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Winter College on Optics and Photonics
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"Fiber Optics II: Simple Fiber Optic Devices"

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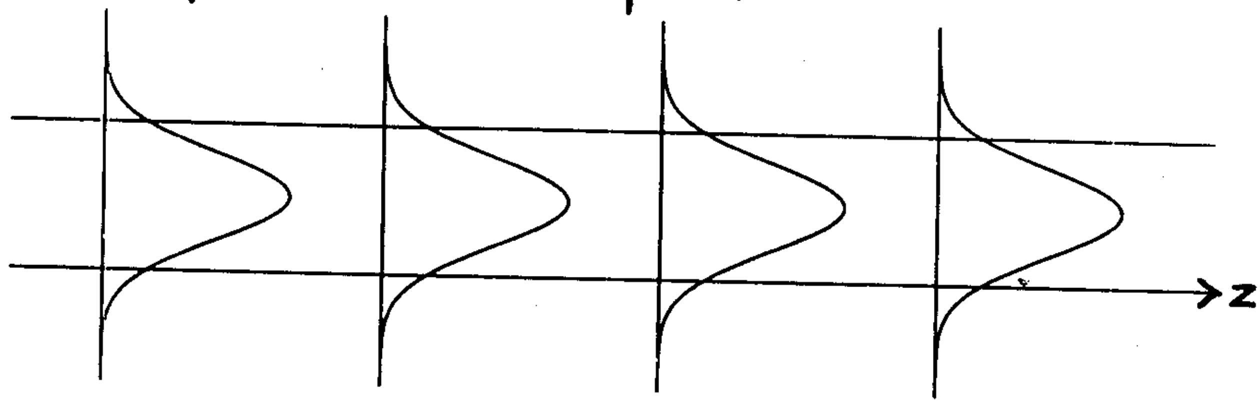
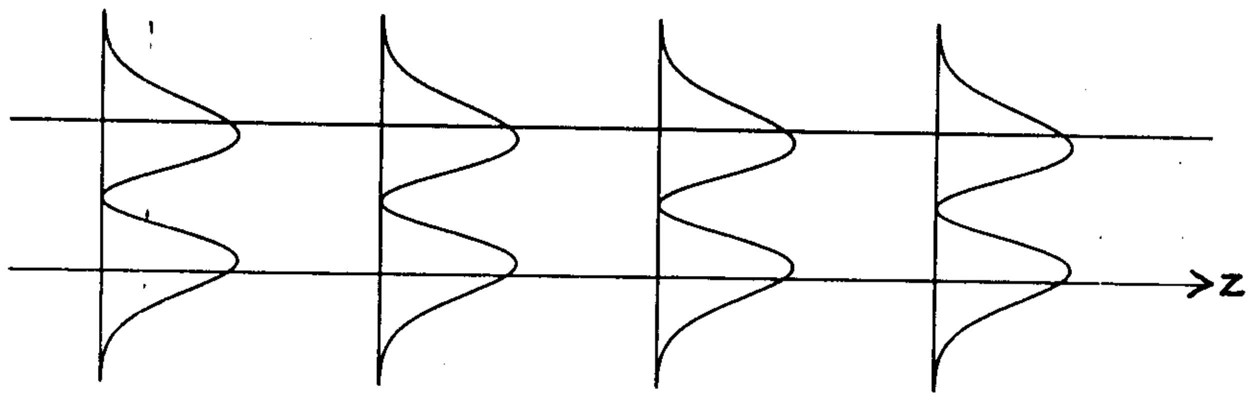
Modes of a perfect waveguide:

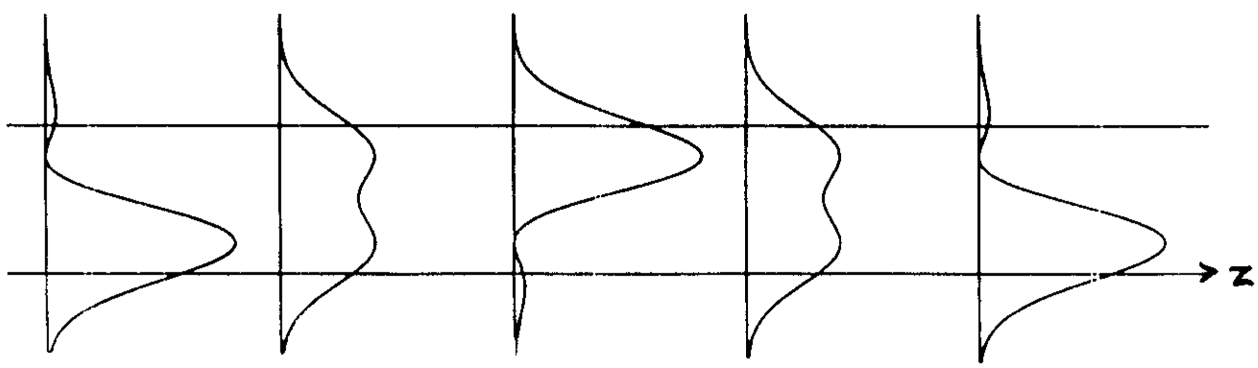
$$E_1(x,z,t) = \psi_1(x)\, e^{i(\omega t - \beta_1 z)}$$



