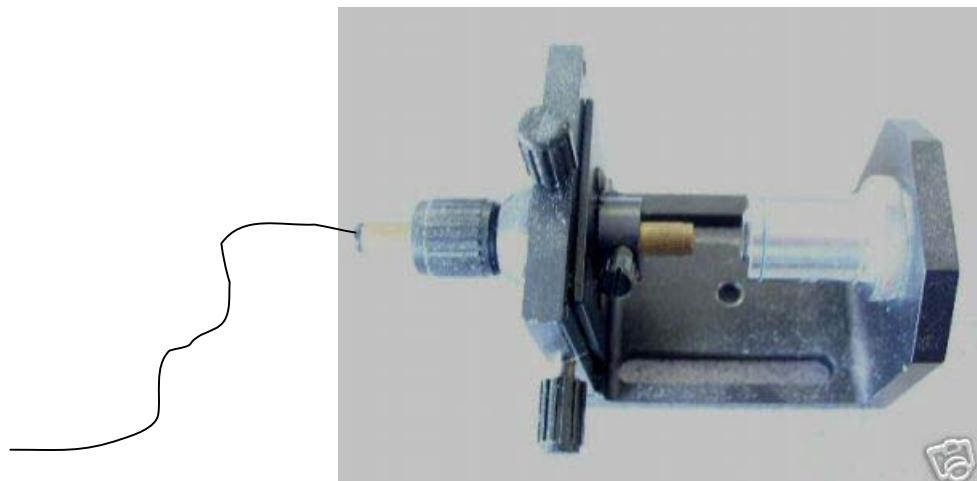


Collimation & Termination

Wei-Chih Wang

Southern Taiwan University of
Technology

Fiber Direct Focusing



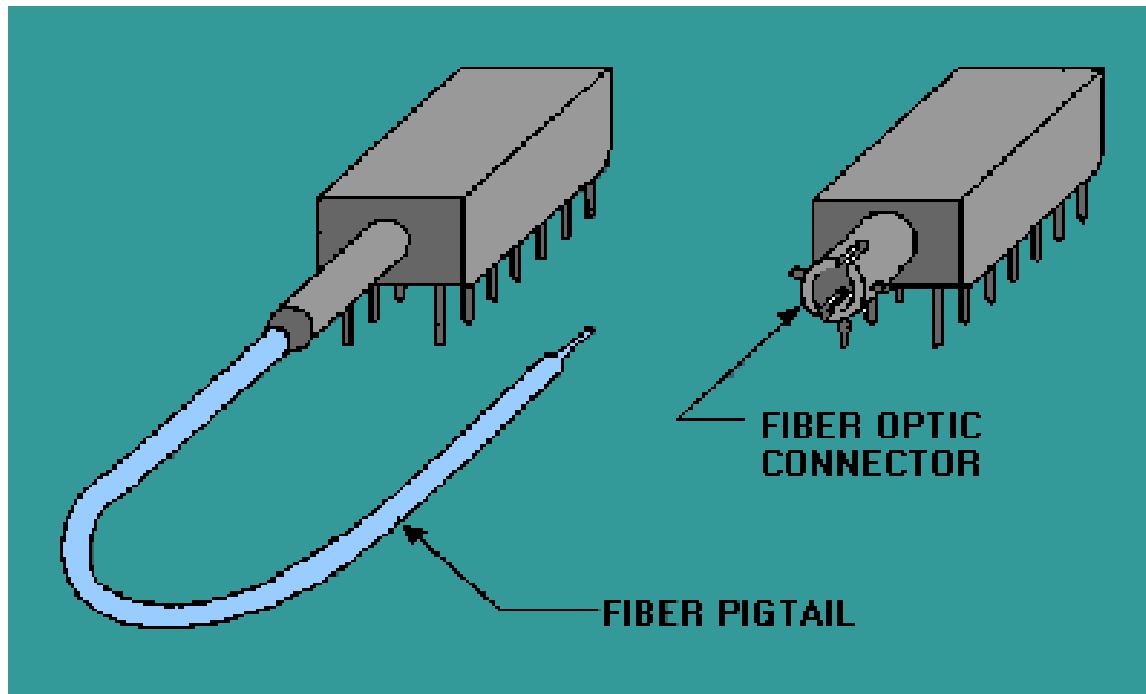
fiber

X-Y
stage

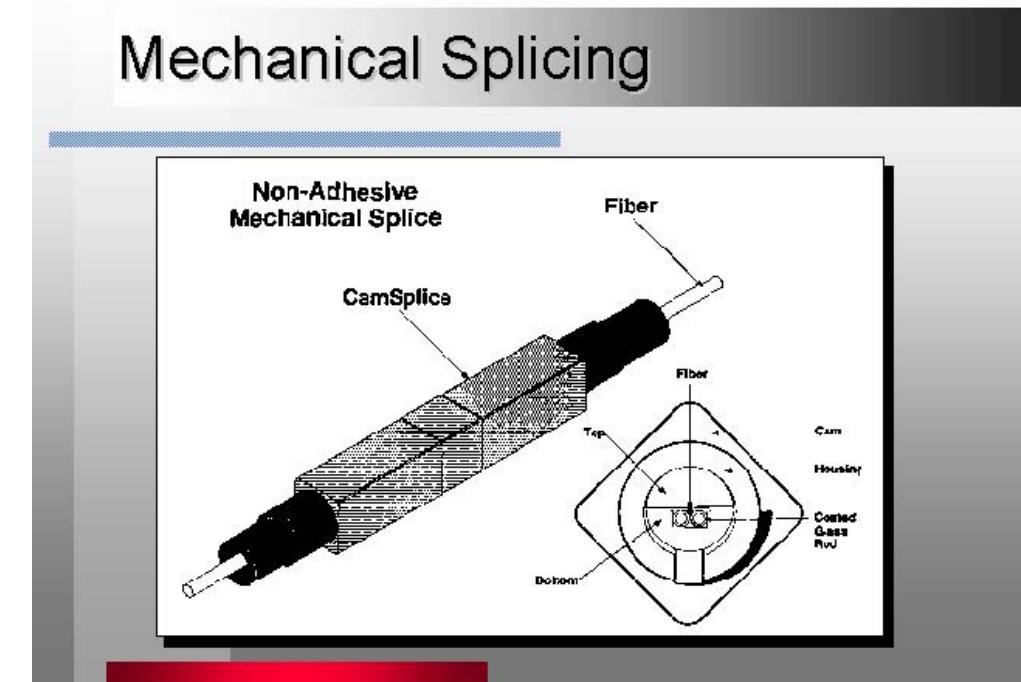
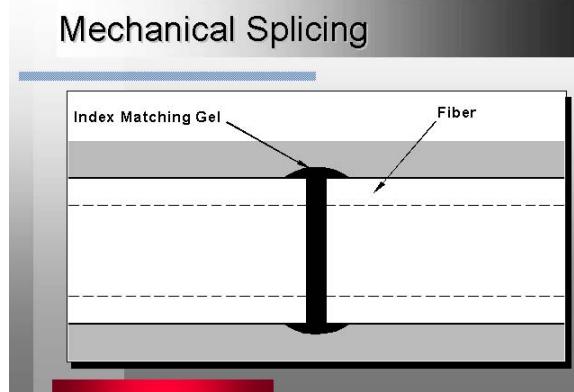
lens

Bare fiber coupling

Pigtailed and connectorized fiber optic devices



Mechanical Splicing



Mechanical coupler



SMA Fiber Optic Coupler

Fiber connector types

Biconic Connector

A single fiber connector, body has a cone shaped tip, and a threaded barrel for securing to the coupler. Ferrule can be either ceramic or stainless steel.

Generally heat cured. Mainly found on older electronic equipment and infrastructure. Generally considered a high loss connector.



ST Connector

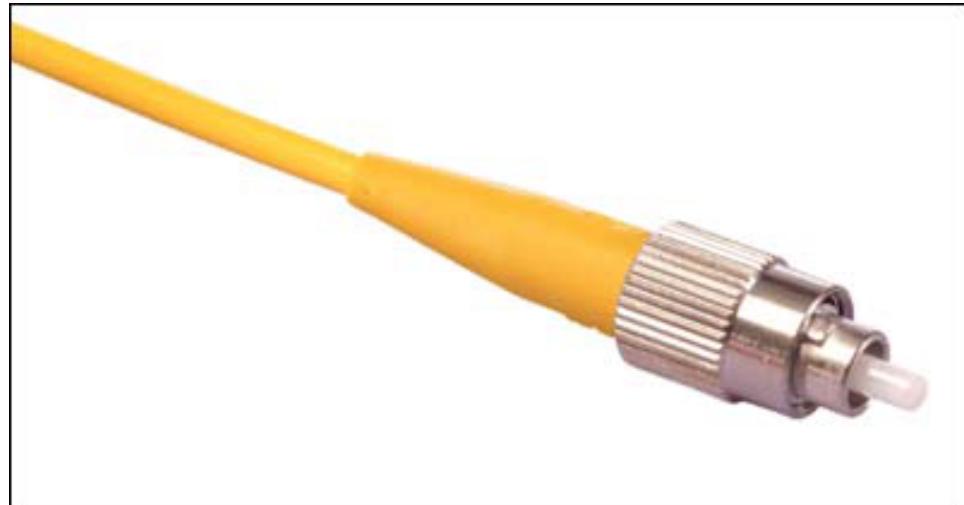
A single fiber connector with either composite or ceramic bayonet style ferrules (2.5mm). Connector body is molded plastic using a twist-lock latching mechanism.

This style of connector is found in many applications, one of the first truly universal connector. Also used in APC (angled) applications.



FC Connector

A single fiber connector with a standard (2.5mm) ceramic ferrule. Connector body can be metal and or plastic molded, and the threaded keyed barrel ensures reliable coupling. This is a good style for high vibration environments. Also a popular APC (angled) style. Found in telecommunication equipment and CCTV & CATV applications.

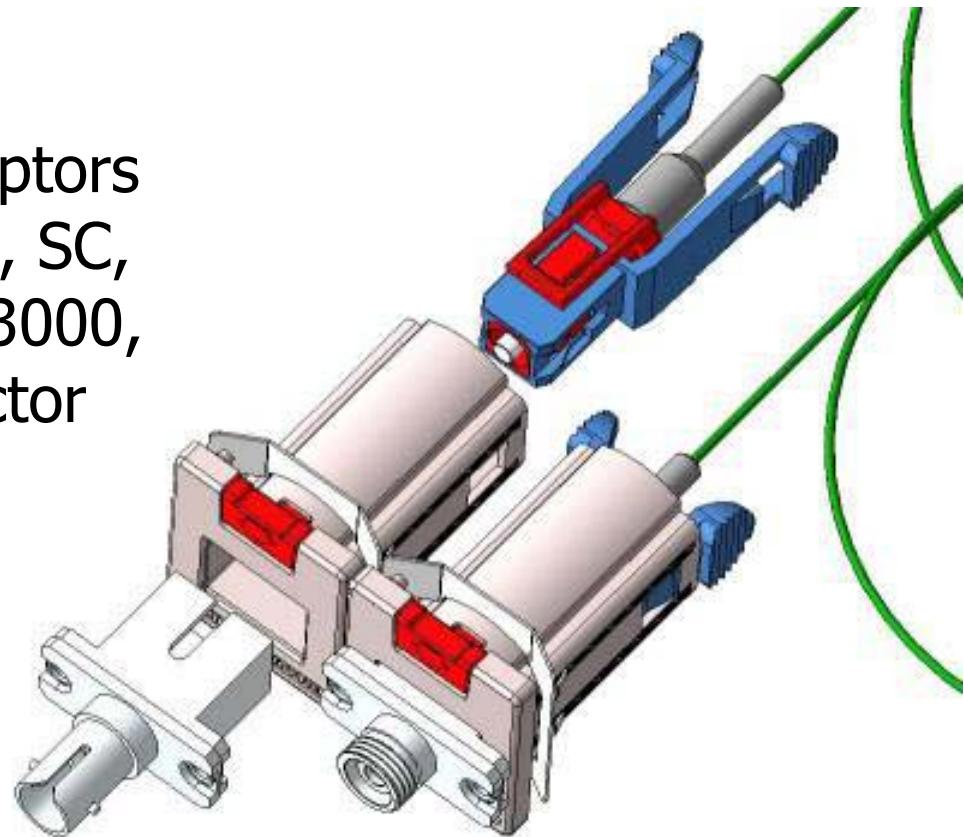


Photonic crystal fiber coupler

- Fiber couplers made with photonic crystal fibers (PCF). Two types of PCF were fabricated by means of stacking a group of silica tubes around a silica rod and drawing them. The fiber couplers were made by use of the fused biconical tapered method. With a fiber that had five hexagonally stacked layers of air holes, a 3367 coupling ratio was obtained, and with a one-layer four-hole fiber, a 4852 coupling ratio was obtained.

