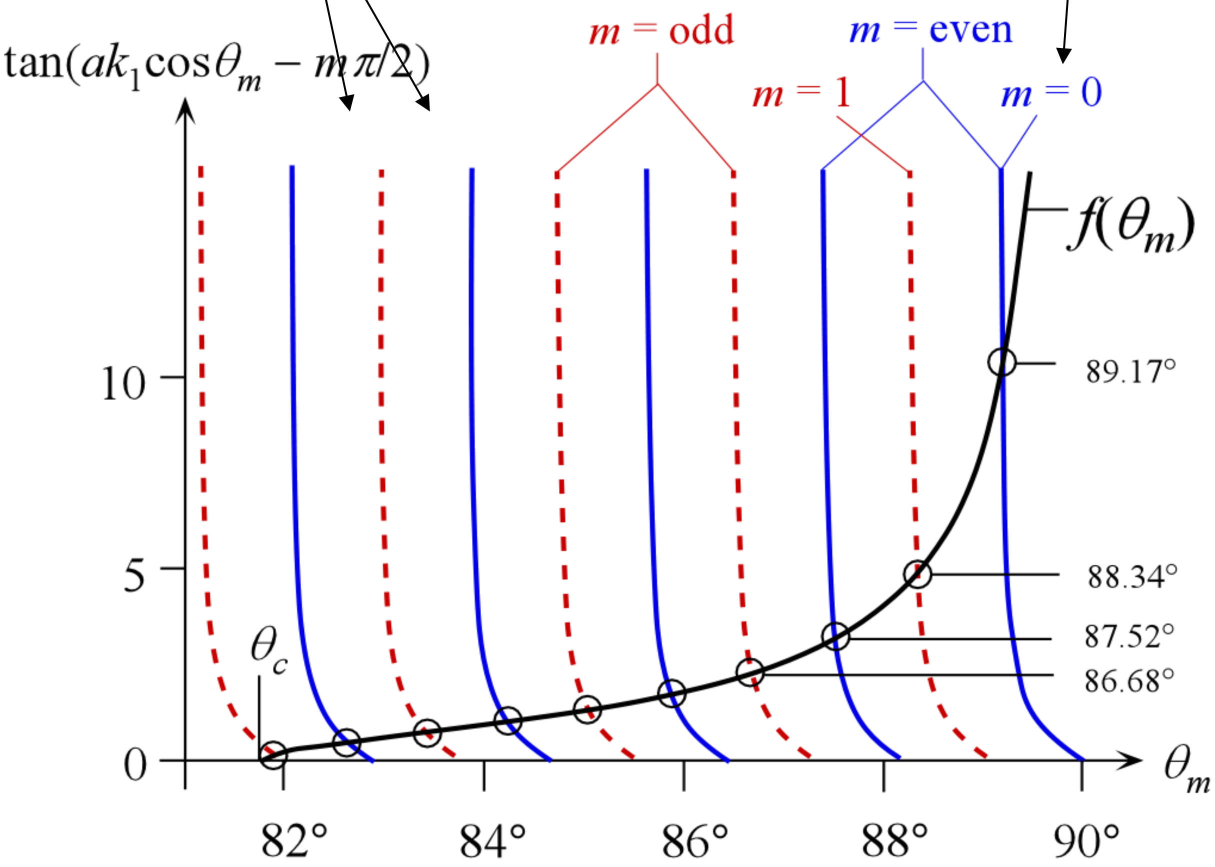
$$\tan\left(ak_1\cos\theta_m - m\frac{\pi}{2}\right) = \frac{\left[\sin^2\theta_m - \left(\frac{n_2}{n_1}\right)^2\right]^{1/2}}{\cos\theta_m} = f(\theta_m)$$

TE mode



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WAVEGUIDE MATERIALS

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WAVEGUIDE MATERIALS

a) Glass Waveguides :(SiO_2) or SiON

b) Electro-Optic Waveguides: $LiNbO_3$

c) Silicon-on-Insulator technology

d) Semiconductor Waveguides

e) Polymer Waveguides

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WAVEGUIDE MATERIALS

Silica on Silicon technology

A number of different technologies are used for the fabrication of silica-on silicon integrated devices including:

a) Flame hydrolysis;
b) Low pressure chemical vapour deposition;
c) Sputtering, ion exchange and ion implantation;
d) **Sol-gel techniques ;**
e) **Plasma enhanced chemical vapor deposition.**

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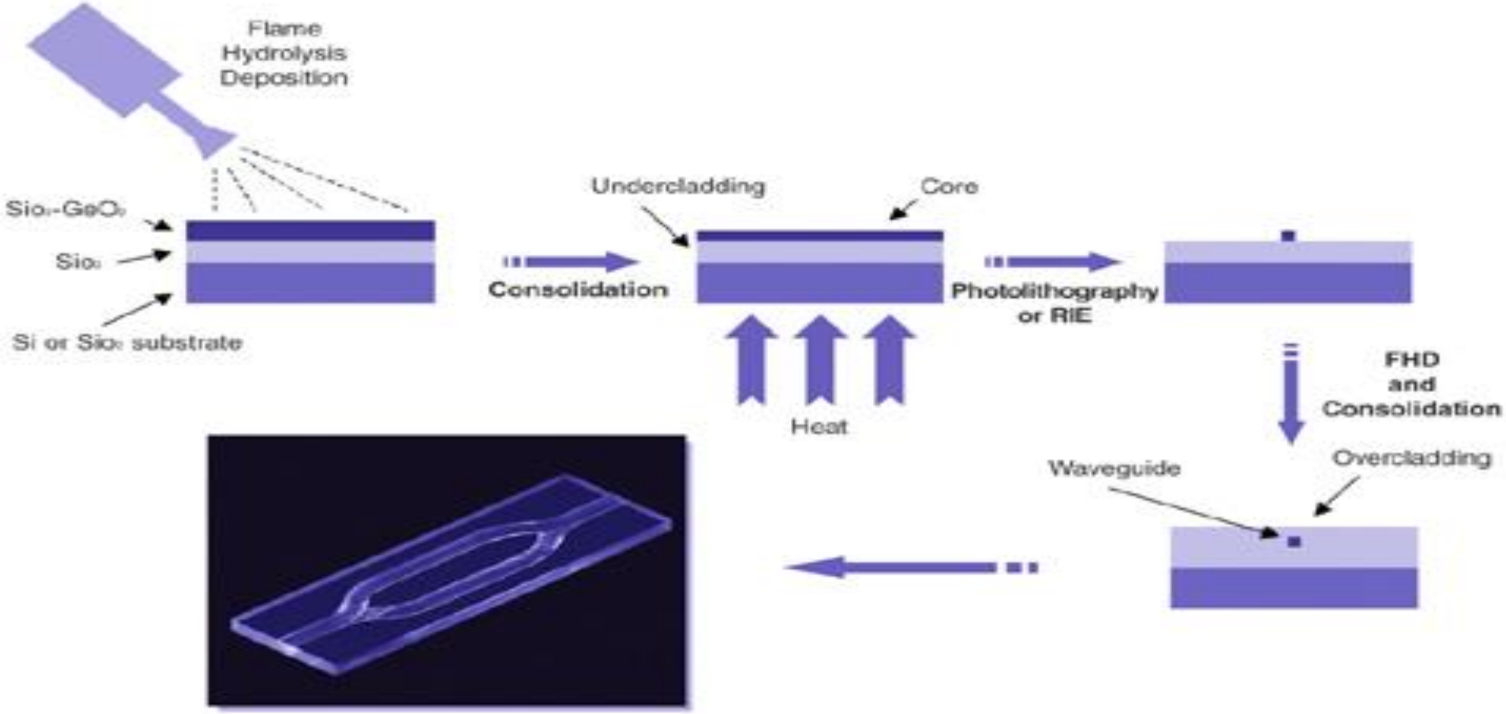
Examples of integrated waveguides

Silica (SiO_2) waveguides (Flame Hydrolsis)

Core: doped silica; claddings: silica (n=1.45)

Advantages:mature technology, ultra-low propagation losses, low fiber coupling losses, tuning by thermal effects

Drawbacks:large bending radius (large size devices), weak nonlinearities,no integration with active devices



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WAVEGUIDE MATERIALS

Lithium niobate(LiNbO$_3$) waveguides

Core: diffused Titanium in LiNbO$_3$; claddings: LiNbO$_3$, air

Advantages: mature technology, high electro-optic effect (electro-optical Mach-Zehndermodulators), efficient coupling to fiber.

Drawbacks: low integration density, polarization dependence, no mass-manufacturing.

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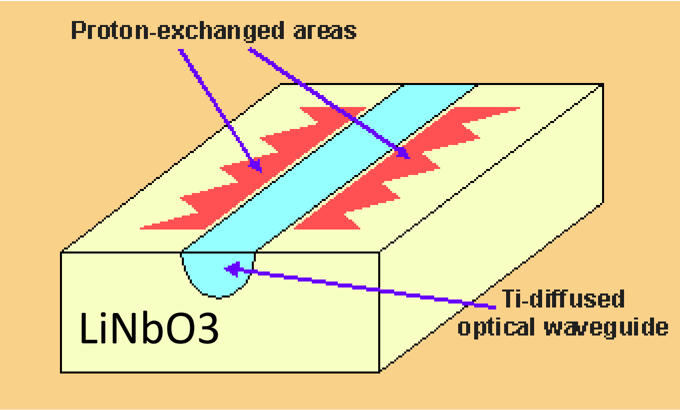

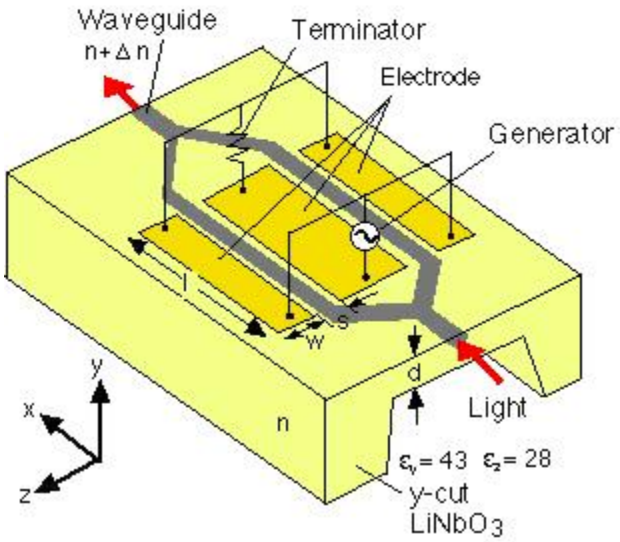

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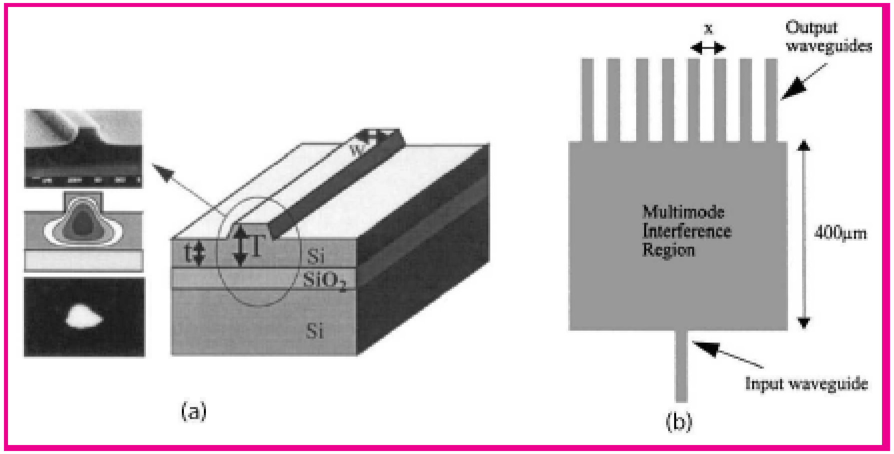
WAVEGUIDE MATERIALS

Silicon-on-Insulator Technology



(a) (b)

- Core waveguide layer is made of Si ($n_1 = 3.45$).
- A silica layer under the core layer is used for lower cladding.
- Air on top acts as the top cladding layer.
- Tightly confined waveguide mode because of large index difference.
- Silica layer formed by implanting oxygen, followed with annealing.