$$E_2(x,z,t) = \psi_2(x)\, e^{i(\omega t - \beta_2 z)}$$

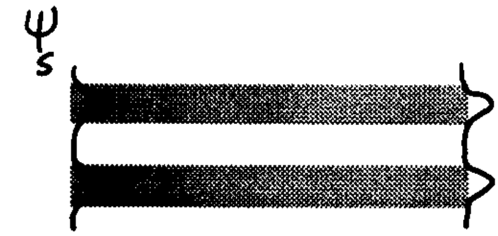


$$E(x,z,t) = \left[A\,\psi_1(x) + B\,\psi_2(x)\, e^{i(\beta_1 - \beta_2 z)}\right] e^{i(\omega t - \beta_1 z}$$



DIRECTIONAL COUPLER

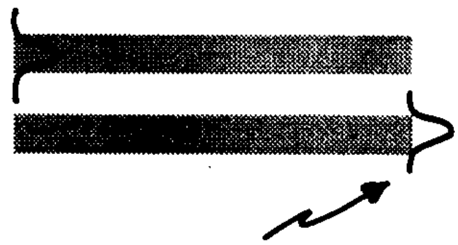
β_s (Symmetric Mode)



β_a (Antisymmetric Mode)

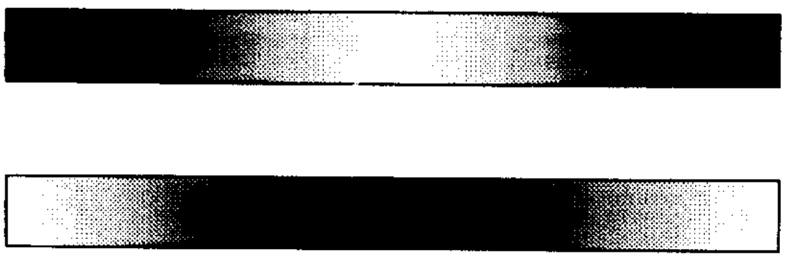
$z = 0$

$\Psi = \Psi_s + \Psi_a$



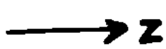
$$z = \frac{\pi}{(\beta_s - \beta_a)}$$

$\Psi = \Psi_s - \Psi_a$

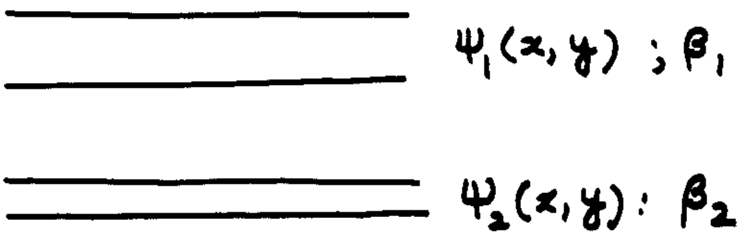


$P_1 = \cos^2 \kappa z$

$P_2 = \sin^2 \kappa z$



The optical fiber directional coupler



$$\psi(x,y,z) \simeq A(z)\,\psi_1(x,y)\,e^{-i\beta_1 z} + B(z)\,\psi_2(x,y)\,e^{-i\beta_2 z}$$