Interchangeable connector

Hybrid SC connector adaptors are available for: MU, FC, SC, ST, LSA (DIN47256), F3000, E2000, LC optical connector types.



Kingfish international

Waveguide Coupling

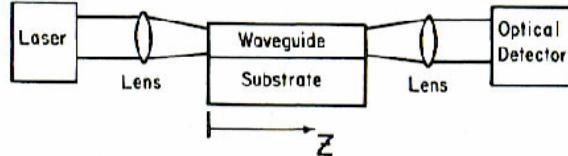
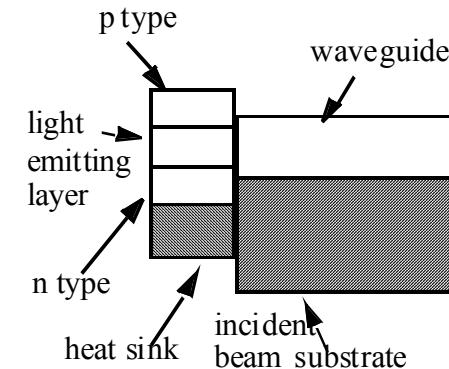
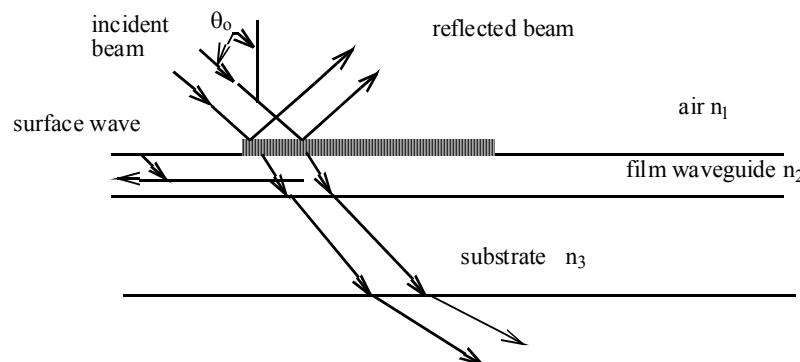


Fig. 6.7. Experimental set-up for measurement of waveguide attenuation employing end-fire coupling

Direct Focusing

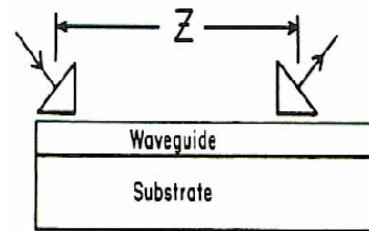


End-Butt Coupling



Grating Coupler

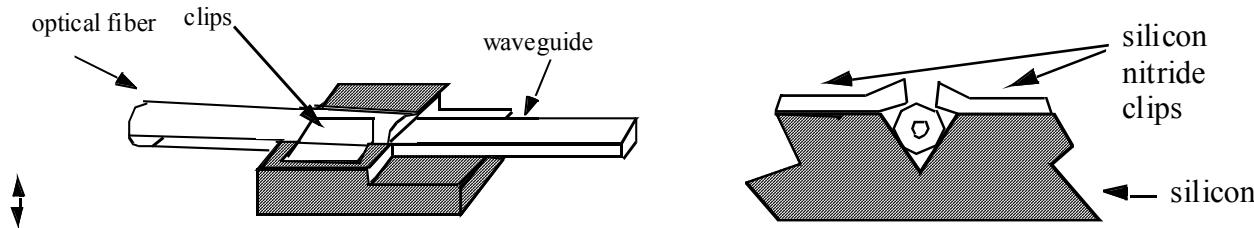
w. wang



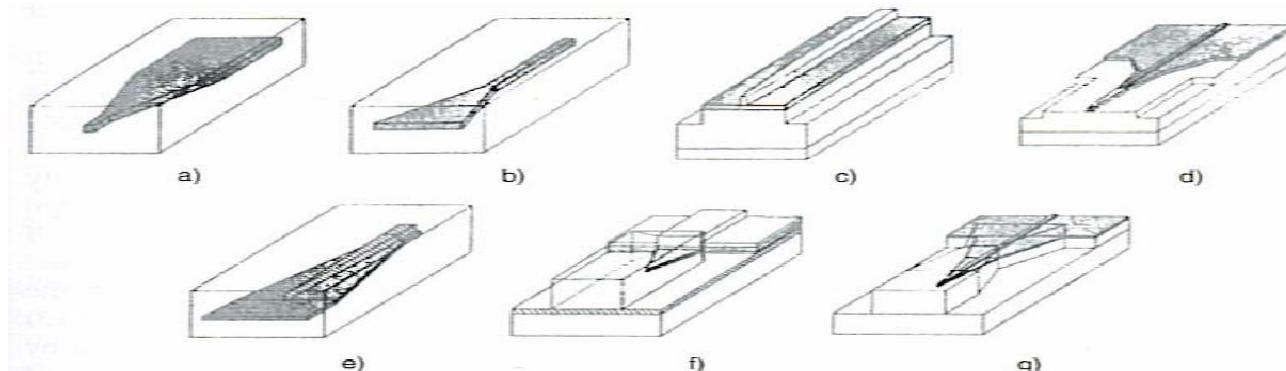
Prism Coupler

Fig. 6.9. Experimental set up for measurement of waveguide attenuation employing prism coupling

Fiber/waveguide to Waveguide Coupling



V-groove with clip connection



Tapered Mode Size Converters

General Definitions



Coupling efficiency to the m -th mode

$$\eta_m = \frac{P_m}{P_{in}}$$

Coupling loss (dB)

$$\mathcal{L} = 10 \log \frac{P_{in}}{P_m}$$

Direct Focusing

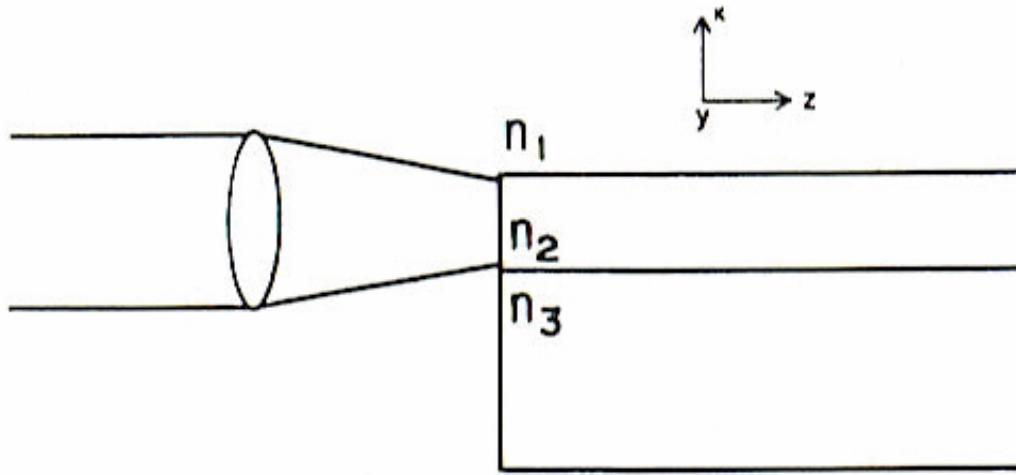


Fig. 7.1. The transverse coupling method, which is sometimes referred to as *end-fire* coupling

$$\gamma_m = \frac{\left| \iint A(x, y) B_m^*(x, y) dx dy \right|^2}{\int |A(x, y)|^2 dx dy \int |B(x, y)|^2 dx dy}$$

$A(x, y)$: Field distribution of the incident beam

$B_m(x, y)$: Field distribution of the m - th mode

Review on Gaussian Beam

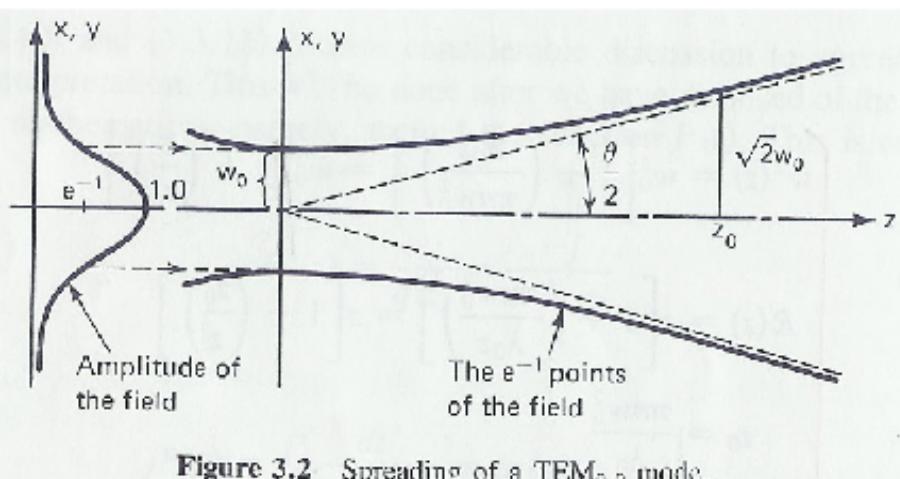


Figure 3.2 Spreading of a $\text{TEM}_{0,0}$ mode.

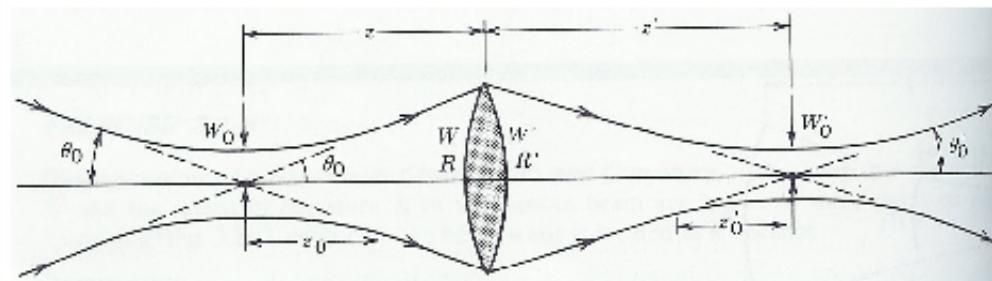


Figure 3.2-1 Transmission of a Gaussian beam through a thin lens.

$$A(r) = A_0 \frac{W_0}{W(z)} \exp \left[-\frac{x^2 + y^2}{W^2(z)} \right]$$

Amplitude factor

$$W(z) = W_0 \sqrt{1 + \left(\frac{z}{z_0} \right)^2}$$

Beam radius

$$x \exp \left\{ -j \left[kz - \tan^{-1} \left(\frac{z}{z_0} \right) \right] \right\}$$

Longitudinal phase

$$R(z) = z \left[1 + \left(\frac{z_0}{z} \right)^2 \right]$$

$$x \exp \left[-j \frac{k(x^2 + y^2)}{2R(z)} \right]$$

Radial phase

$$z_0 = \frac{\pi W_0^2}{\lambda}$$

End-Butt Coupling

Approximation: (assuming all waveguide modes are well confined, and $t_g < t_L$)

$$\eta_m = \frac{64}{(m+1)^2 \pi^2} \frac{n_L n_g}{(n_L + n_g)^2} \cos^2\left(\frac{\pi t_g}{2t_L}\right) \frac{1}{\left[1 - \left(\frac{t_g}{(m-1)t_L}\right)^2\right]^2} \frac{t_g}{t_L} \cos^2\left(\frac{m\pi}{2}\right)$$