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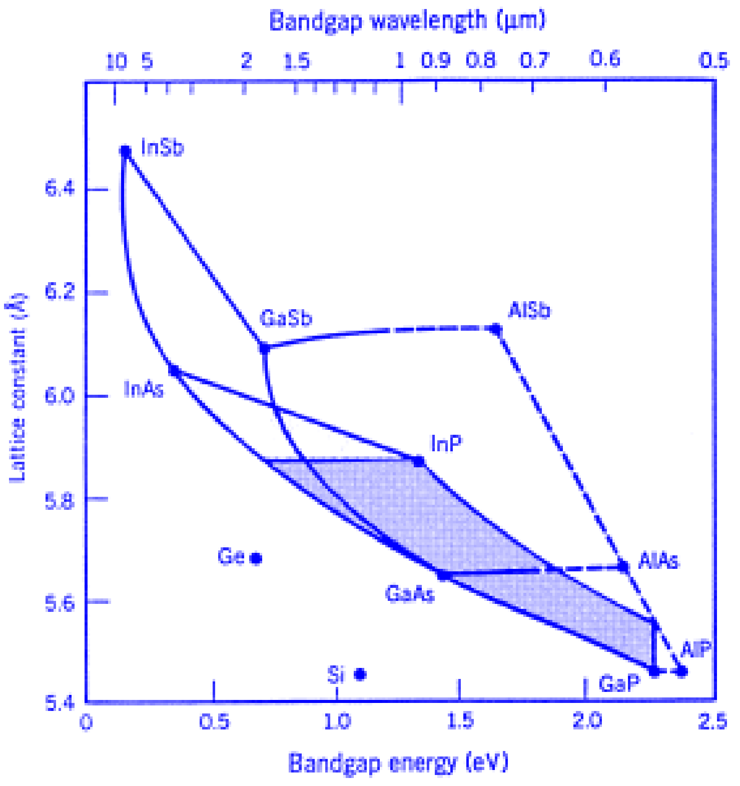
WAVEGUIDE MATERIALS

Semiconductor Waveguides

Useful for semiconductor lasers, modulators, and photodetectors.

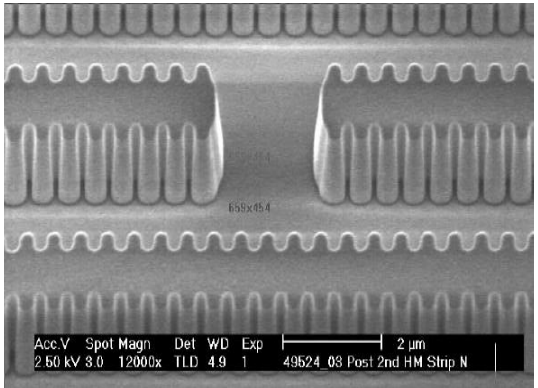
- Semiconductors allow fabrication of electrically active devices.
- Semiconductors belonging to III–V Group often used.
- Two semiconductors with different refractive indices needed.
- They must have different bandgaps but same lattice constant.
- Nature does not provide such semiconductors.



WAVEGUIDE MATERIALS

Silicon Oxynitride Waveguides

- Employ Si substrate but use SiON for the core layer.
- SiON alloy is made by combining SiO_2 with Si_3N_4, two dielectrics with refractive indices of 1.45 and 2.01.
- Refractive index of SiON layer can vary from 1.45–2.01.
- SiON film deposited using plasma-enhanced chemical vapor deposition (SiH_4 combined with N_2O and NH_3).
- Low-pressure chemical vapor deposition also used (SiH_2Cl_2 combined with O_2 and NH_3).
- Photolithography pattern formed on a 200-nm-thick chromium layer.
- Propagation losses typically <0.2 dB/cm.



Silicon oxynitride grated waveguides
Courtesy: Jeff Viens, MIT

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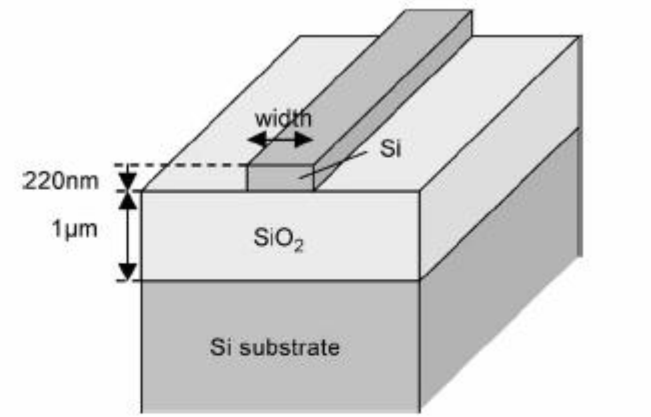
Examples of integrated waveguides

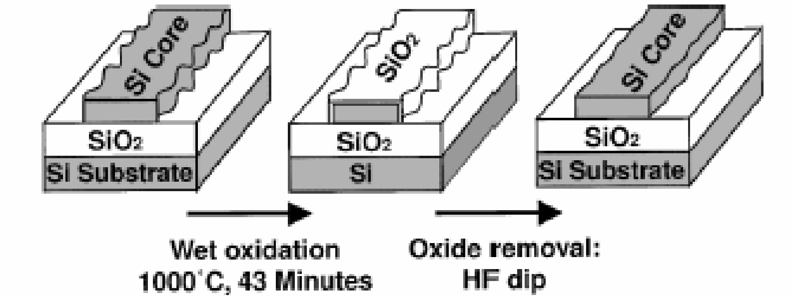
Silicon wires (strip waveguides)

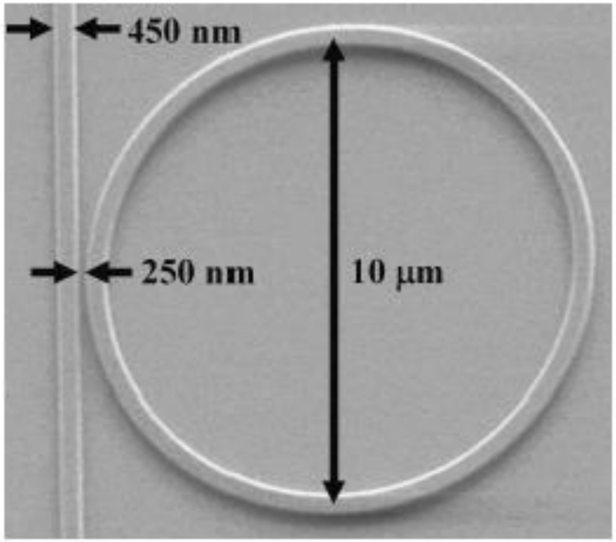
Core: Silicon (n=3.5); claddings: silica, air

Advantages: Integration of on-chip electronics/photonics, mass manufacturing, high density of integration, strong confinement

Drawbacks: propagation losses (>1dB/cm), weak nonlinearities, negligible electro-optic effect, inefficient coupling







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WAVEGUIDE MATERIALS

Laser-Written Waveguides

- CW or pulsed light from a laser used for "writing" waveguides in silica and other glasses.
- Photosensitivity of germanium-doped silica exploited to enhance refractive index in the region exposed to a UV laser.
- Absorption of 244-nm light from a KrF laser changes refractive index by $\sim 10^{-4}$ only in the region exposed to UV light.
- Index changes $> 10^{-3}$ can be realized with a 193-nm ArF laser.
- A planar waveguide formed first through CVD, but core layer is doped with germania.
- An UV beam focused to $\sim 1\ \mu$m scanned slowly to enhance n selectively. UV-written sample then annealed at 80°C.

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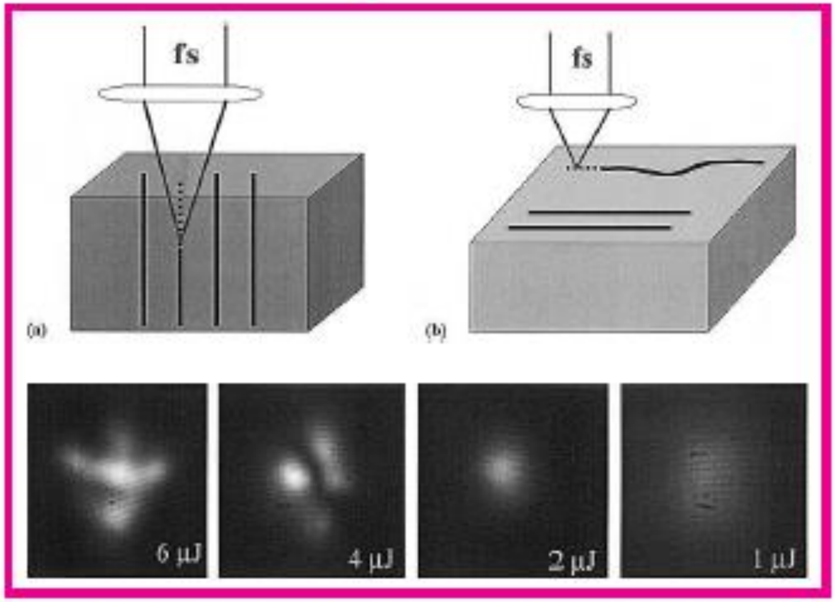
WAVEGUIDE MATERIALS

Laser-Written Waveguides



- Femtosecond pulses from a Ti:sapphire laser can be used to write waveguides in bulk glasses.
- Intense pulses modify the structure of silica through multiphoton absorption.
- Refractive-index changes $\sim 10^{-2}$ are possible.

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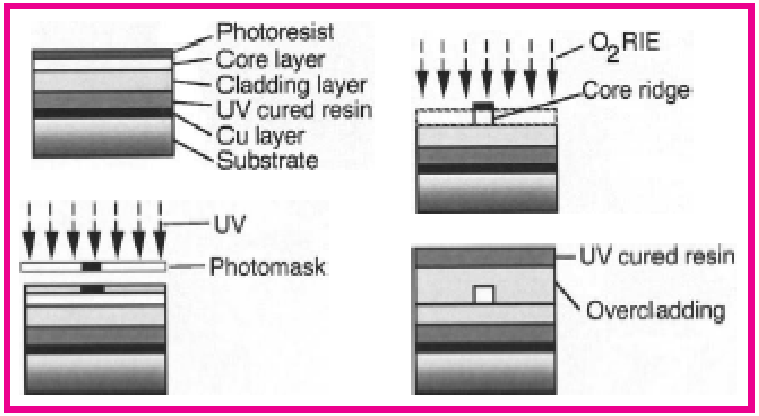
WAVEGUIDE MATERIALS

Polymer Waveguides



- Polymers such as halogenated acrylate, fluorinated polyimide, and deuterated polymethylmethacrylate (PMMA) have been used.
- Polymer films can be fabricated on top of Si, glass, quartz, or plastic through spin coating.
- Photoresist layer on top used for reactive ion etching of the core layer through a photomask.