$$\frac{dA}{dz} = -i\,\kappa_{12}\,B\,e^{i(\Delta\beta)z}$$

$$\frac{dB}{dz} = -i\,\kappa_{21}\,A\,e^{-i(\Delta\beta)z}$$

$$\frac{P_1(z)}{P_1(0)} = 1 - \frac{\kappa^2}{\gamma^2}\sin^2\gamma z$$

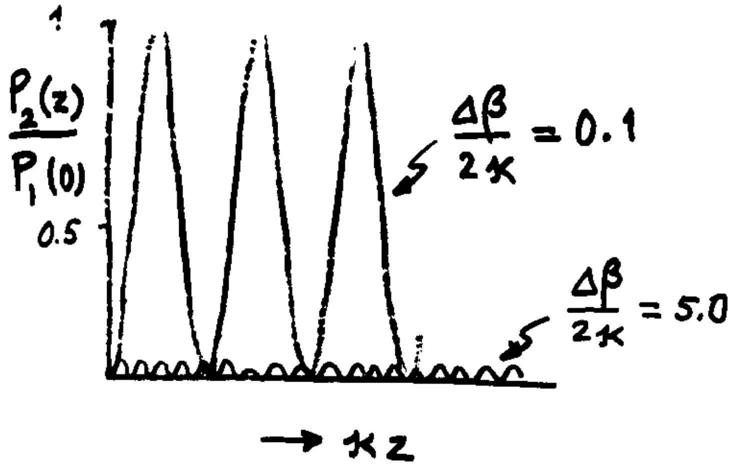
$$\gamma^2 = \kappa^2 + \frac{1}{4}(\Delta\beta)^2$$

$$\frac{P_2(z)}{P_1(0)} = \frac{\kappa^2}{\gamma^2}\sin^2\gamma z$$

$$\kappa \equiv \sqrt{\kappa_{12}\,\kappa_{21}}$$

$$P_1(z) + P_2(z) = P_1(0)$$

$$\frac{P_2(z)}{P_1(0)} = \frac{\kappa^2}{\gamma^2} \sin^2 \gamma z \qquad \gamma^2 = \kappa^2 + \frac{1}{4}(\Delta\beta)^2$$

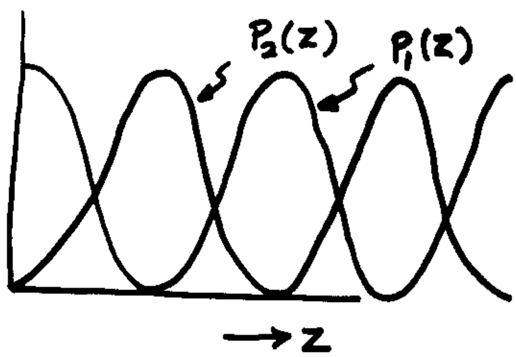


If $\beta_1 = \beta_2 \Rightarrow \Delta\beta = 0$

$\Rightarrow$

$$\frac{P_1(z)}{P_1(0)} = \cos^2 \kappa z$$

$$\frac{P_2(z)}{P_1(0)} = \sin^2 \kappa z$$



Complete transfer of power for $\kappa L = \frac{\pi}{2}, \frac{3\pi}{2}, \ldots$

More details on Coupled mode theory & also on Periodic waveguides can be found in Introduction to Fiber Optics by Ghatak & Thyagarajan, Cambridge U Press (1998)

Using identical couplers

$$P_2(z) = P_1(0)\ \sin^2 \kappa z$$

$$\kappa = \kappa(\lambda_0)$$

e.g. $\kappa(1.55\,\mu m) = 6.496\ cm^{-1}$

$\kappa(1.3\,\mu m) = 4.872\ cm^{-1}$

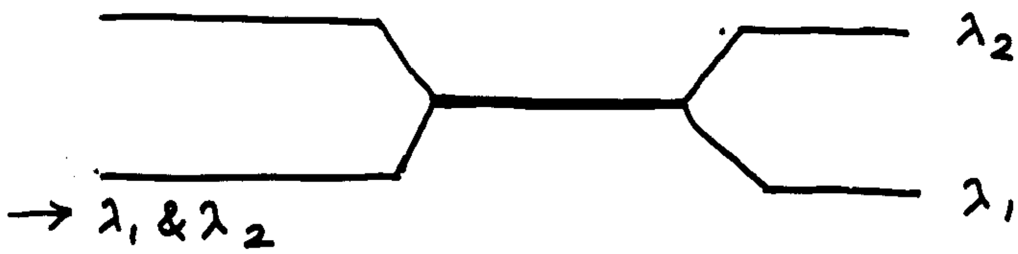
If $L = 9.67\ mm$

then

at $\lambda = 1.55\mu m$ $\quad \kappa L \simeq 2\pi \quad P_2(z) \approx 0$

&

at $\lambda = 1.3\mu m$ $\quad \kappa L \simeq \frac{3\pi}{2} \quad P_2(z) \simeq P_1$