↑
normalization reflection ↑
↑
Area mismatch
Overlap integral

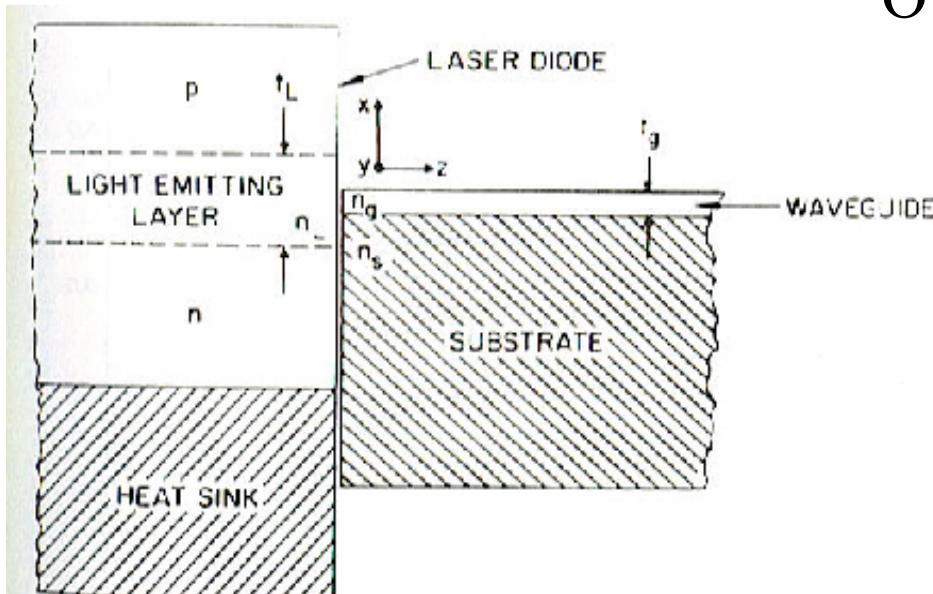


Fig. 7.2. Parallel end-butt coupling of a laser diode and thin-film waveguide

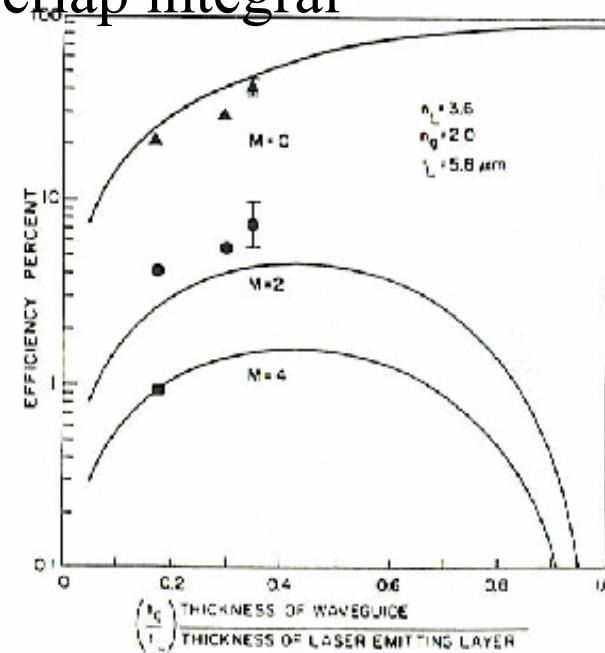


Fig. 7.3. Comparison of experimental coupling efficiency data with theoretical curves as a function of waveguide thickness [7.2]

Misalignment Effect

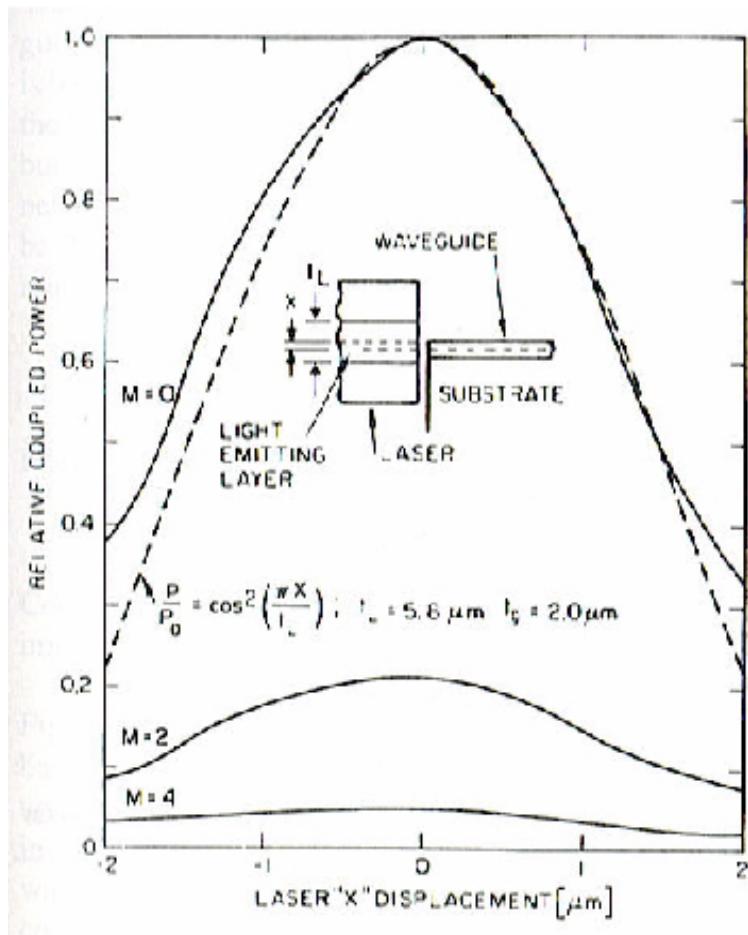


Fig. 7.4. Comparison of experimental coupling efficiency data (solid line) with theoretical curve (dashed) as a function of lateral misalignment of laser and waveguide [7.2]

$$\frac{P}{P_0} = \cos^2 \left[\frac{\pi X}{t_L} \right] \quad \text{for } t_g < t_L, \quad X < \frac{t_L - t_g}{2}$$

W. wang

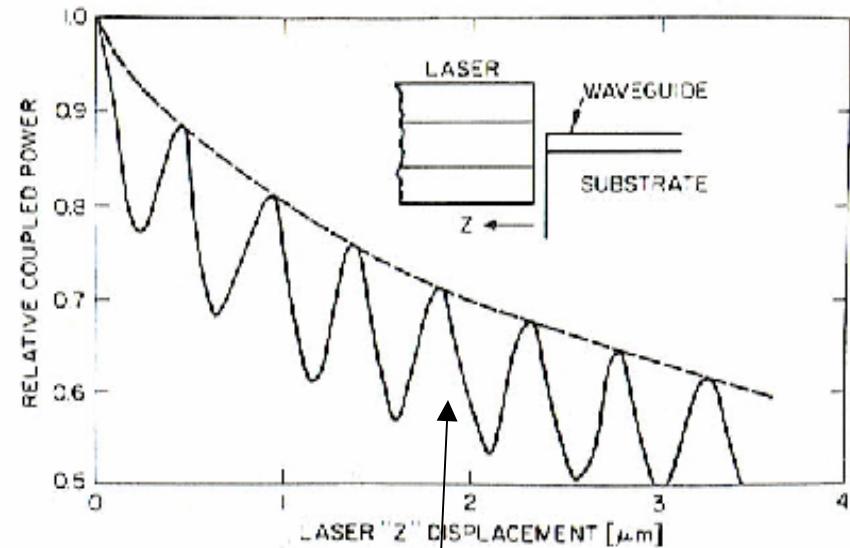


Fig. 7.5. Experimentally measured dependence of coupling efficiency on spacing between laser and waveguide [7.2]

Interference created
By waveguide and
Fiber surfaces

X = misalignment

End-butting Method

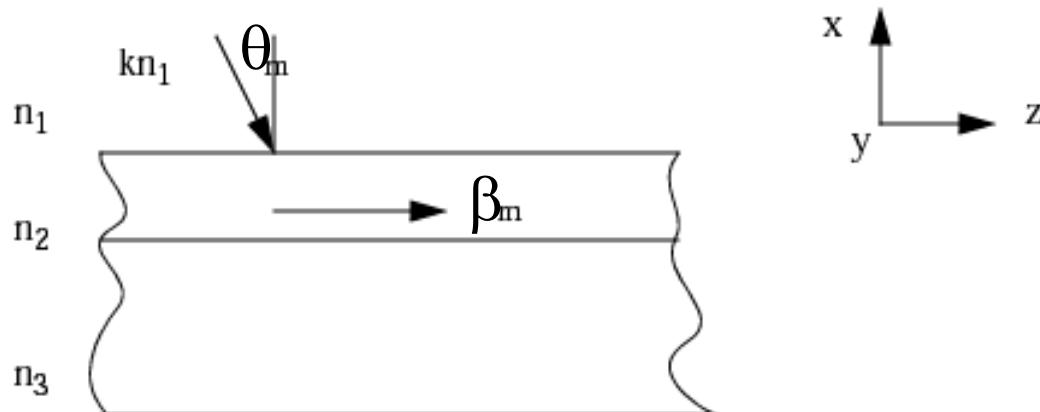
1. practical in case of coupling a waveguide to a semiconductor laser or to another waveguide such as the end of a commercial optical fiber.
2. Efficiently coupling an uncollimated divergent laser beam (10 to 20°) emitted from a semiconductor laser, which is difficult to achieved using either prism, grating, or tapered film couplers.

High efficient coupling is achieved by making the thickness of the waveguide approximately equal to that of the light emitting layer of the laser and aligned as shown in Figure 13a (A. Yariv, *IEEE J. QE-9*, 919 (1973)), and also by the fact that the field distribution of the fundamental lasing mode is matched to the TE_0 waveguide mode. The efficiency can be further improve if indices of the laser emitting layer and waveguide are close and the ratio of the thickness of waveguide to the laser emitting layer is small. To eliminate any oscillatory shape of output due to the Fabry-Perot etalon formed by the plane parallel faces of the laser and waveguide (when separation between them are less than a wavelength), epoxy of the matching index between the laser and waveguide must be used. This method is useful if an unpackaged laser diode is used.

Prism Coupler

One of the ways to couple light into the waveguide is to utilize a prism.

The prism coupler allows light to be coupled at an oblique angle. For this to happen, the components of phase velocities of the waves in the z direction be the same in both the waveguide and the incident beam



Thus, a phase-matching condition must be satisfied in z direction, which requires

$$\beta_m = kn_1 \sin \theta_m = \frac{2\pi}{\lambda_o} n_1 \sin \theta_m$$

However, we know for a waveguided mode, $\beta_m > kn_1$, this leads to the result that $\sin \theta_m > 1$.

One solution to the problem of phase matching is to use a prism.

Prism Coupler

If prism spacing is small enough so that tail of waveguide modes overlap the tail of the prism mode, there is a coherent coupling of energy from prism mode to the m th waveguide mode when θ_m is chosen so that $\beta_p = \beta_m$ (phase matching condition based on E field is continuous). The condition for matching of the β terms is given by

$$\beta_p = \frac{2\pi}{\lambda_o} n_p \sin \theta_m = \beta_m$$

a single prism can be used to couple to many different modes by merely changing the angle of incidence of the optical beam.

The modes in the waveguide are only weakly coupled to the mode in the prism. Hence, negligible perturbation of the basic mode shapes occurs. Of course, the condition

$$\theta_m > \theta_c = \arcsin \frac{n_1}{n_p}$$

must be satisfied if total internal reflection is to occur in the prism, where θ_c is the critical angle.