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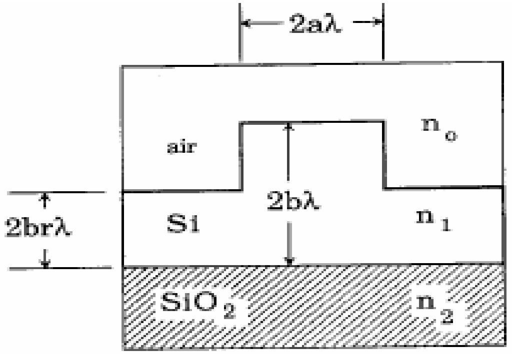
Examples of integrated waveguides

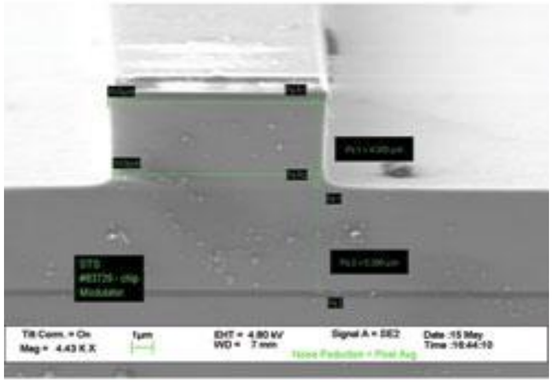
Silicon Rib waveguides

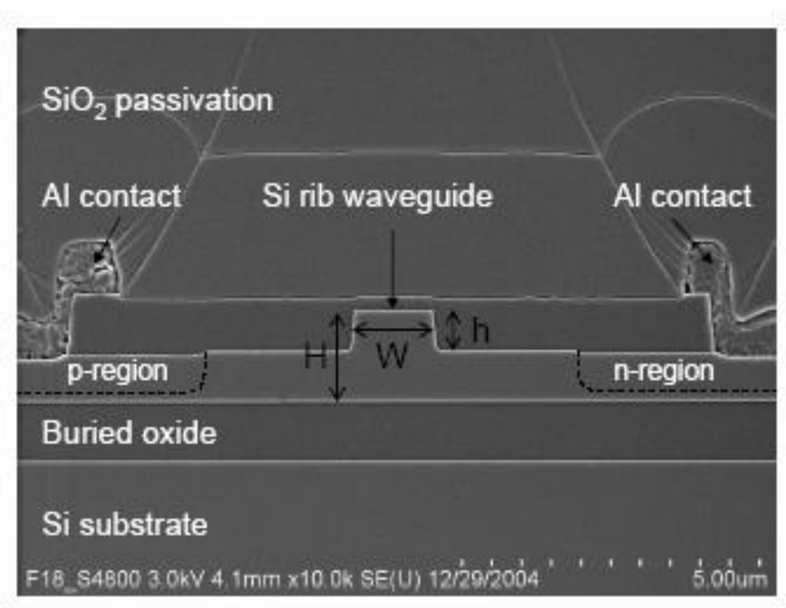
Core: Silicon (n=3.5); claddings: silica, air

Advantages: efficient coupling (large mode size), low losses, single mode (in spite of the large core size), monolithic integration with electronics

Drawbacks: weak nonlinearities, large sizes (bends), not suitable for high-density integration.







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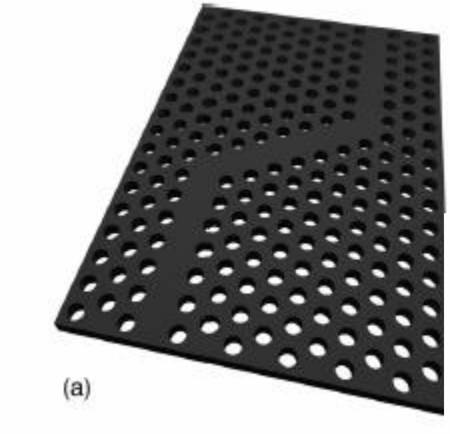
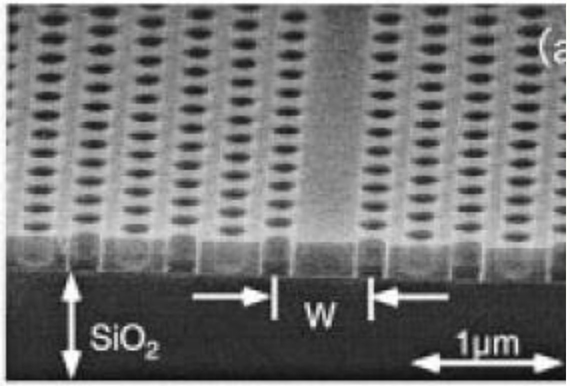
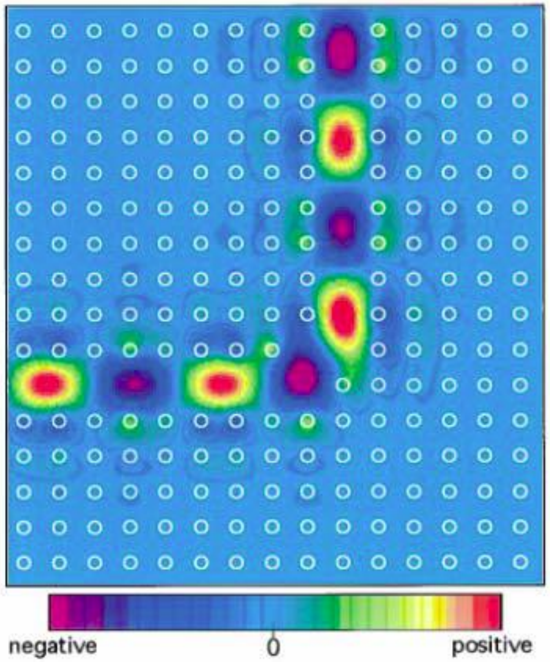
Examples of integrated waveguides

Photonic crystal waveguides

-The core can be of low or high index
-Materials: the same than in TIR-based optical waveguides
-Light can not escape from the waveguide since it is not permitted in the cladding due to the existence of a photonic band gap
-Possibility of strong bending with low losses



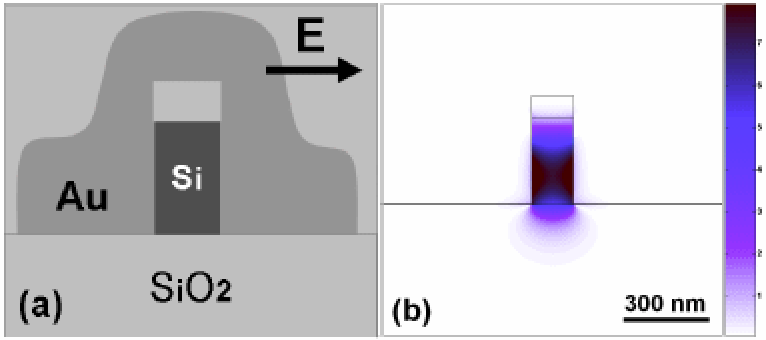


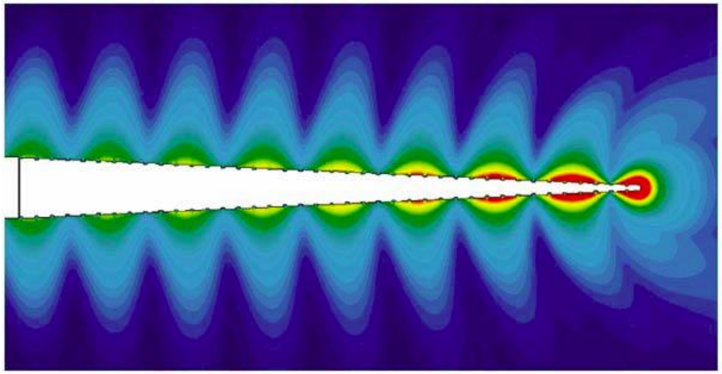


Examples of integrated waveguides

Plasmonic waveguides

-Guidings of plasmons(photons + electrons)
-Metal/dielectric interfaces
-Quite high losses
-Ultra high field confinement in the interface.





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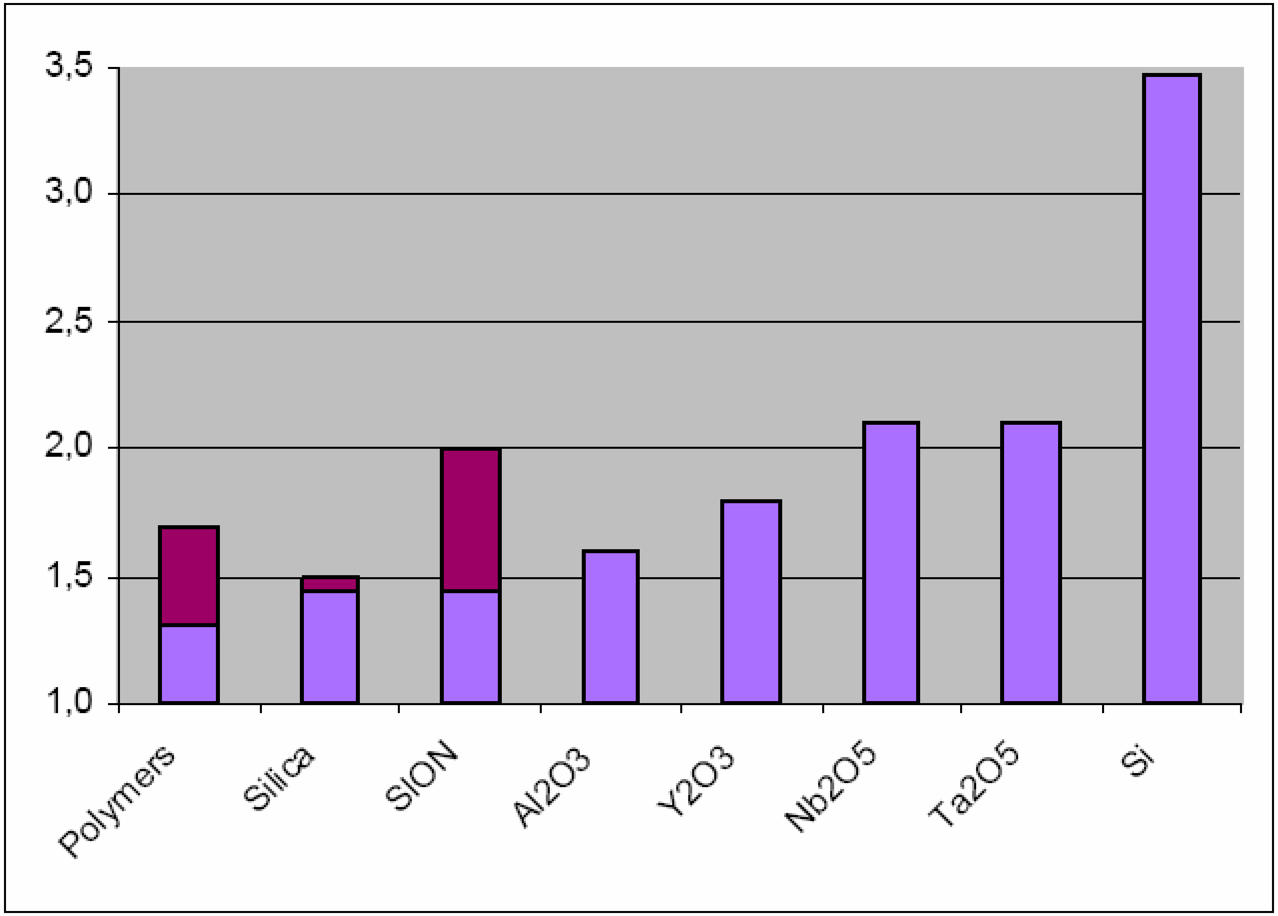
Examples of integrated waveguides