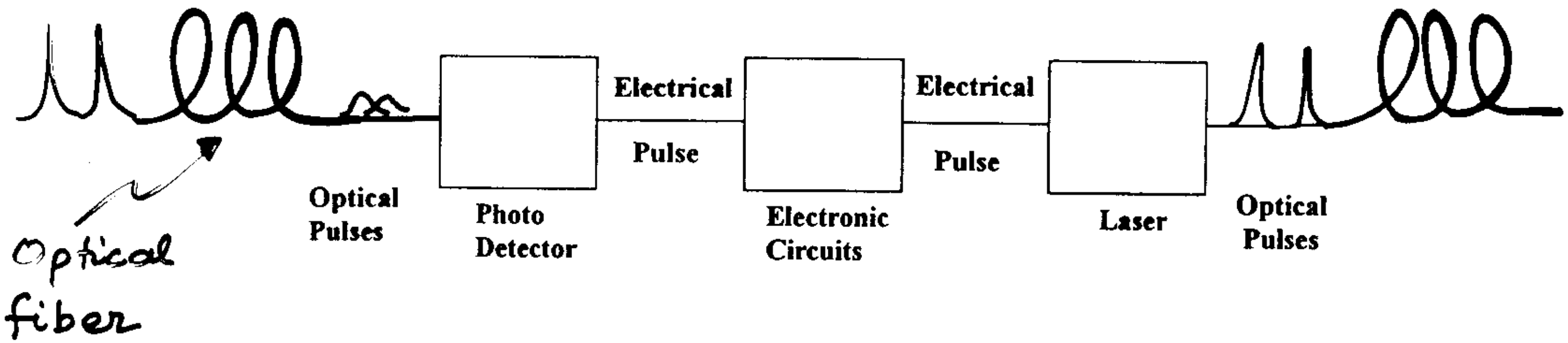
Wavelength division demultiplexer

Can fiber loss be compensated optically?

↓ YES

FIBER AMPLIFIERS

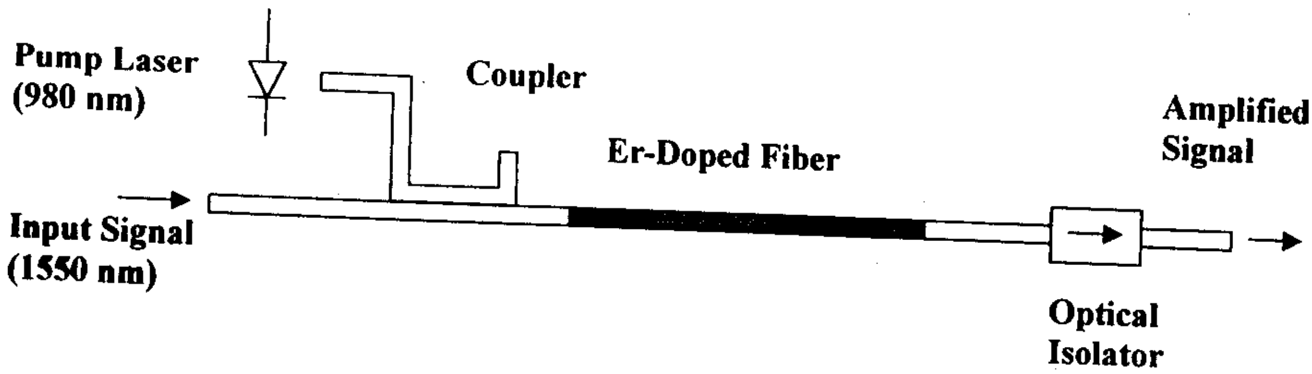
A Conventional Repeater:

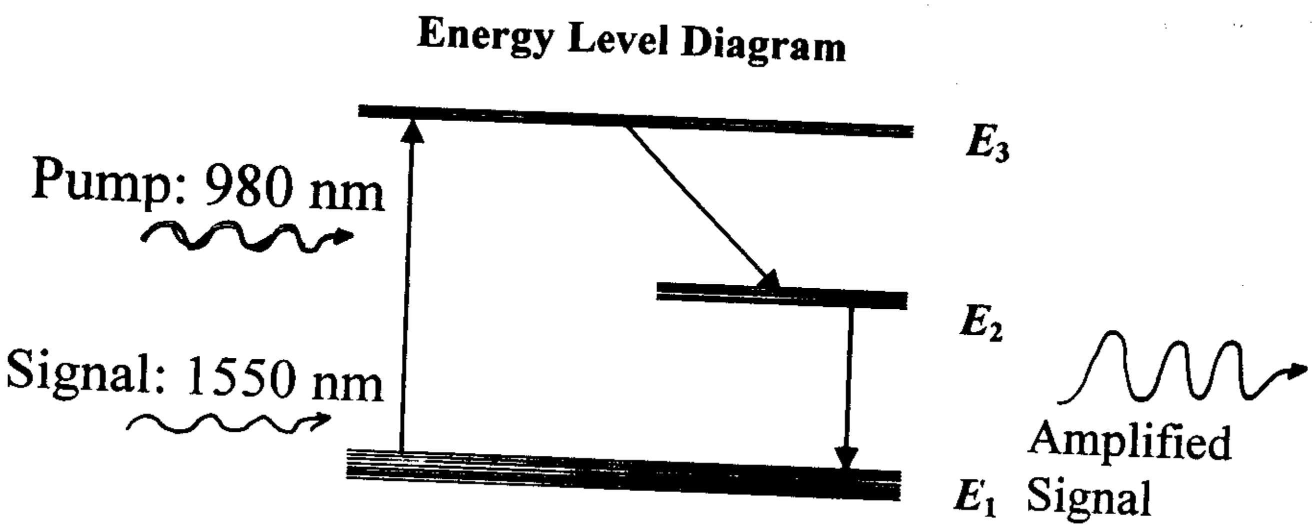


OPTICAL AMPLIFIER

Direct amplification of optical pulses

ERBIUM DOPED FIBER AMPLIFIER





Absorption of 980 nm pump

↓

Population Inversion between E_2 and E_1

↓

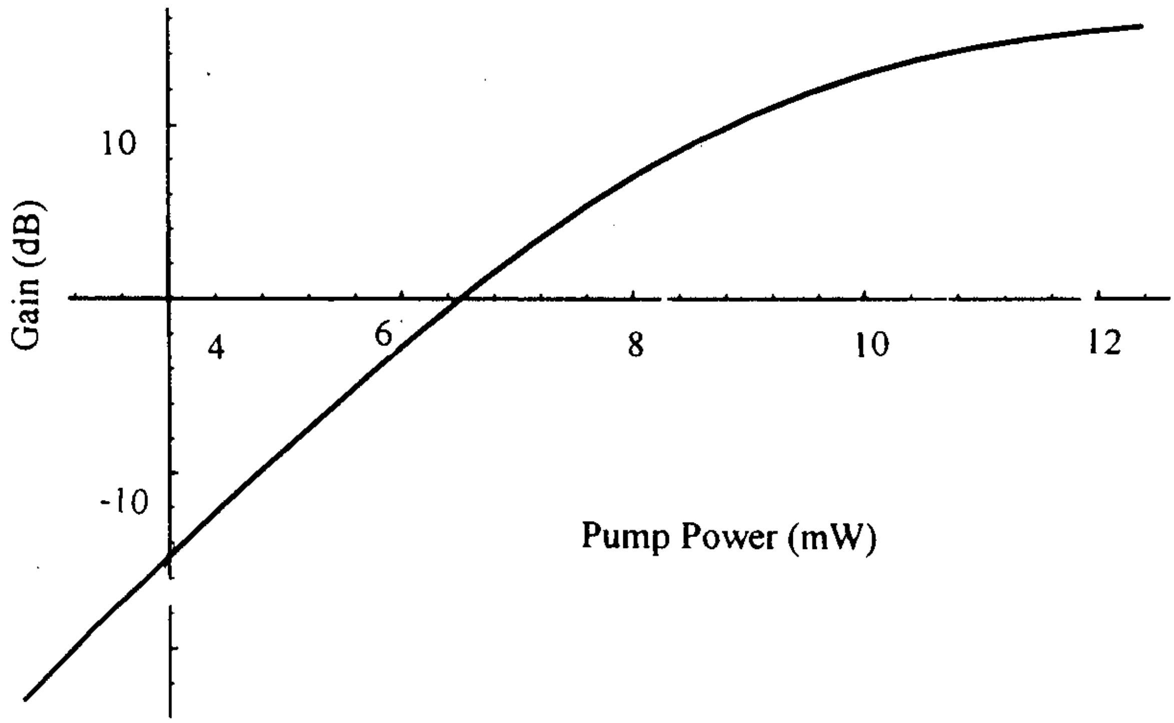
Amplification of signal (at 1550 nm)