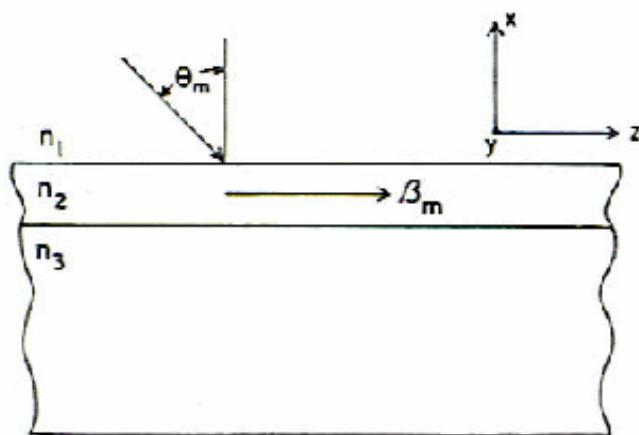


Fig. 7.6. Diagram of an attempt to obliquely couple light into a waveguide through its surface

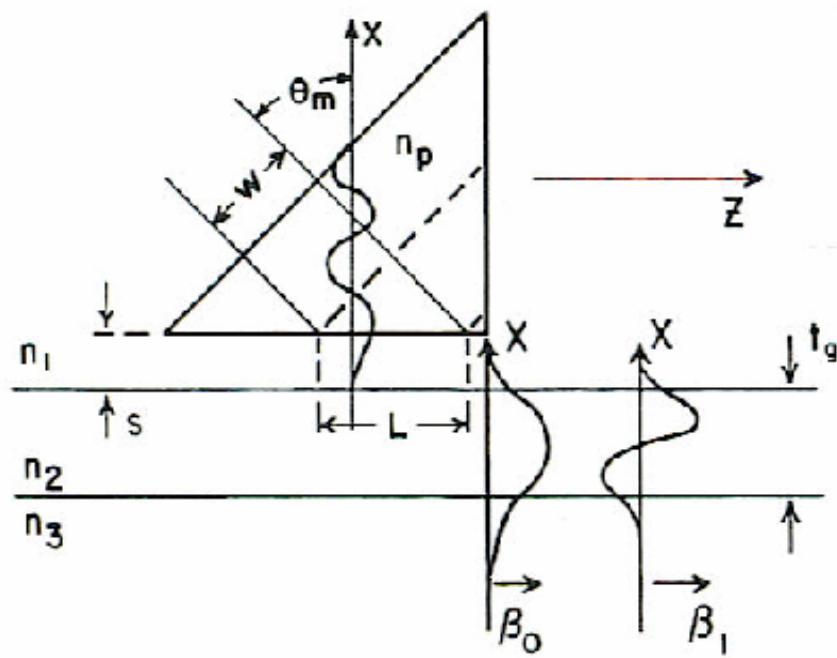
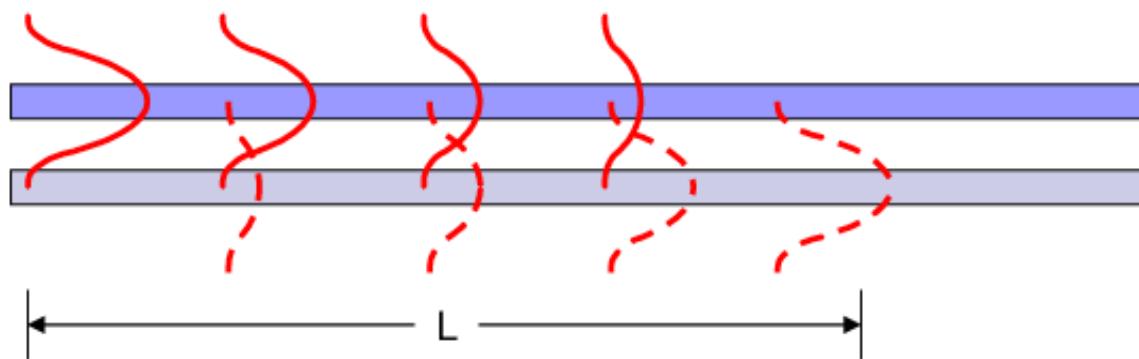


Fig. 7.7. Diagram of a prism coupler. The electric field distributions of the prism mode and the $m = 0$ and $m = 1$ waveguide modes in the x direction are shown

Coupled-Mode Theory



$$\kappa L = \frac{\pi}{2}$$

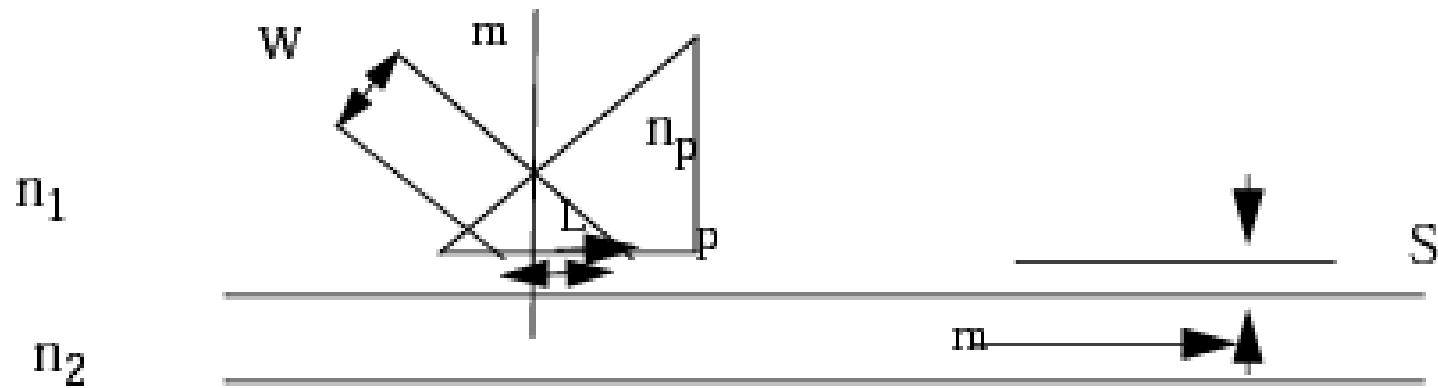
κ : Coupling efficient (overlap integral
between the prism mode and the waveguide mode)

$$L = \frac{W}{\cos \theta_m} = \frac{\pi}{2\kappa}$$

For a given L , the coupling coefficient required for complete coupling:

$$\kappa_{\text{w. wan}} = \frac{\pi \cos \theta_m}{2W}$$

This condition for complete coupling assumes that the amplitude of the electric field is uniform over the entire width W of the beam. In practical case this is never true. Also the trailing edge of the beam must exactly intersect the right-angle corner of the prism. If the beam intersects too far to the right, some of the incident power will be either reflected or transmitted directly into the waveguide and will not enter the prism mode. If the beam is incident too far to the left, some of the power coupled into the waveguide will be coupled back out into the prism.



Why prism coupler?

The advantage of prism coupler is that it can be used as an input and output coupling devices.

If more than one mode is propagating in the guide, light is coupled in and out at specific angles corresponding to each mode.

If a gas laser is used, the best method for coupling is using either prism or grating coupler

Disadvantage is that mechanical pressure must be applied to prism during each measurement so that spacing between prism and waveguide remains constant to get consistent coupling coefficient.

Other disadvantage is prism coupler index must be greater than the waveguide.

Another disadvantage is that the incident beam must be highly collimated because of the angular dependence of the coupling efficiency on the lasing mode.

For most semiconductor waveguides, $\beta_m \sim kn_2 \rightarrow$
Difficult to find prism materials

Table 7.1. Practical prism materials for beam couplers

Material	Approximate refractive index	Wavelength range
Strontium titanat	2.3	visible – near IR
Rutile	2.5	visible – near IR
Germanium	4.0	IR

Assignment: Output Prism Coupler

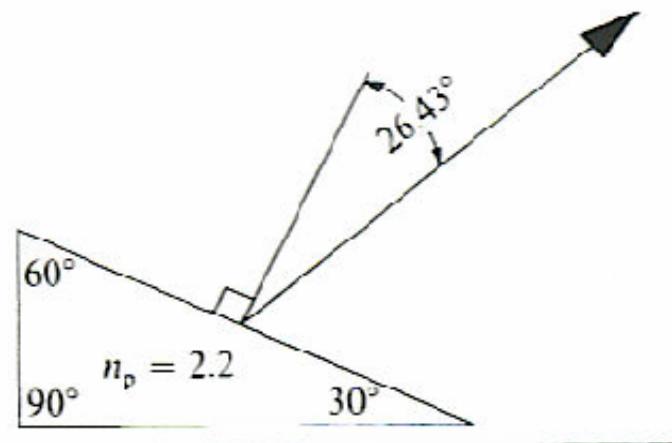
He-Ne laser, $\lambda_0 = 632.8$ nm

$$\beta_m = ?$$

$$n_1 = 1.0$$

$$n_2 = 1.5$$

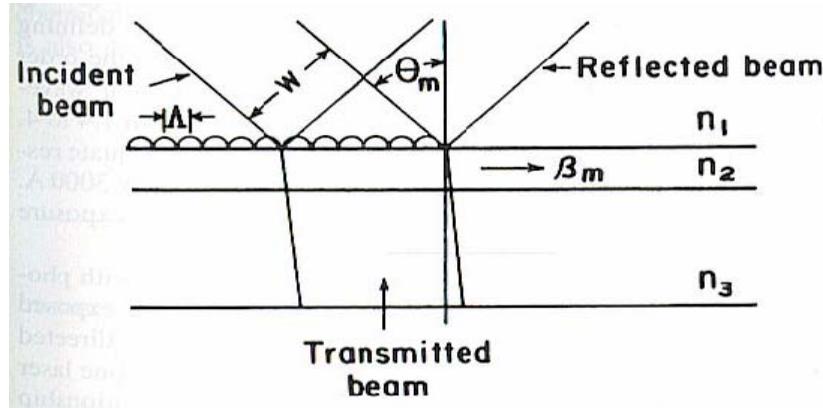
$$n_3 = 1.4$$



Assignment

What are the coupling angles for modes that are guided? Given $n_1 = 1.0$, $n_2 = 1.6$, $n_3 = 1.5$, $n_p = 2.2$ and waveguide thickness $h = 10\mu\text{m}$, $\lambda = 1.310\mu\text{m}$ and $W = 9 \mu\text{m}$ and base of the prism is 1mm.

Grating Coupler



The light coupled into the thin film is achieved by the fact that the diffracted incident light is phase-matched to a mode of the film. Grating couplers viewed as surface-wave to leaky-wave converter (output coupler)

Because of its periodic nature, the grating perturbs the waveguide modes in the region underneath the grating, thus causing each one of them to have a set of **spatial harmonics with z-direction propagation constants given by**

$$\beta_v = \beta_0 + \frac{v2\pi}{\Lambda}, \quad v = 0, \pm 1, \pm 2, \dots$$

The fundamental factor is approximately equal to the of the particular mode in the waveguide region not covered by the grating. Because of the negative values of v , the phase matching condition $\beta_m = kn_1 \sin \theta_m$ (continuity of tangential field component) can now be satisfied so that

$$\beta_v = kn_1 \sin \theta_m$$

Why grating coupler?

1. A simple reproducible and permanent coupler compatible with planar device technology.
2. The grating coupler can also be used on high-index semiconductor waveguide where it is difficult to obtain suitable prism material.

Example

Grating: $\Lambda = 0.4\mu\text{m}$ on a GaAs planar waveguide

$\lambda_o = 1.15\mu\text{m}$

Propagation constant for the lowest-order mode in the waveguide:
 $\beta_o = 3.6\text{k}$

Assume 1st order coupling, $|\nu| = 1$, what incident angle should the Light make in order to couple to the lowest-order mode?

Assignment

Grating: $\Lambda = 0.4\mu\text{m}$ on a SiO planar waveguide

$\lambda_o = 1.310\mu\text{m}$

Propagation constant for the lowest-order mode in the waveguide:
 $\beta_o = 3.6\text{k}$

Assume 1st order coupling, $|\nu| = 1$, what incident angle should the Light make in order to couple to the lowest-order mode?
At what λ_0 do we start to need higher-order coupling?