Refractive indexes of materials employed to build optical waveguides

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Characterization Methodologies of Optical Waveguides

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Characterization of Optical Waveguides

1. Geometrical Inspection → **SEM, DEKTEK,**

2. Refractive Index Measurements
    - 2.1 Reflectometry and Ellipsometry
    - 2.2 Surface Plasmon Resonance
    - 2.3 Prism Coupling
    - 2.4 M-Line Spectroscopy (MLS)

3. Coupling Techniques

4. Optical Losses

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Reflectometry and Ellipsometry

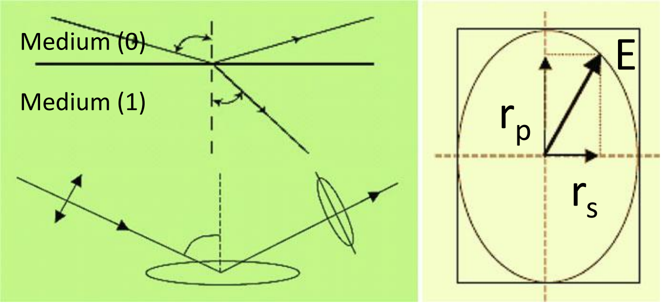
Refractive index (n) is a complex number comprising a real refractive index and an imaginary part: the absorption (or extinction) coefficient:

n= n’ – n”

The real part (n’)describes how the speed of light changes as it enters the material.
The extinction coefficient (n”) describes how light is absorbed .

The **fundamental equation of ellipsometry** can be expressed as :

$$\rho_e = \tan \Psi e^{\Delta}$$
$$\Psi = |R_p|/|R_s|$$



where Δ is the phase change between rp and rs upon reflection

Ψ is the angle whose tangent is the ratio of the intensity of the Rp and Rs components.

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Reflectometry and Ellipsometry

With these parameters, the complex refractive index of the sample (thin film of optical waveguide) can be calculated as:

$$\tilde{n}_1 = \frac{\left[\sqrt{1 - 4\sin^2(\theta_0)\tan(\Psi)e^{j\Delta} + 2\tan(\Psi)e^{j\Delta}\tan^2(\Psi)e^{j\Delta}}\right]\tilde{n}_0\sin(\theta_0)}{\cos(\theta_0)[1+\tan(\Psi)e^{j\Delta}]}$$

where n_0 is the complex reflective index of the ambient.
θ_0 is the angle of incidence.

The data from the ellipsometer are values of Ψ and Δ as a function of wavelength.

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Reflectometry and Ellipsometry

In the **reflectometry measurement**, the sample surface is illuminated with s- and p-polarized light.

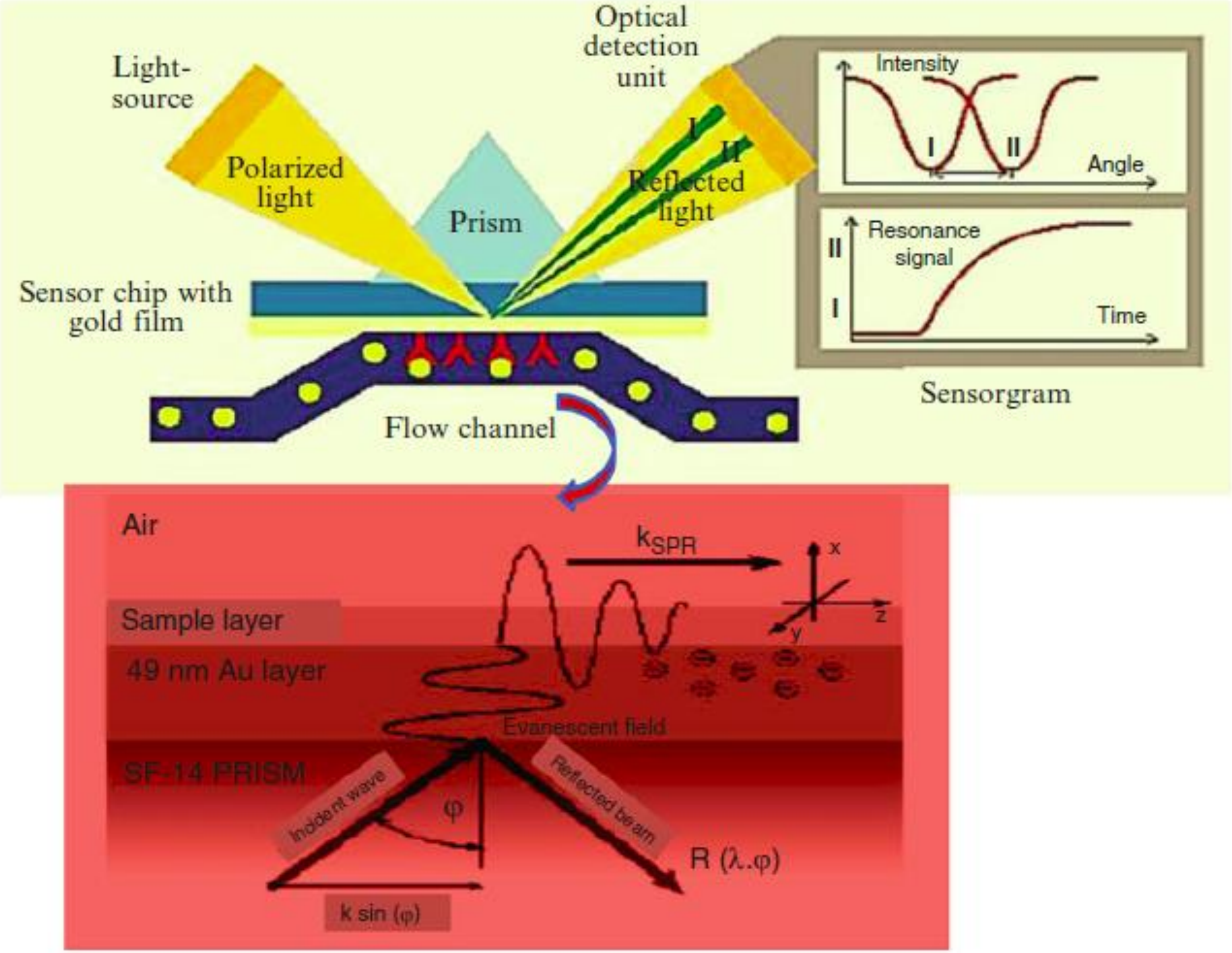
The reflected intensities Rp and Rs of the p and s polarized components are measured, and are used to calculate a refractive index using the form of the **Fresnel equations for a transparent substrate**:

$$n_{\mathrm{R}} = \sin\theta_{\mathrm{i}} \sqrt{1 + \left(\frac{1-\rho}{1+\rho}\right)^2 \tan^2\theta_{\mathrm{i}}}$$

$$\rho = \sqrt{R_{\mathrm{p}}/R_{\mathrm{s}}}$$

For the types of material that reflectometry is aimed at, the simplified measurement of refractive index generally works very well. However, if **the surface is rough**, the reflected light will be scattered over a range of angles making the analysis extremely difficult.

Surface Plasmon Resonance



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Surface Plasmon Resonance

$$k \sin \varphi = k_{\mathrm{SPR}}$$

$$k_0 n_{\mathrm{prism}} \sin \varphi_{\mathrm{i}} = k_0 \sqrt{\frac{\varepsilon_{\mathrm{Au}} n_{\mathrm{s}}^2}{\varepsilon_{\mathrm{Au}} + n_{\mathrm{s}}^2}}$$

where k_0 is wave vector of light in a vacuum, k_{SPR} is wave vector of the surface plasmon, ns is a refraction index of the dielectric film above the metal layer, εAu is a real part of the dielectric complex constant of the active plasmon layer (e.g., Au), nprism is a refraction index of the prism, and φi is an incident angle of light against the normal to the prism base.

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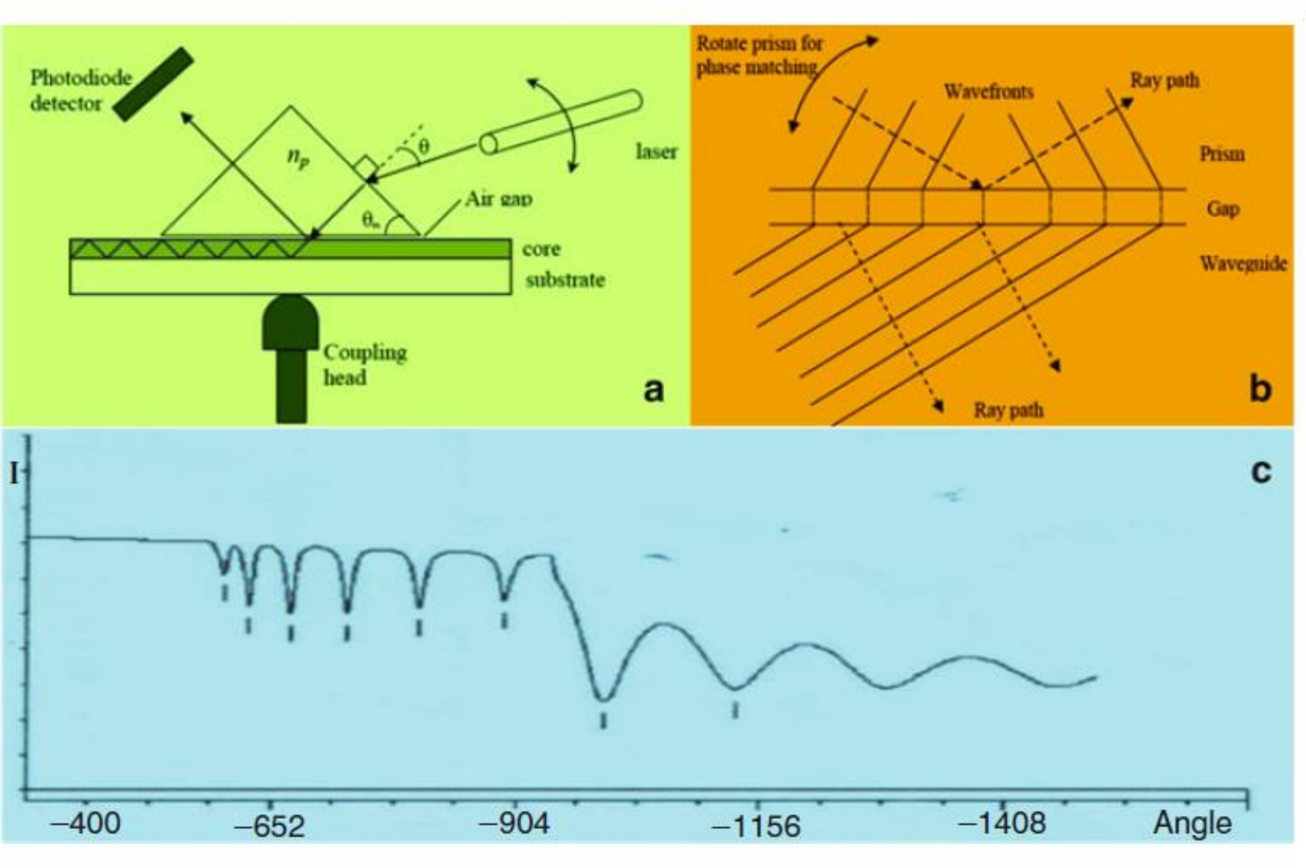
Prism Coupling



(a) Prism coupling assembly;
(b) phase-matching condition at prism–waveguide interface;
(c) rotation spectra against angle of incidence θ of the prism.