Gain vs. Pump Power

Signal Wavelength = 1.534 μm

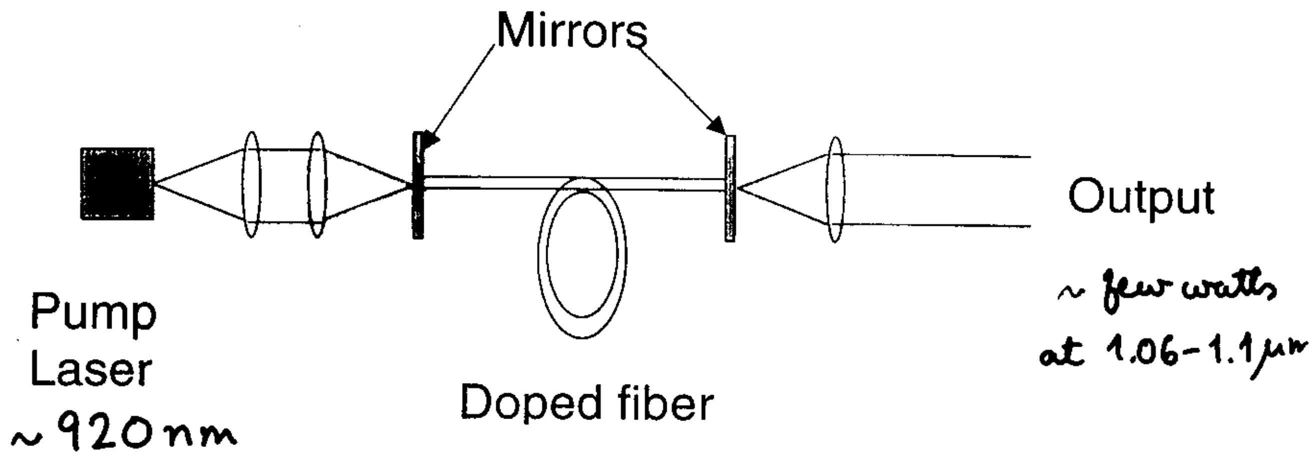
Input Signal Power = 15 μW

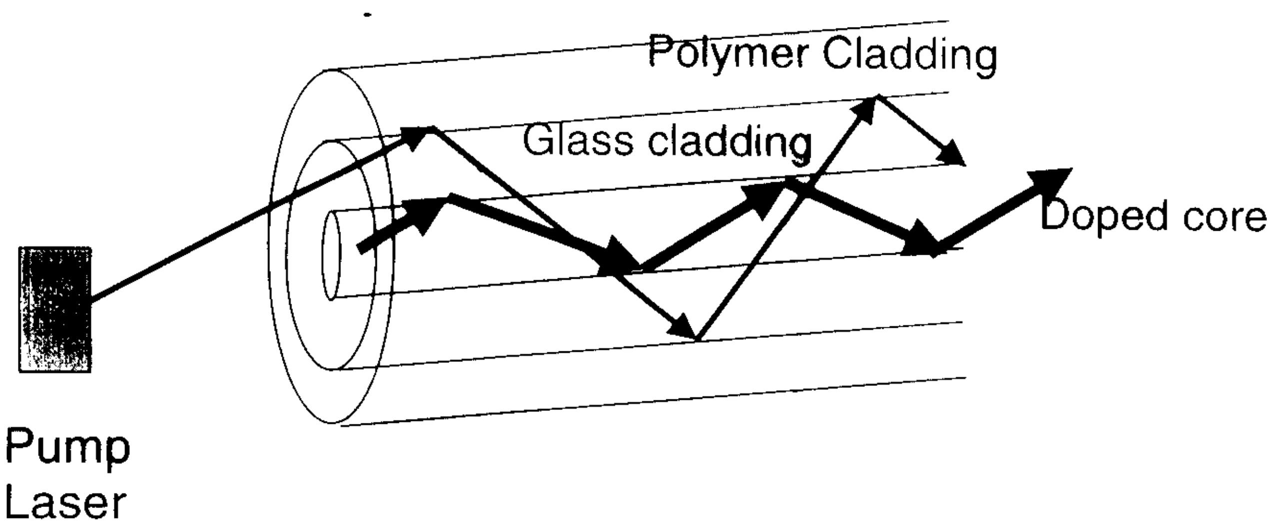
Fiber Length = 8.5 m



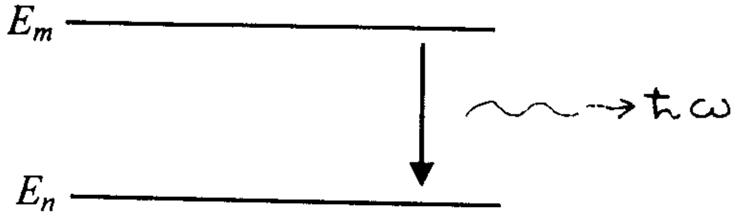
More details on Fiber Amplifiers
can be found in
Introduction to Fiber Optics
by A. Ghatak & K. Thyagarajan