Tapered Mode Size Converters

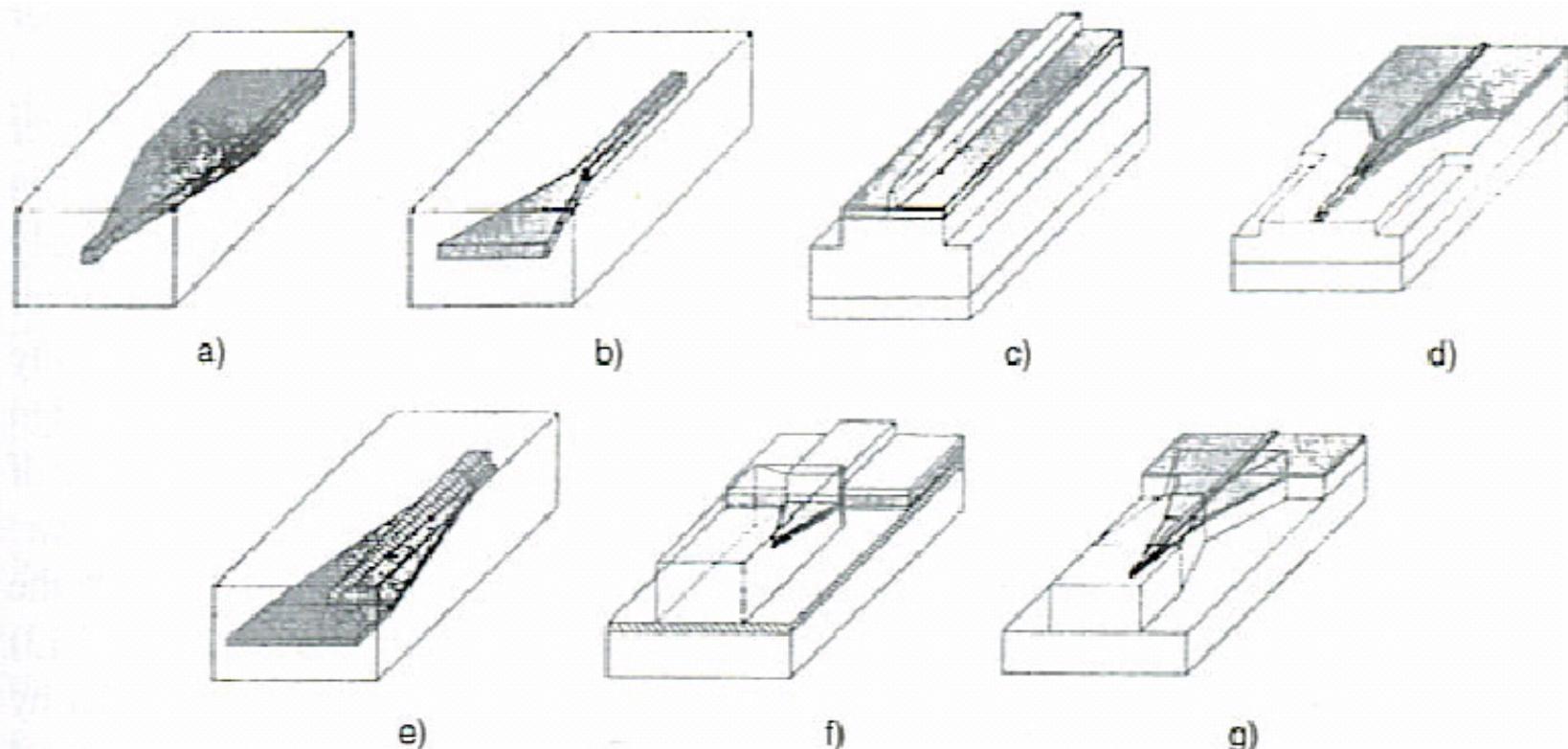
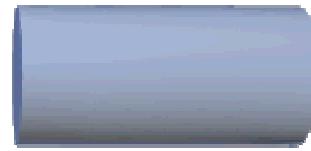
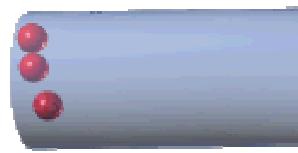


Fig. 7.12a–g. Lateral taper designs. **a** Lateral down-tapered buried waveguide. **b** Lateral up-tapered buried waveguide. **c** Single lateral taper transition from a ridge waveguide to a fiber-matched waveguide. **d** Multisection taper transition from a ridge waveguide to a fiber-matched waveguide. **e** Dual lateral overlapping buried waveguide taper. **f** Dual lateral overlapping ridge waveguide taper. **g** Nested waveguide taper transition from a ridge waveguide to a fiber-matched waveguide [7.25] ©1997 IEEE

Fiber to Fiber coupling loss

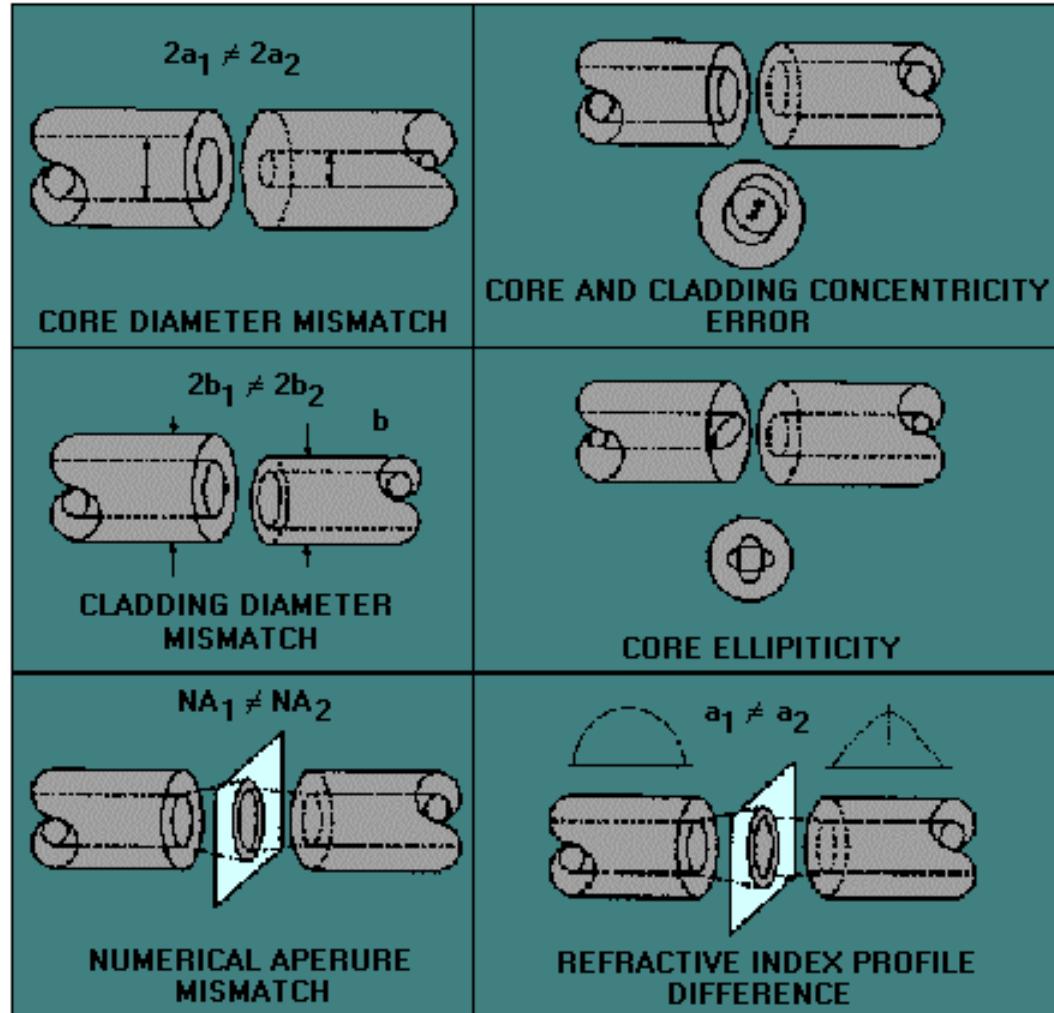


Joseph C. Palais

Fiber to Fiber connection loss

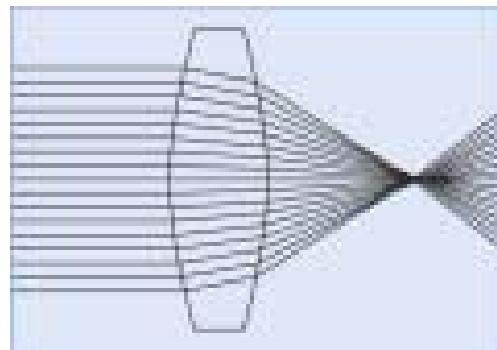
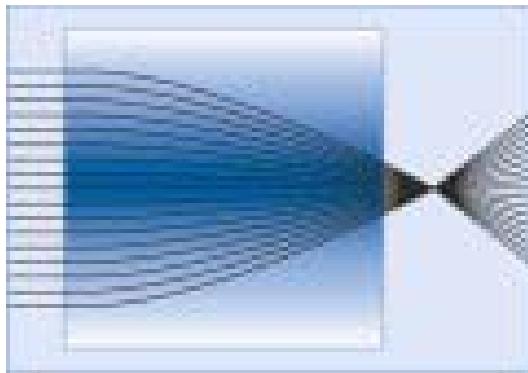
- Reflection losses
- Fiber separation
- Lateral misalignment
- Angular misalignment
- Core and cladding diameter mismatch
- Numerical aperture (NA) mismatch
- Refractive index profile difference
- Poor fiber end preparation

Fiber mismatches



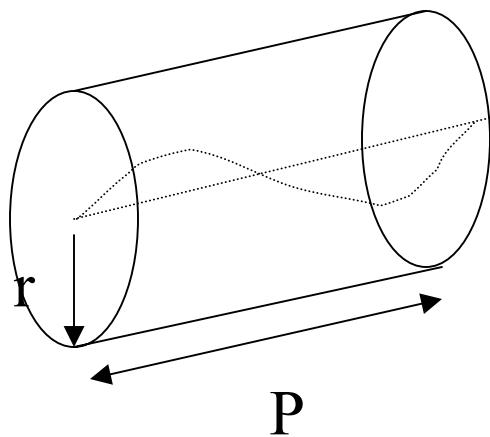
GRIN Lens

Gradient index micro lenses represent an innovative alternative to conventional spherical lenses since the lens performance depends on a continuous change of the refractive index within the lens material.