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Prism Coupling

$$n_{\mathrm{eff}(m)} = n_{\mathrm{p}} \sin\left(\theta_{\mathrm{p}} + \sin^{-1}\left(\frac{\sin\theta}{n_{\mathrm{p}}}\right)\right)$$

where np is the prism index, θp is the prism angle, and θ is the measured incident angle for mode m ¼ 0, 1, ...

The following factors limit the utilization of the prism coupling technique:

(a) The film must be thick enough to permit the propagation of at least two modes.

(b) The method is a contact method and it is necessary to press the film against the base of the prism. Extra care must be taken when measuring polymers. In general, the technique is non destructive.

(c) Alignment of small samples with the coupling spot requires a certain degree of skill and experience. Typically, the laser spot is collimated to approximately 1.0 mm^2 and this can be a challenge where the proton beam written samples are only about 2.0 mm^2 in size.

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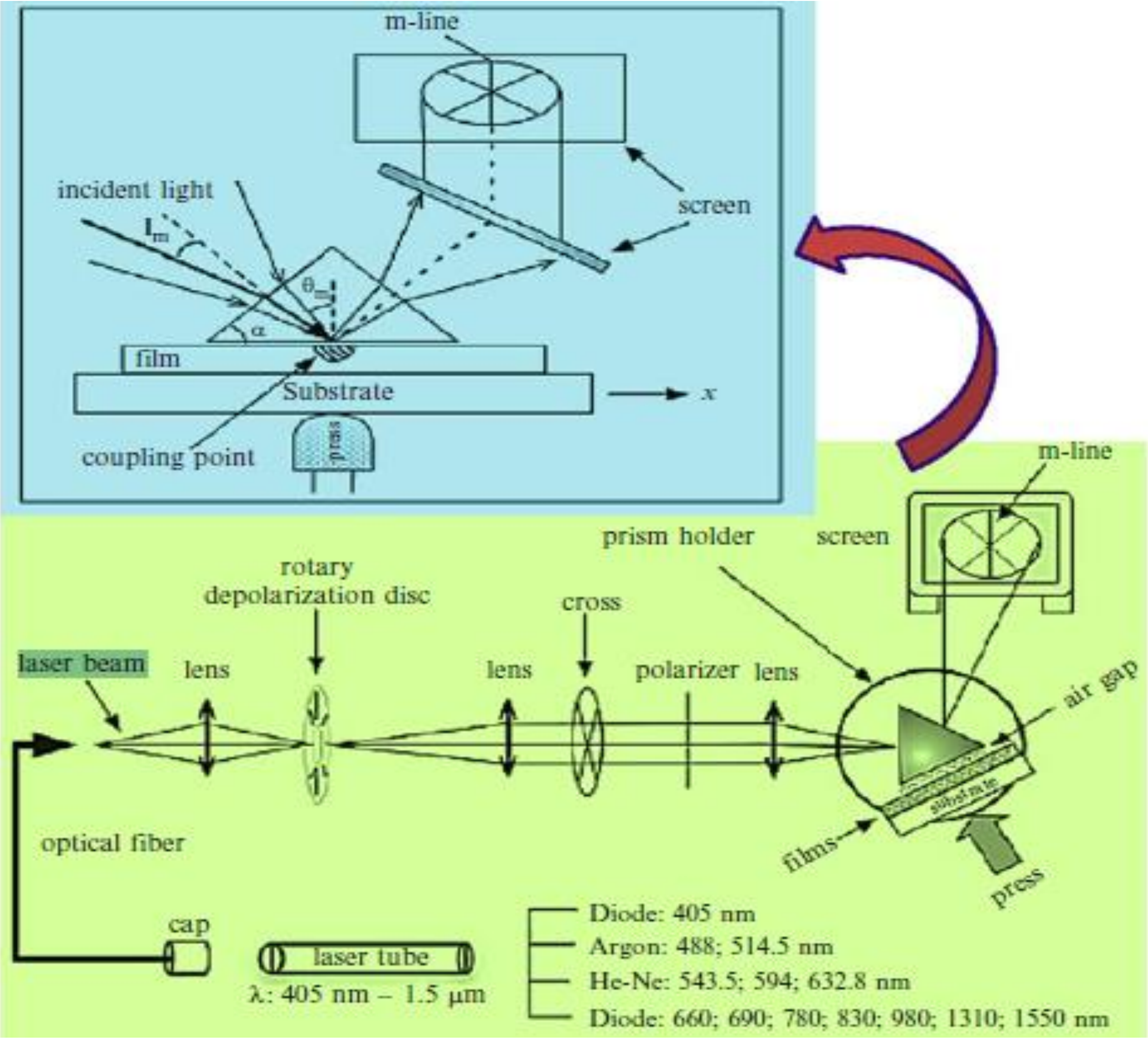
M-Line Spectroscopy (MLS)



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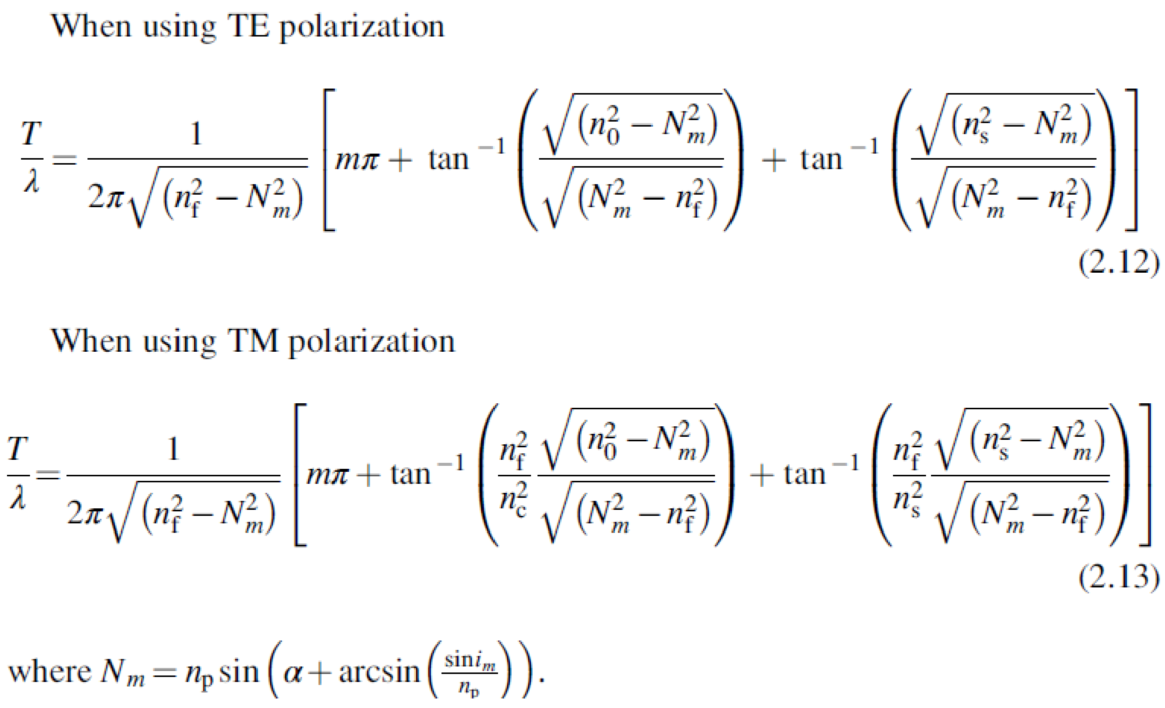
M-Line Spectroscopy (MLS)

The refractive index (**n_f**) and thickness (**T**) of the thin film can be calculated using **the step-index model:**



When using TE polarization

$$\frac{T}{\lambda}=\frac{1}{2\pi\sqrt{(n_\mathrm{f}^2-N_m^2)}}\left[m\pi+\tan^{-1}\left(\frac{\sqrt{(n_0^2-N_m^2)}}{\sqrt{(N_m^2-n_\mathrm{f}^2)}}\right)+\tan^{-1}\left(\frac{\sqrt{(n_\mathrm{s}^2-N_m^2)}}{\sqrt{(N_m^2-n_\mathrm{f}^2)}}\right)\right] \tag{2.12}$$

When using TM polarization

$$\frac{T}{\lambda}=\frac{1}{2\pi\sqrt{(n_\mathrm{f}^2-N_m^2)}}\left[m\pi+\tan^{-1}\left(\frac{n_\mathrm{f}^2}{n_\mathrm{c}^2}\frac{\sqrt{(n_0^2-N_m^2)}}{\sqrt{(N_m^2-n_\mathrm{f}^2)}}\right)+\tan^{-1}\left(\frac{n_\mathrm{f}^2}{n_\mathrm{s}^2}\frac{\sqrt{(n_\mathrm{s}^2-N_m^2)}}{\sqrt{(N_m^2-n_\mathrm{f}^2)}}\right)\right] \tag{2.13}$$

where $N_m=n_\mathrm{p}\sin\left(\alpha+\arcsin\left(\frac{\sin i_m}{n_\mathrm{p}}\right)\right)$.

If the agreement between experimental and calculated values of N_m is in the range of 0.001 or less, the step-index model is satisfied.

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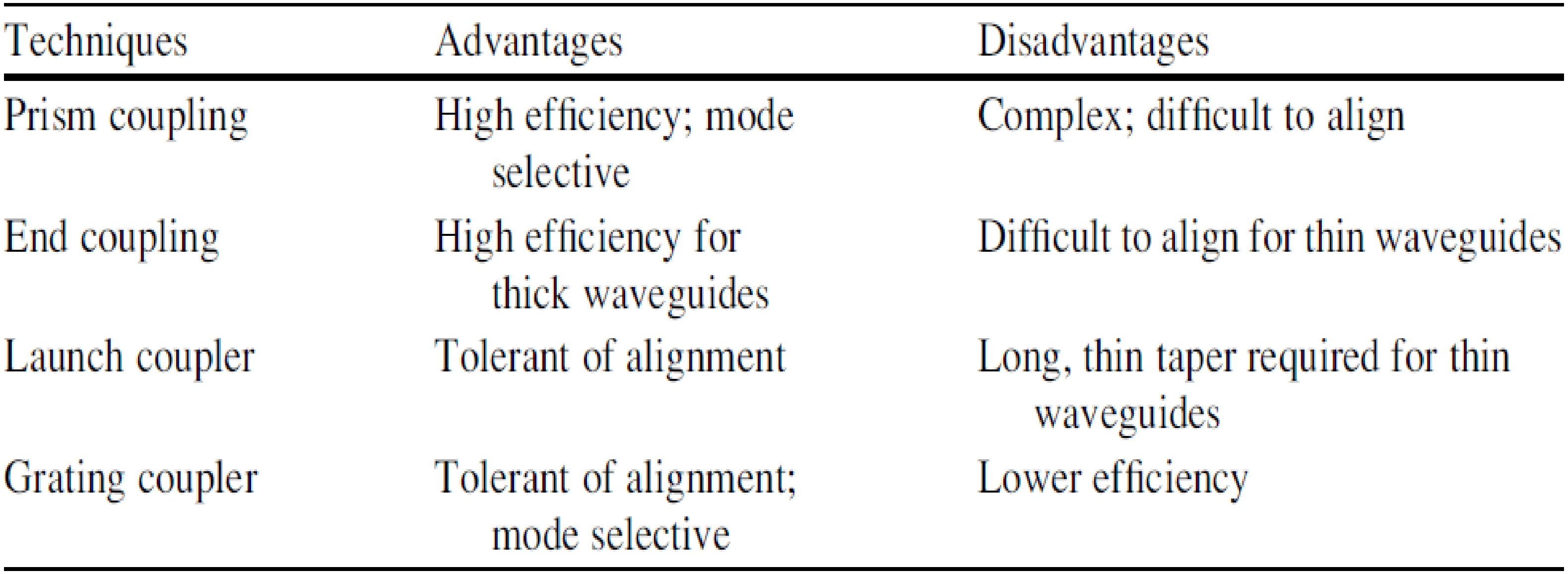
Coupling Techniques

For an integrated optical waveguide system, It is necessary to **find a technique to effectively confine and couple the laser beam with the waveguide**. Several techniques have been used , including **prism coupling**, **end coupling**, tapered and/or **lunch coupling**, and **grating coupling**.



Techniques	Advantages	Disadvantages
Prism coupling	High efficiency; mode selective	Complex; difficult to align
End coupling	High efficiency for thick waveguides	Difficult to align for thin waveguides
Launch coupler	Tolerant of alignment	Long, thin taper required for thin waveguides
Grating coupler	Tolerant of alignment; mode selective	Lower efficiency

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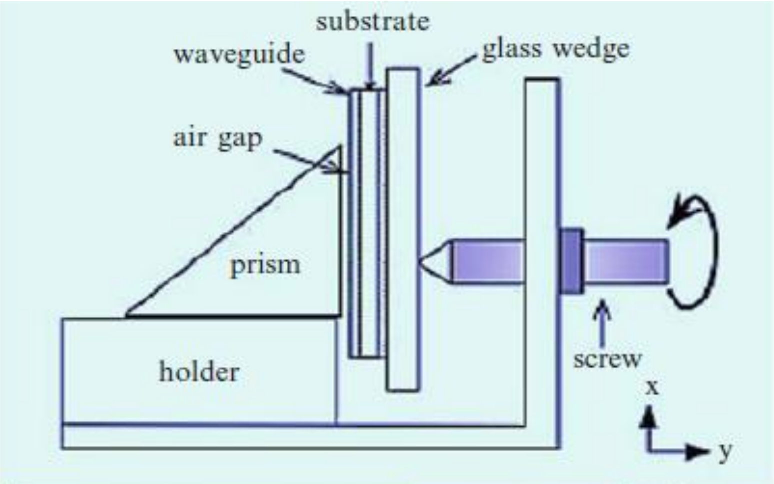
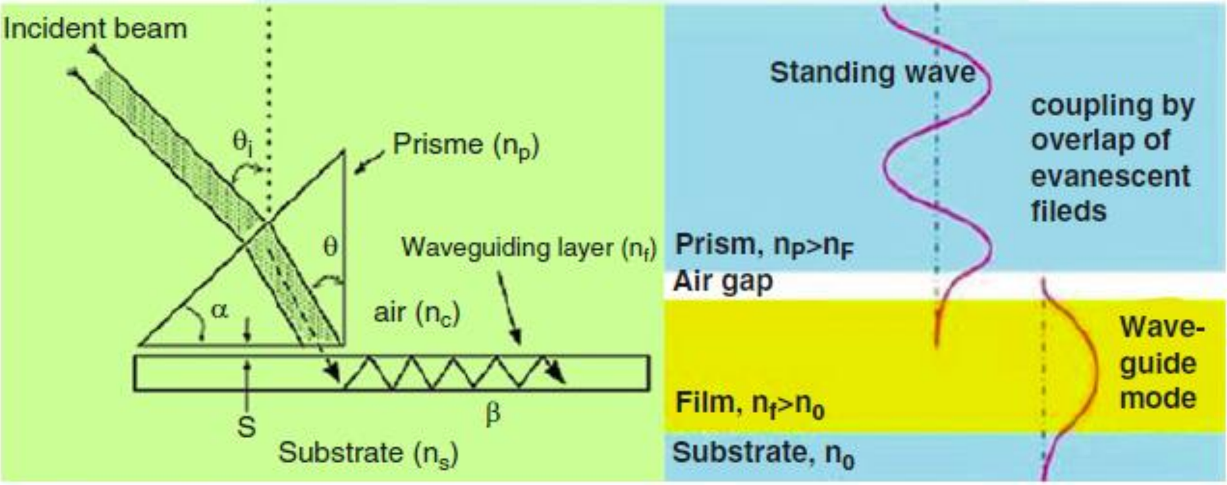
Prism Coupling Method





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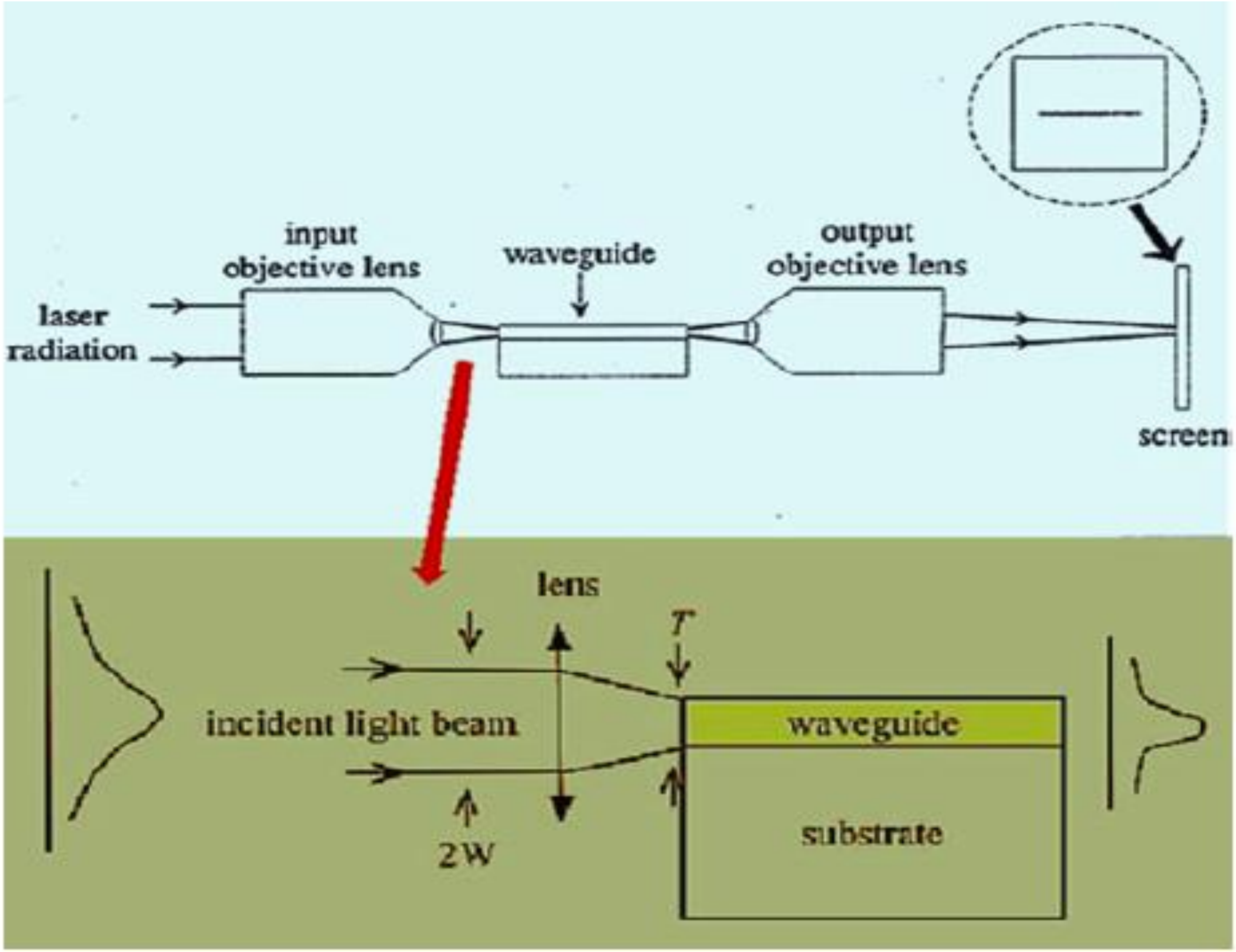
End-Coupling Method



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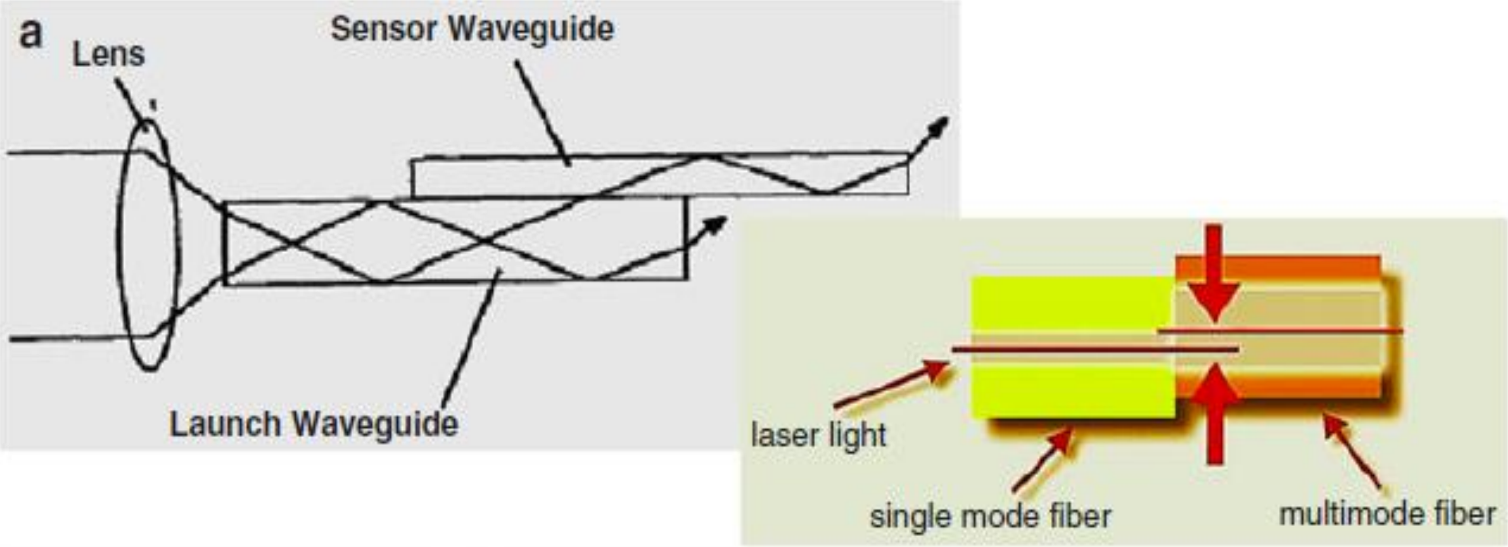
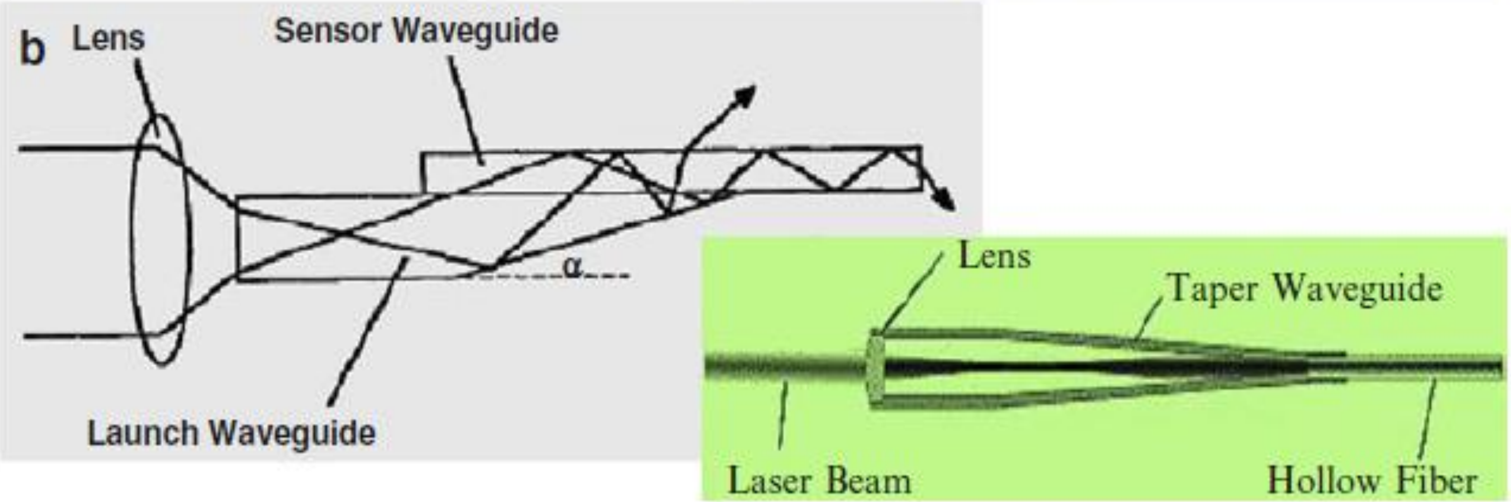
Lunch and Tapered-Coupling Method