1. GRIN objective lenses with an angle of view of 60° are produced in standard diameters of 0.5, 1.0 und 1.8 mm. Typical object distances are between 5 mm and infinity.
2. Instead of curved shaped surfaces only plane optical surfaces are used which facilitate assembly. The light rays are continuously bent within the lens until finally they are focused on a spot.
w. wang

GRIN Lenses



$$n(r) = n_0(1-Ar^2/2)$$

Where

n_0 -- Index of Refraction at the Center

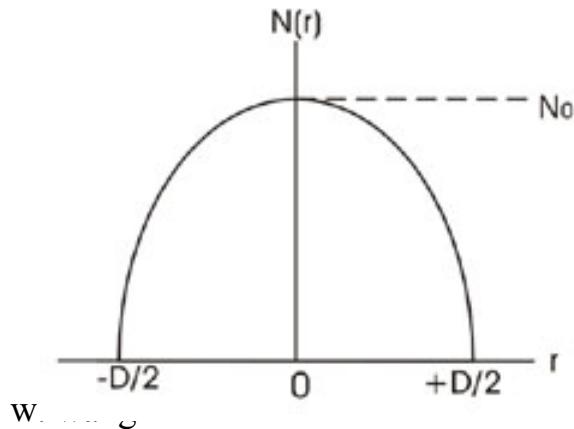
r -- Diameter of Grin Lens

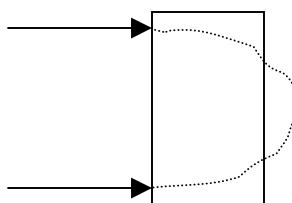
A -- Gradient Constant

The quadratic $n(r)$ results in a sinusoidal ray path

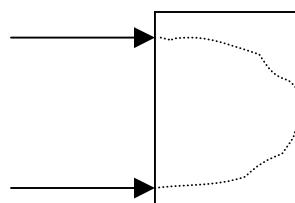
$$P = 2\pi/A^{0.5}$$

For length $L = P/4 \Rightarrow$ quarter pitch lens
 $= P/2 \Rightarrow 1/2$ pitch lens

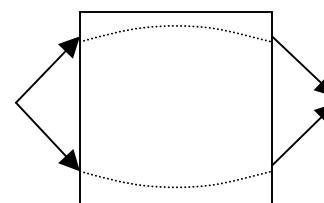




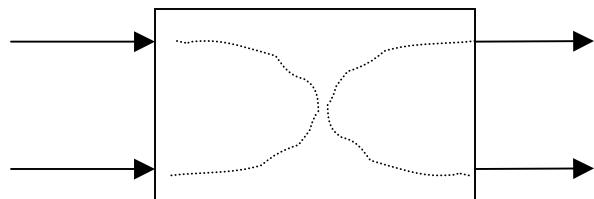
0.23P



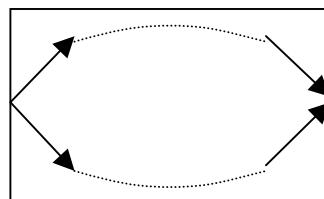
0.25P



0.29P

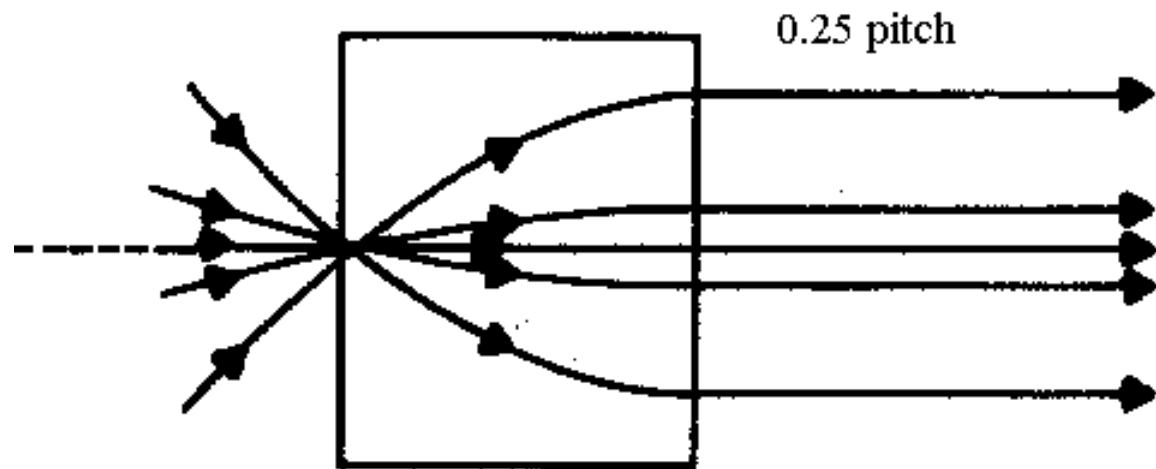


0.5P



0.5P

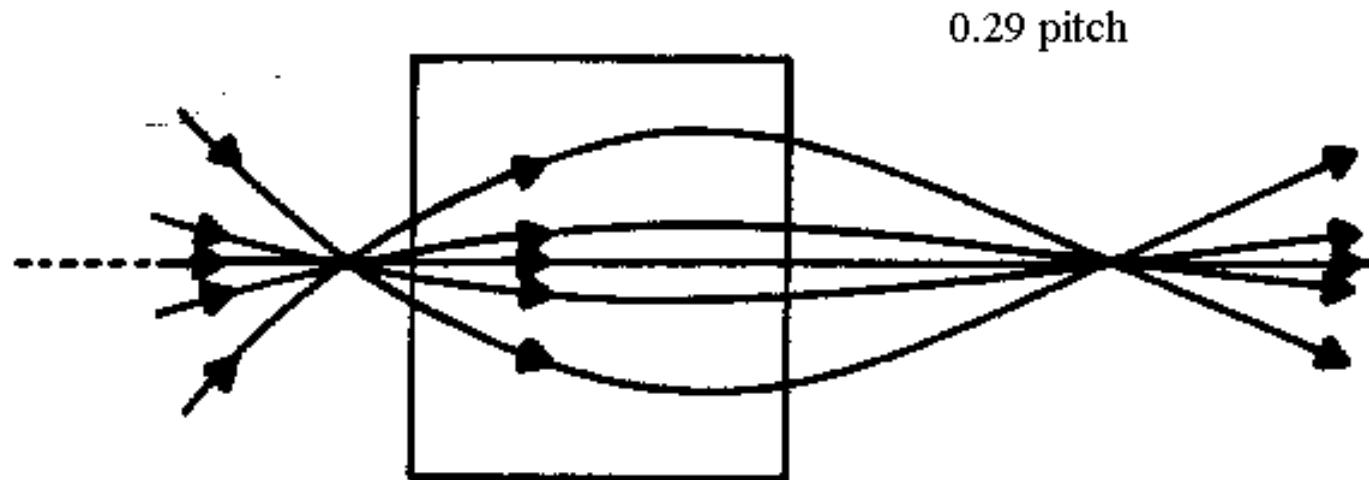
GRIN Lens



Light exiting a fiber can be collimated into a parallel beam when the output end of the fiber is connected to the GRIN lens. (0.25P)

GRIN Lens

Focusing of the fiber output onto a small detector or focusing of the output of a source onto the core of a fiber can be accomplished by increasing the length of the GRIN lens to 0.29 pitch. Then the source can be moved back from the lens and the transmitted light can be refocused at some point beyond the lens. Such an arrangement is useful for coupling sources to fibers and fibers to detectors.

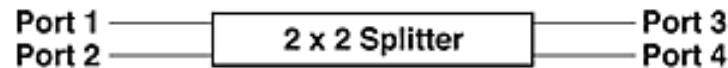


Why a GRIN ?

- Conventional designs
 - Conical elements
 - Aberrated lenses
 - Diffractive
- GRIN design
 - Well suited for small-diameter designs
 - Allows back-focal offset, unlike conical element
 - Simpler alignment than multiple lens solutions
 - Lower dispersion than diffractive axicon

Coupling between Waveguides

2x2 Coupler

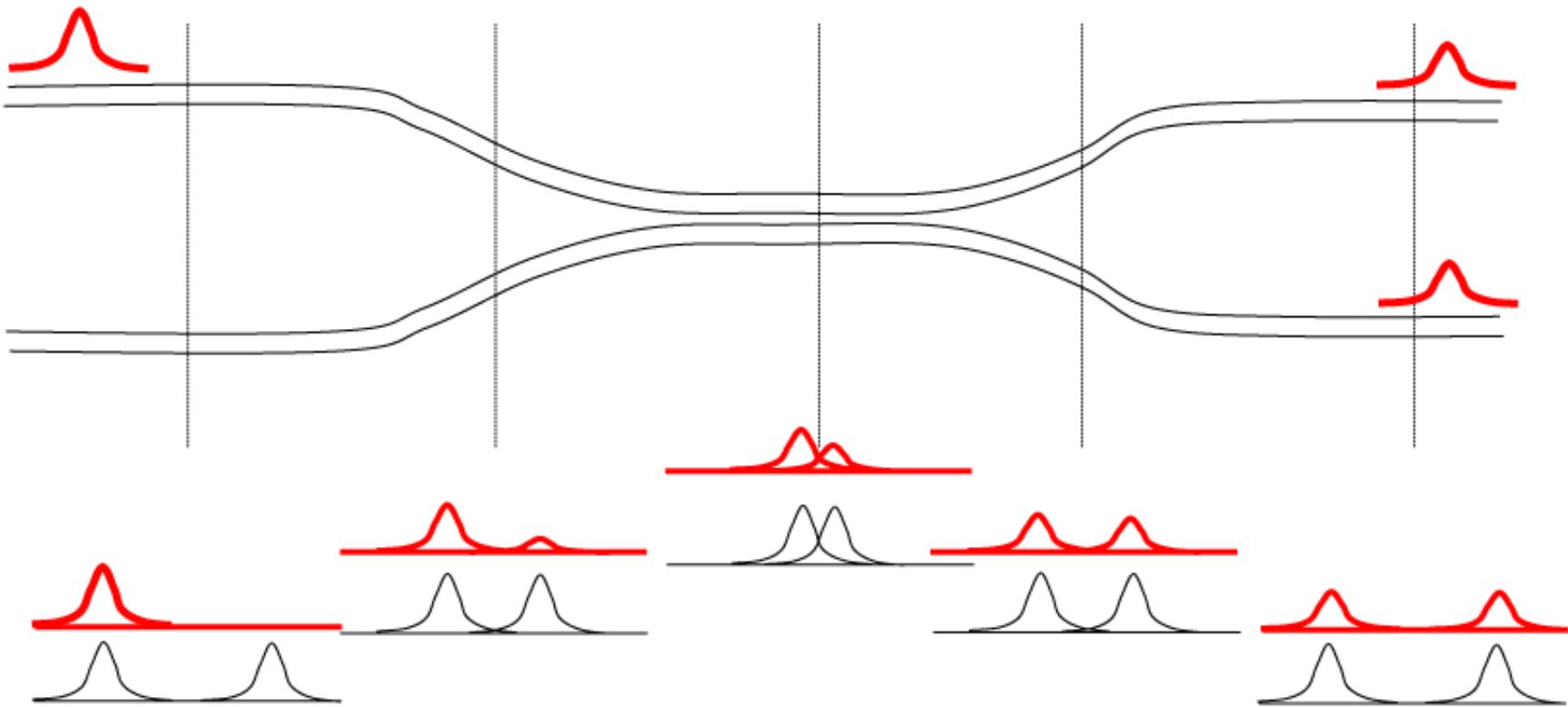


Operating Wavelength		$\lambda_{op} \pm \Delta\lambda$	
Input Port	Output Port	Transmission (I.L.) at λ_{op}	
		3	4
1	1	99% (0.04dB)	1% (20.0dB)
2	2	1% (20.0dB)	99% (0.04dB)

NOTE: Table is used for illustration purposes only. Not for product specifications.

Thor Labs

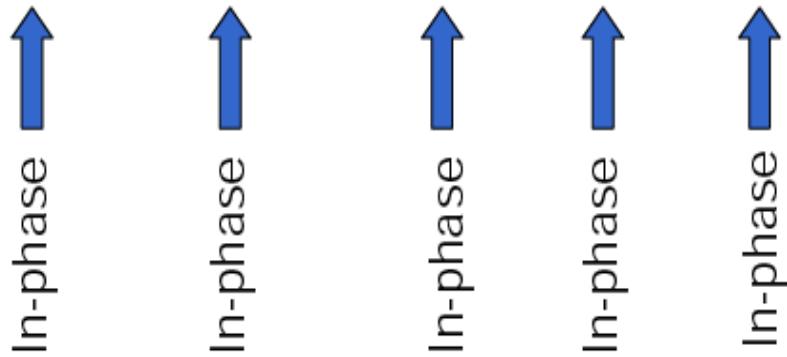
Directional Couplers



- **Coupling:** Mixing of two adjacent modes, exchanging power as they propagate along adjacent paths.
- Energy transfer in a coherent fashion. " Direction of propagation maintained.