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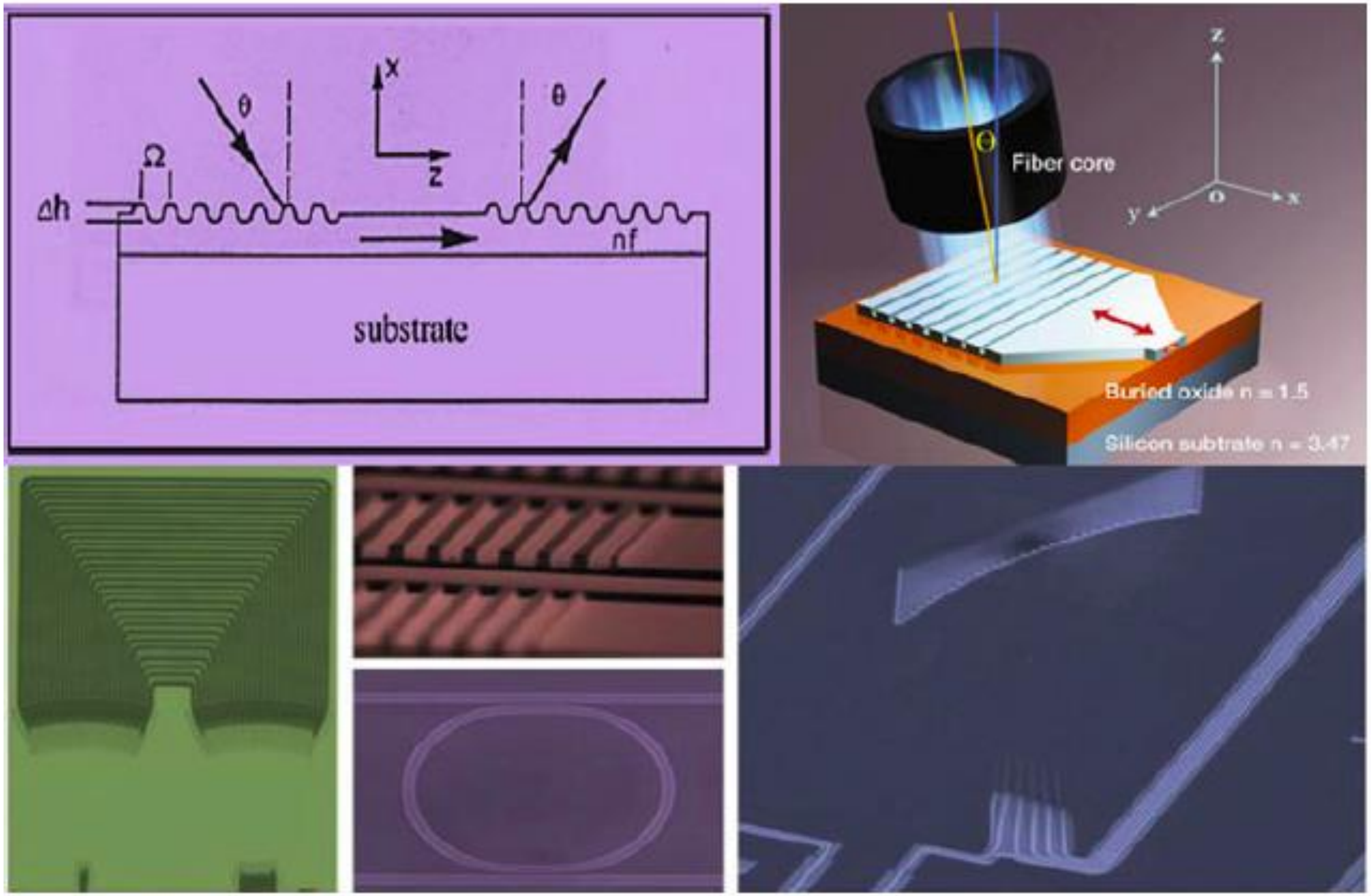
Grating Coupling Method



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Optical Loss

$$I(x) = I_0 10^{\left(-\frac{\alpha x}{10}\right)}$$

where I_0 is the initial power, $I(x)$ is the transmitted power through the waveguide at a distance x (cm), and α is defined as the attenuation coefficient of the waveguide, measured in decibels per centimeter (dB/cm). The loss, L in decibels (dB) is defined as:

$$L(\mathrm{dB}) = -10\log\left(\frac{I(x)}{I_0}\right)$$

Many factors are considered to disturb the light propagation and increase the propagation losses:

(a) Radiation losses due to the guided mode converse to the radiation mode.

(b) Mode conversion losses due to conversion from the excited mode to other guided modes

(c) Absorption losses due to light absorption in the waveguide materials.

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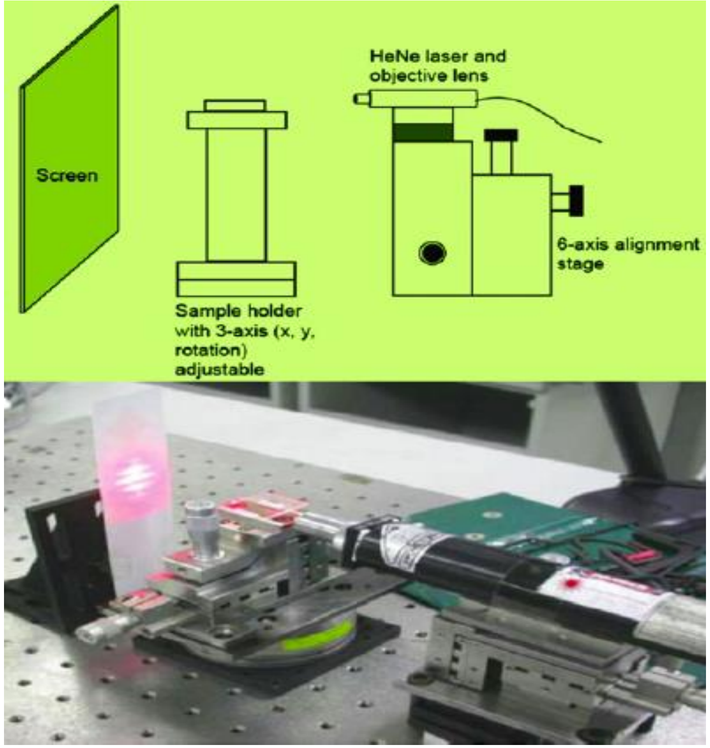
(d) Diffusion losses or scattering losses due to the imperfection of the waveguide structure.
(e) Tunneling losses that only occurs in barrier optical waveguides produced by ion modification

Measurement of Propagation Losses



Cutback Method

WAVEGUIDE DEVICES

- Passive components
  - ⋆ Y and X Junctions
  - ⋆ Grating-assisted Directional Couplers
  - ⋆ Mach–Zehnder Filters
  - ⋆ Multimode Interference Couplers
  - ⋆ Star Couplers
  - ⋆ Arrayed-waveguide Gratings
- Active components
  - ⋆ Semiconductor lasers and amplifiers
  - ⋆ Optical Modulators
  - ⋆ Photodetectors

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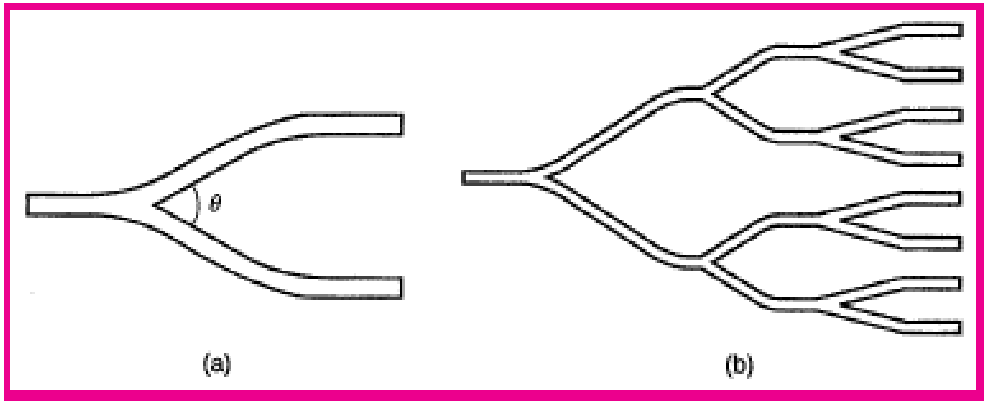
WAVEGUIDE DEVICES

Y Junctions



- A three-port device that acts as a power divider.
- Made by splitting a planar waveguide into two branches bifurcating at some angle θ.
- Similar to a fiber coupler except it has only three ports.
- Conceptually, it differs considerably from a fiber coupler.
- No coupling region exists in which modes of different waveguides overlap.

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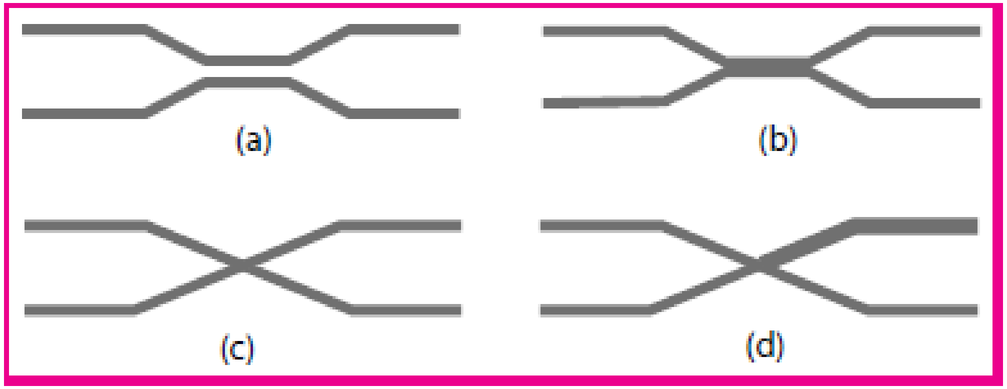
WAVEGUIDE DEVICES

Four-Port Couplers



- Spacing between waveguides reduced to zero in coupled Y junctions.
- Waveguides cross in the central region in a X coupler.
- In asymmetric X couplers, two input waveguides are identical but output waveguides have different sizes.
- Power splitting depends on relative phase between two inputs.
- If inputs are equal and in phase, power is transferred to wider core; when inputs are out of phase, power is transferred to narrow core.