Synchronous Versus Asynchronous

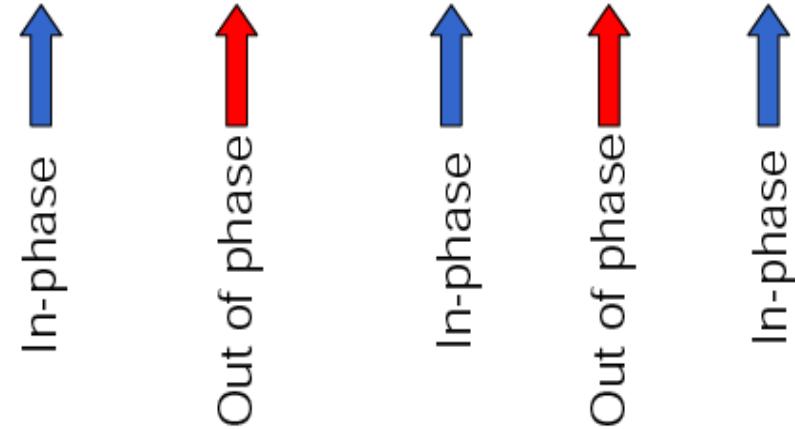
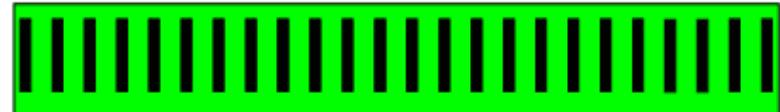
Synchronous: Both waveguides are identical



Power transfer continues all the time.

-> **Complete power transfer**

Asynchronous: Both waveguides are not identical



The power transfer that occurs while the waves are in phase is reversed when the waves are out of phase. -> **Incomplete power transfer**

Dual-Channel Directional Coupler

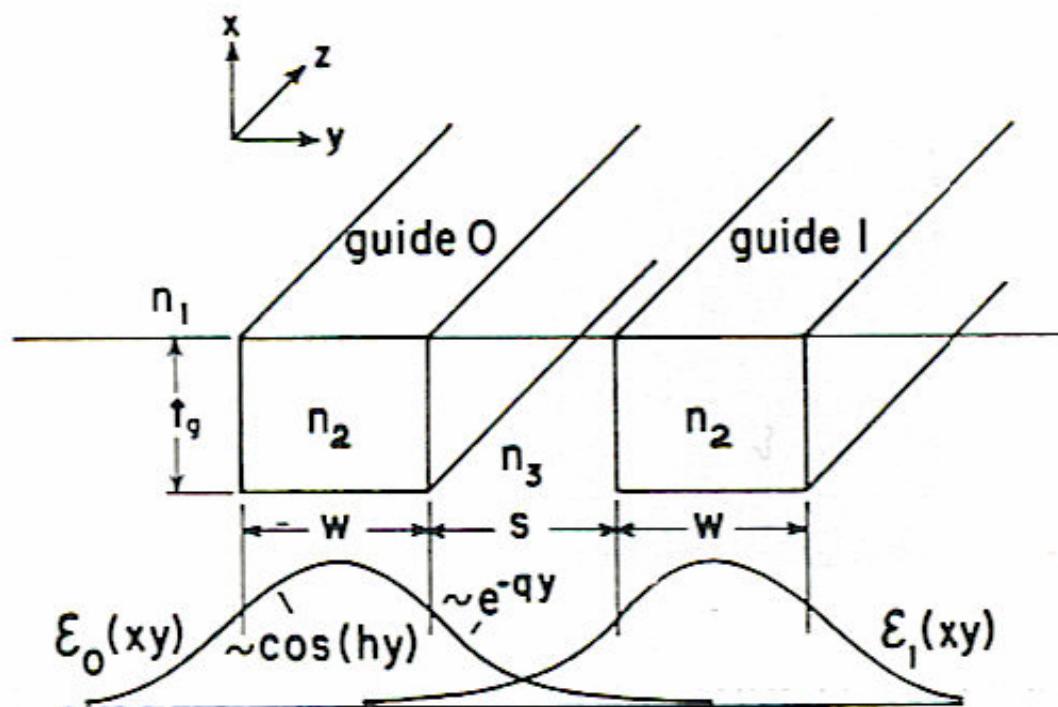
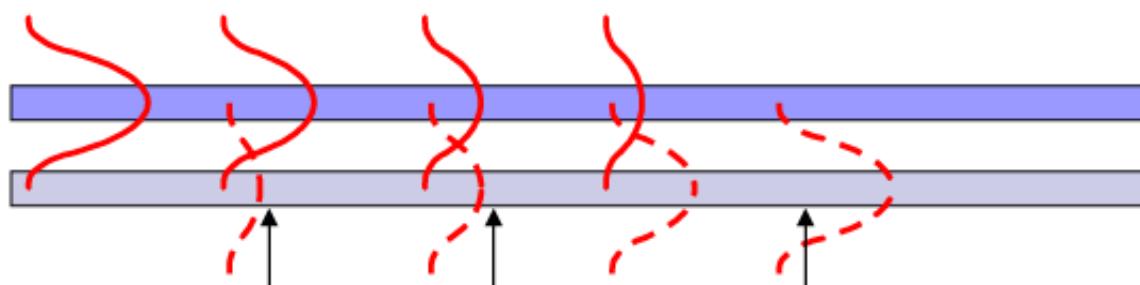


Fig. 8.2. Diagram of dual-channel directional coupler. The amplitudes of the electric field distributions in the guides are shown below them

- Fraction of the power coupled per unit length determined by overlaps of the modes.
- Determine the amount of transmitted power by bending away the secondary channel at proper point.



Transmission Characteristics

3dB directional coupler,
interaction length = 1 mm

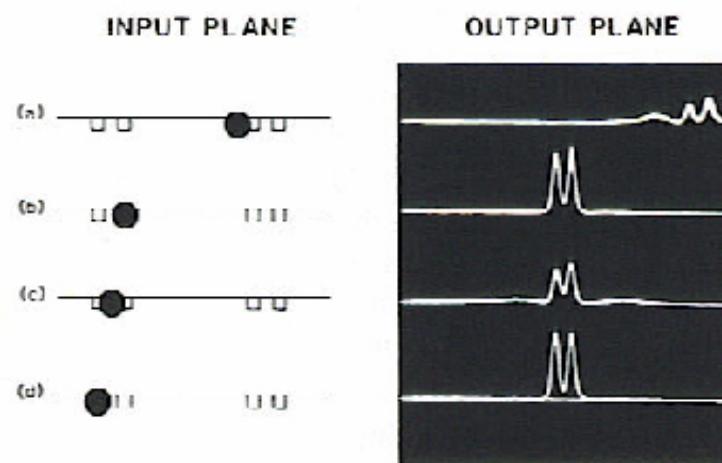


Fig. 8.3. Optical power distribution at the output of a 3 dB dual-channel directional coupler, for various input conditions (as explained in the text). The oscillographs of output power were made using a scanning system like that shown in Fig. 2.3. The waveguides, which were formed by proton bombardment of the GaAs substrate, had $3 \mu\text{m} \times 3 \mu\text{m}$ cross-section and were separated by $3 \mu\text{m}$. The interaction length was 1 mm

100% directional
coupler interaction
length : 2.1 mm

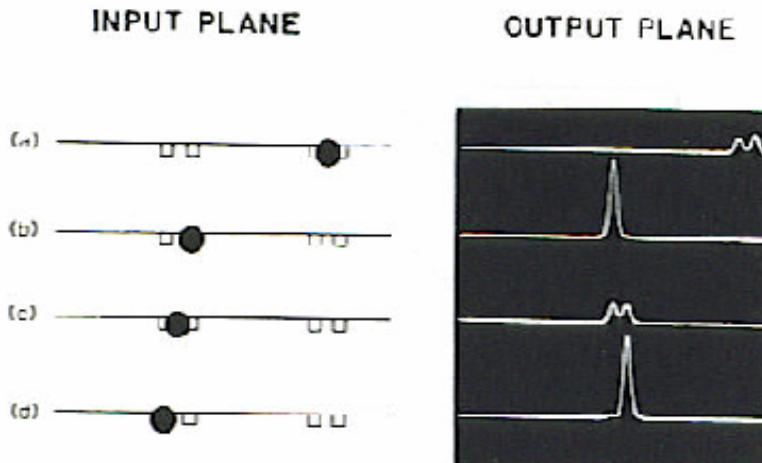


Fig. 8.4. Optical power distribution at the output of a 100% dual-channel directional coupler for various input conditions. The waveguides were like those of Fig. 8.3, except the interaction length was 2.1 mm

Coupled-Mode Theory

Synchronous Coupling

Electric field of the propagating mode in the waveguide:

$$\mathbf{E}(x, y, z) = A(z) \mathbf{E}_0(x, y)$$

$A(z)$: Complex amplitude, including phase term $e^{-j\beta z}$

$\mathbf{E}_0(x, y)$: Field distribution in one waveguide, assuming the other waveguide is absent.

Coupled-mode equations:

$$\frac{dA_0(z)}{dz} = -j\beta A_0(z) - j\kappa A_1(z)$$

$$\frac{dA_1(z)}{dz} = -j\beta A_1(z) - j\kappa A_0(z)$$

Initial condition:

$$A_0(0) = 1$$

$$A_1(0) = 0$$

Solutions:

$$A_0(z) = \cos(\kappa z) \exp(-j\beta z)$$

$$A_1(z) = -j \sin(\kappa z) \exp(-j\beta z)$$

$$\beta = \beta_r - j \frac{\alpha}{2}$$

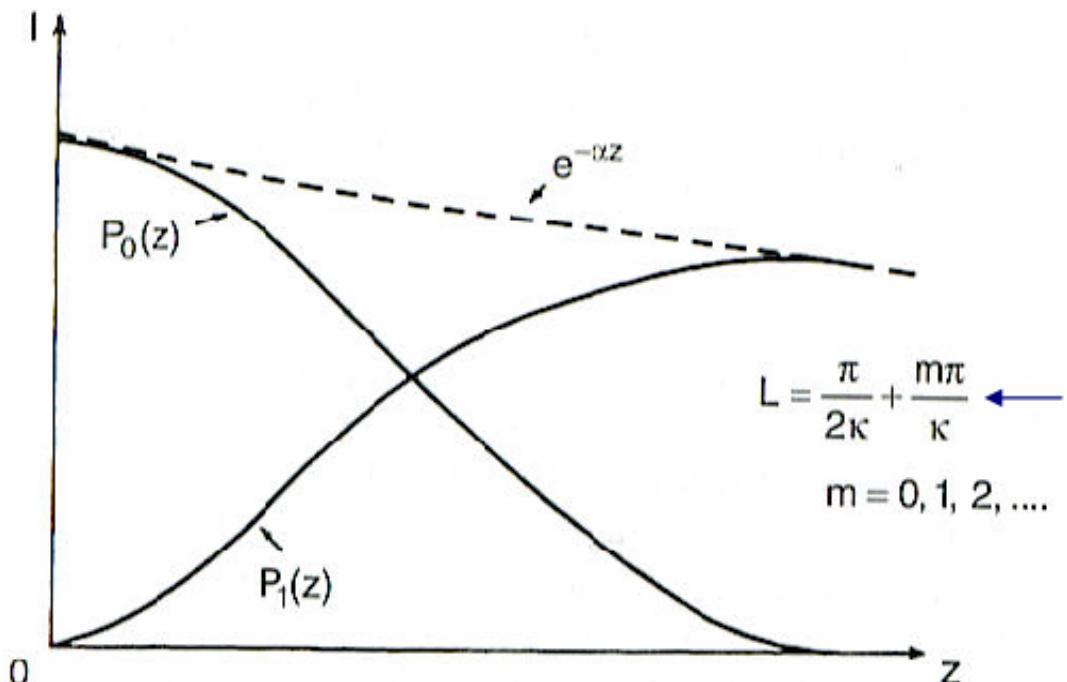
α : Loss coefficient

Power Transfer in Synchronous Coupling

Power flow:

$$P_0(z) = |A_0(z)|^2 = \cos^2(\kappa z) \exp(-\alpha z)$$

$$P_1(z) = |A_1(z)|^2 = \sin^2(\kappa z) \exp(-\alpha z)$$



Length necessary for complete transfer of power from one waveguide to the other.

Fig. 8.5. Theoretically calculated power distribution curves for a dual-channel directional coupler. The initial condition of $P_0(0) = 1$ and $P_1(0) = 0$ has been assumed

Coupled-Mode Theory

Asynchronous Coupling

Coupled-mode equations:

$$\frac{dA_0(z)}{dz} = -j\beta_0 A_0(z) - j\kappa A_1(z)$$

$$\frac{dA_1(z)}{dz} = -j\beta_1 A_1(z) - j\kappa A_0(z)$$

Define:

$$\begin{bmatrix} A_0(z) \\ A_1(z) \end{bmatrix} = \begin{bmatrix} a_0(z) \\ a_1(z) \end{bmatrix} \exp(-j\beta z)$$

: Coupled propagation constant

Condition for non-trivial
solutions results in:

$$\beta = \bar{\beta} \pm g$$

$$\bar{\beta} = \frac{\beta_0 + \beta_1}{2}$$

$$g^2 \equiv \kappa^2 + \left[\frac{\Delta\beta}{2} \right]^2$$

Initial condition:

$$A_0(0) = 1$$

$$A_1(0) = 0$$

Power Transfer in Asynchronous Coupling

Power flow:

$$P_0(z) = \cos^2(gz)e^{-\alpha z} + \left[\frac{\Delta\beta}{2} \right]^2 \frac{\sin^2(gz)}{g^2} e^{-\alpha z}$$

$$P_1(z) = |A_1(z)|^2 = \frac{\kappa^2}{g^2} \sin^2(gz)e^{-\alpha z}$$

$\Psi = g$ (= κ for synchronous coupling)

Assuming lossless for the figures.

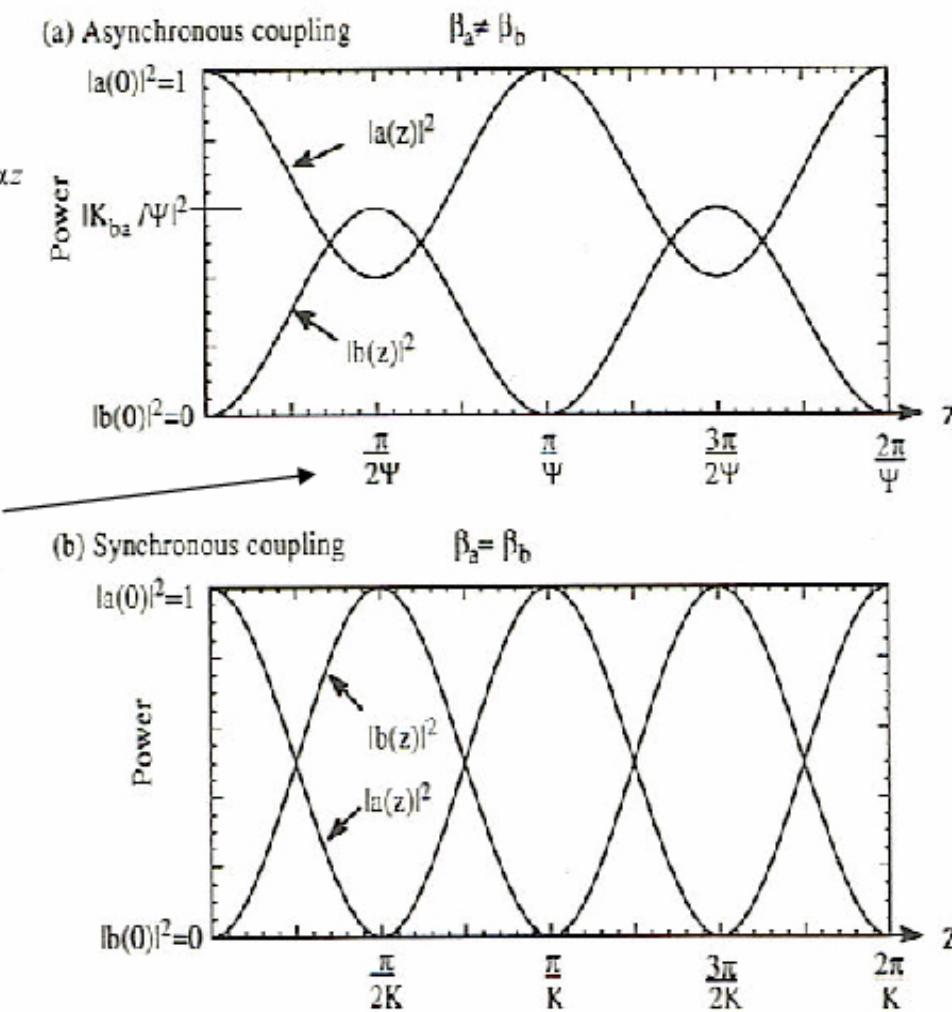


Figure 8.13. Guided powers $|a(z)|^2$ and $|b(z)|^2$ vs. the coupling distance z ; (a) asynchronous coupling $\beta_a \neq \beta_b$, (b) synchronous coupling $\beta_a = \beta_b$.

Applications: Modulators and Switches

MathCAD program

$$z = 1$$

$$\kappa := 10^2$$

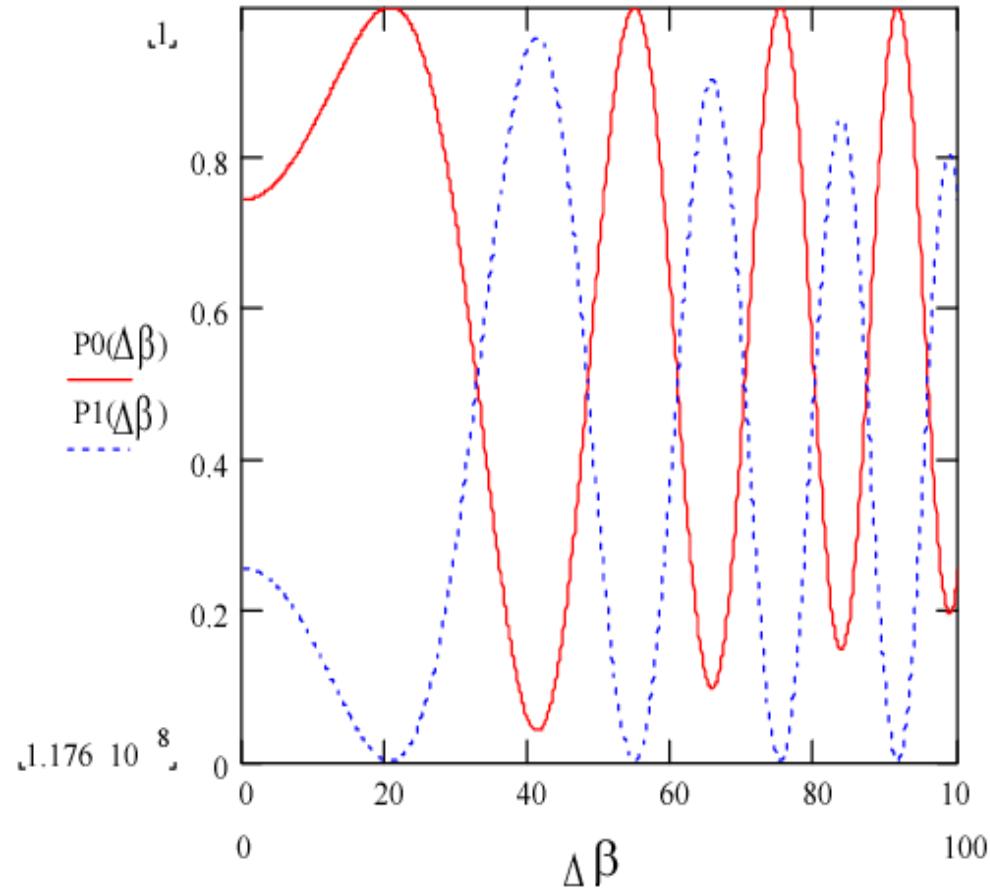
Coupling length, in mm

$$g(\Delta\beta) := \sqrt{\kappa^2 + \left(\frac{\Delta\beta}{2}\right)^2}$$

$$P_0 = \cos(g(\Delta\beta)z)^2 + \left[\frac{\Delta\beta}{2}\right]^2 \frac{\sin[g(\Delta\beta)z]^2}{g(\Delta\beta)^2}$$

$$P_1 = \left[\frac{\kappa^2}{g(\Delta\beta)^2}\right] \sin(g(\Delta\beta)z)^2$$

Control $\Delta\beta$ electrically



Multilayer Planar Waveguide Coupler

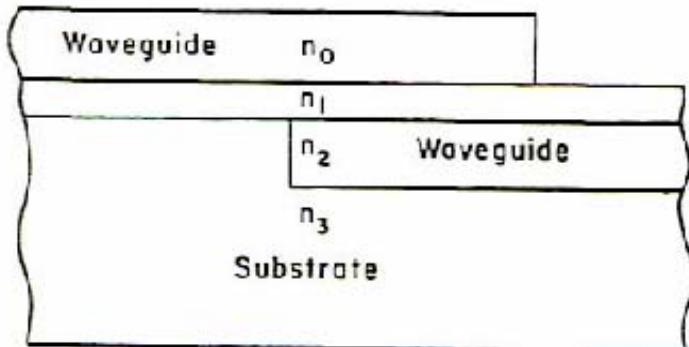


Fig. 8.1. Coupling between two planar waveguides by optical tunneling. Transfer of energy occurs by phase coherent synchronous coupling through the isolation layer with index n_1

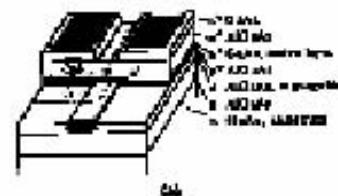


Fig. 1. Opt View of integrated TTS lines with the corresponding response. The 2D-based lines are shown as shaded patterns in top. Lower shaded lines are the optically measured lines corresponding. (b) Optical pattern of the same device with various noise mode profiles of each nodes recorded.



Fig. 1. Opt View of integrated TTS lines with the corresponding response. The 2D-based lines are shown as shaded patterns in top. Lower shaded lines are the optically measured lines corresponding. (b) Optical pattern of the same device with various noise mode profiles of each nodes recorded.



1. (a) View of longitudinal TIR how when no vegetation or only scattered trees is shown as shaded, perhaps at high density shaded as in optical model of the savanna-grass. (b) Cross-section of the same with scattered trees model results of one location overlaid.



1. (a) View of longitudinal TIR how when no vegetation or only scattered trees is shown as shaded, perhaps at high density shaded as in optical model of the savanna-grass. (b) Cross-section of the same with scattered trees model results of one location overlaid.

Ref: G. A. Vawter, J. L. Merz, and L. A. Coldren,
"Monolithically integrated transverse-junction-strip laser with
an external waveguide in GaAs/AlGaAs, J. Quantum
Electronics, v. 25, no. 2, p. #54-#62, #989.

Because of the size of the prism, the interaction between prism and waveguide mode can occur only over the length L . The theory of weakly coupled mode indicates that a complete interchange of energy between phase matched modes occurs if the interaction length in the z direction satisfies the relation

$$kL = \frac{\pi}{2}$$

where k is coupling coefficient. The coefficient depends on n_1 , n_p and n_2 , which determine the shape of the mode tails and on the prism spacing.

The length required for complete coupling is given by

$$L = \frac{W}{\cos\theta_m}$$

For a given length, the coupling coefficient required for complete coupling is thus given by

$$\kappa = \frac{\pi \cos\theta_m}{2W}$$

Fiber to fiber connection loss

The loss in optical power through a connection is defined similarly to that of signal attenuation through a fiber. Optical loss is also a log relationship. The loss in optical power through a connection is defined as:

$$\text{loss} = 10 \log_{10} \frac{P_i}{P_o}$$

Fiber to fiber connection loss

Intrinsic coupling losses are limited by reducing fiber mismatches between the connected fibers. This is done by procuring only fibers that meet stringent geometrical and optical specifications. Extrinsic coupling losses are limited by following proper connection procedures.