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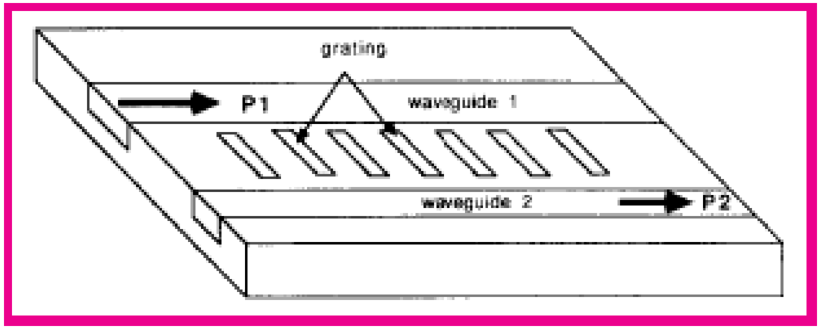
WAVEGUIDE DEVICES

Grating-Assisted Directional Couplers



- An asymmetric directional coupler with a built-in grating.
- Little power will be transferred in the absence of grating.
- Grating helps to match propagation constants and induces power transfer for specific input wavelengths.
- Grating period $\Lambda = 2\pi/|\beta_1 - \beta_2|$.
- Typically, $\Lambda \sim 10\ \mu$m (a long-period grating).
- A short-period grating used if light is launched in opposite directions.

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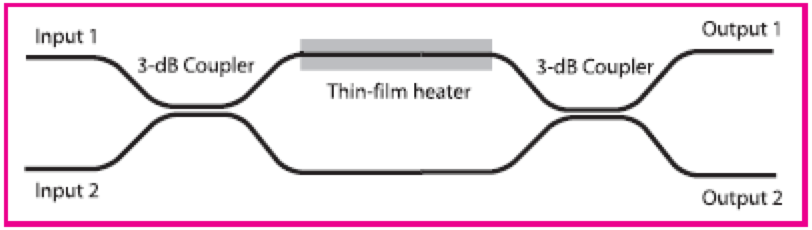
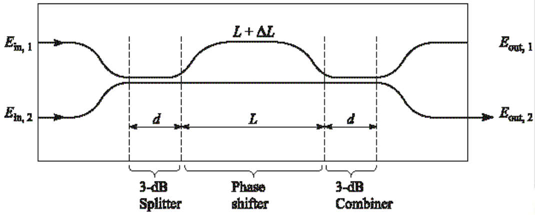
Mach–Zehnder Switches

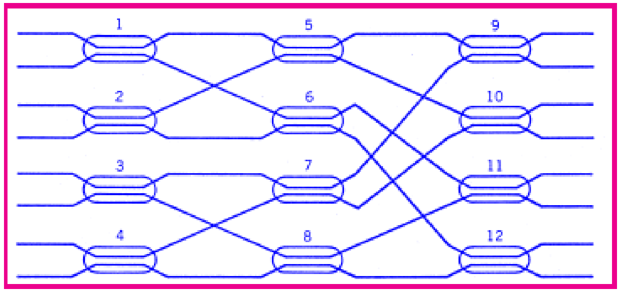


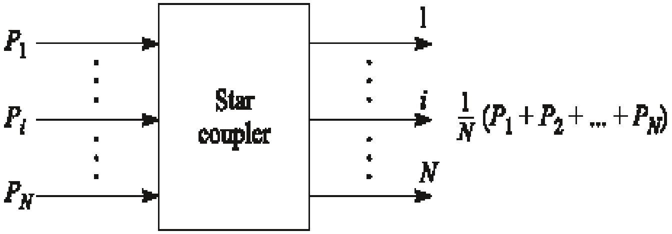


- Two arm lengths equal in a symmetric MZ interferometer.
- Such a device transfers its input power to the cross port.
- Output can be switched to bar port by inducing a π phase shift in one arm.
- Phase shift can be induced electrically using a thin-film heater (a thin layer of chromium).
- Thermo-optic effect is relatively slow.
- Much faster switching using electro-optic effect in $LiNbO_3$.

WAVEGUIDE DEVICES

Star Couplers





- Some applications make use of $N \times N$ couplers designed with N input and N output ports.
- Such couplers are known as star couplers.
- They can be made by combining multiple 3-dB couplers.
- A 8×8 star coupler requires twelve 3-dB couplers.
- Device design becomes too cumbersome for larger ports.

- **Can be wavelength selective/nonselective**
- **Up to N =M = 64, typically N, M < 10**

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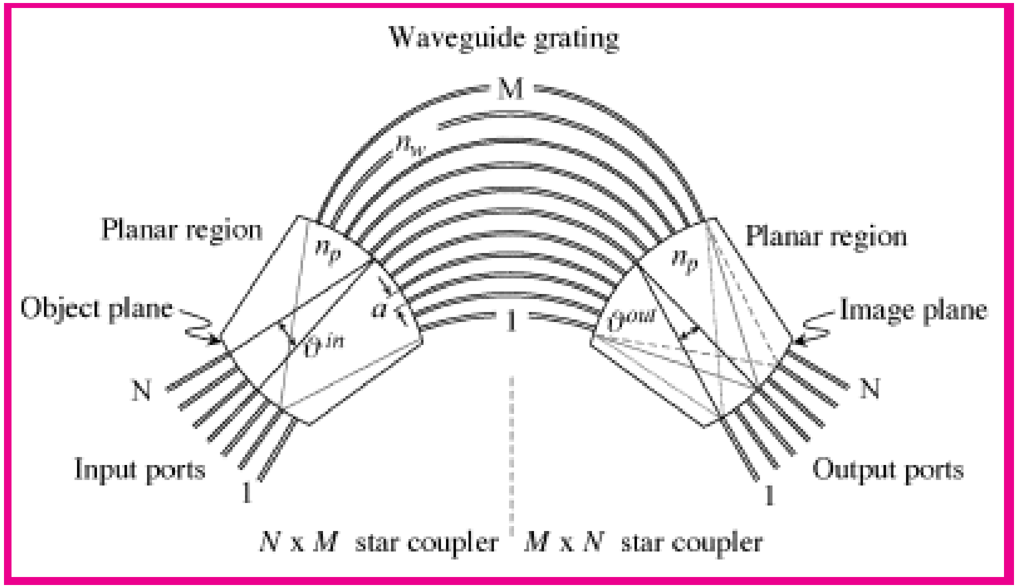
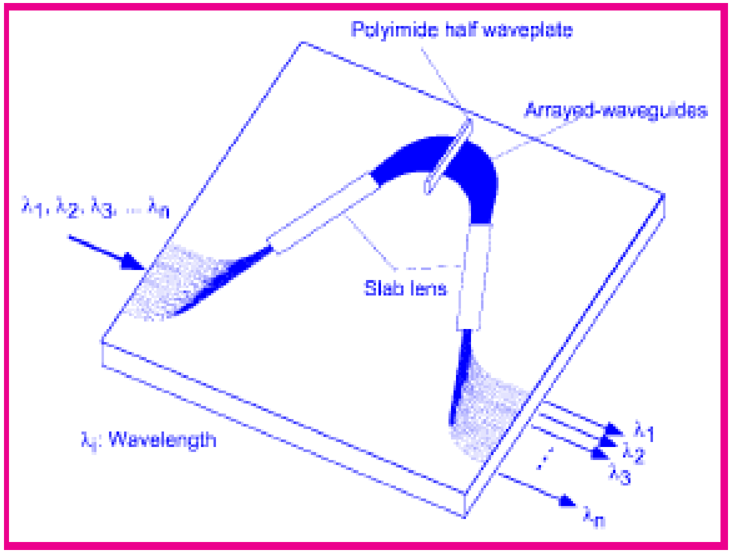
Arrayed-Waveguide Gratings



- AWG combines two $N \times M$ star couplers through an array of M curved waveguides.
- Length difference between neighboring waveguides is constant.
- Constant phase difference between neighboring waveguides produces grating-like behavior.

WAVEGUIDE DEVICES

Fabrication of AWGs



- AWGs are fabricated with silica-on-silicon technology.
- Half-wave plate helps to correct for birefringence effects.
- By 2001, 400-channel AWGs were fabricated .
- Such a device requiring fabrication of hundreds of waveguides on the same substrate.

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WAVEGUIDE DEVICES

Semiconductor Lasers and Amplifiers

- Semiconductor waveguides useful for making lasers operating in the wavelength range 400–1600 nm.
- Semiconductor lasers offer many advantages.
  - ⋆ Compact size, high efficiency, good reliability.
  - ⋆ Emissive area compatible with fibers.
  - ⋆ Electrical pumping at modest current levels.
  - ⋆ Output can be modulated at high frequencies.
- First demonstration of semiconductor lasers in 1962.
- Room-temperature operation first realized in 1970.
- Used in laser printers, CD and DVD players, and telecommunication systems.

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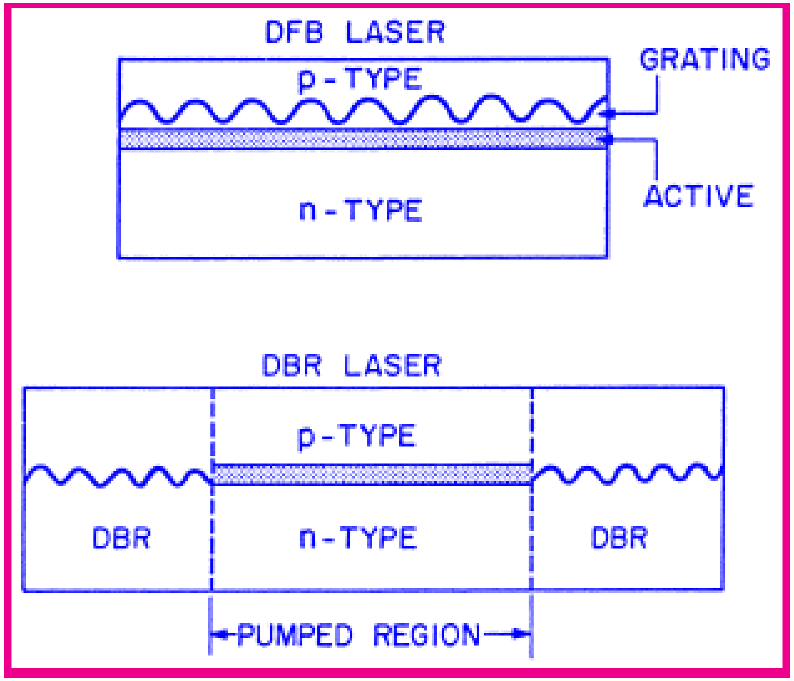
WAVEGUIDE DEVICES

Distributed Feedback Lasers



- Feedback is distributed throughout cavity length in DFB lasers.
- This is achieved through an internal built-in grating
- Bragg condition satisfied for $\lambda = 2\bar{n}\Lambda$.