Cambridge University Press (1998)

Fiber Lasers





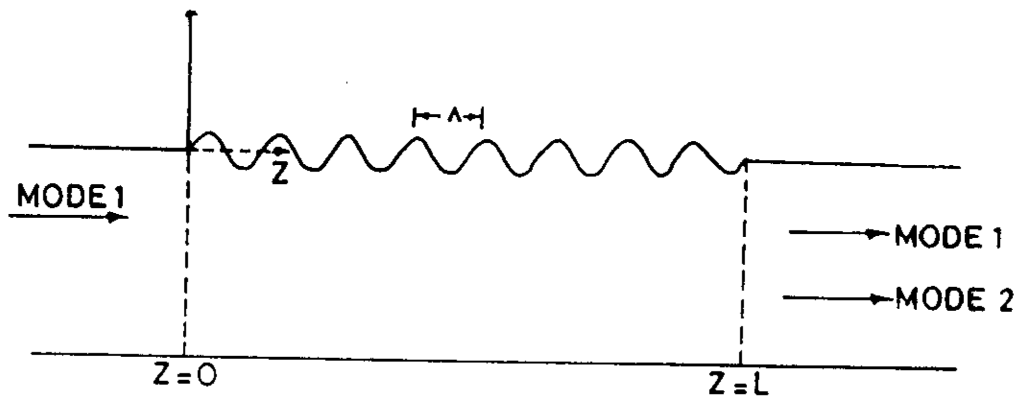
Stationary States



Transitions require a harmonic perturbation such that

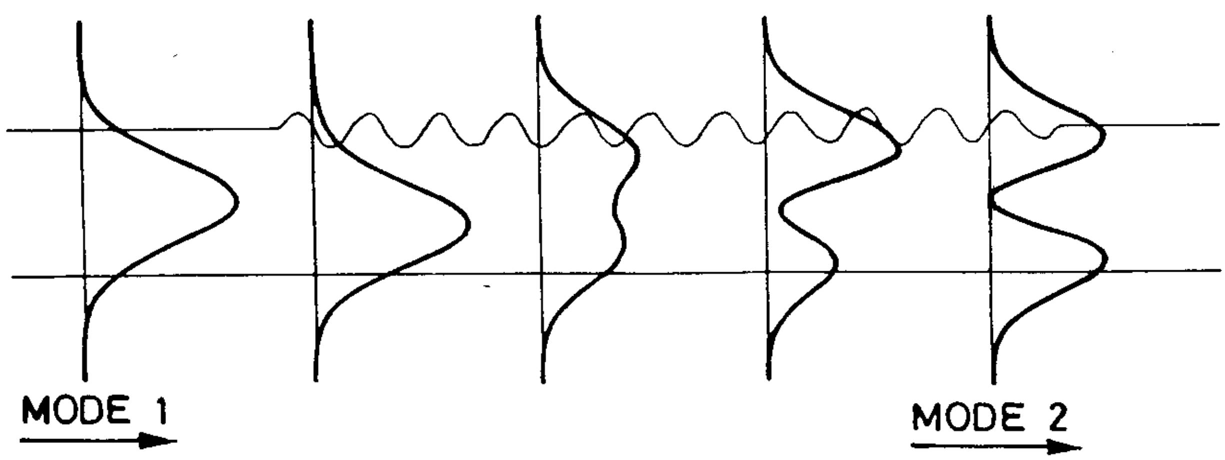
$$\hbar\omega \approx E_m - E_n \qquad \text{(Resonance Condition)}$$

Periodic Perturbation

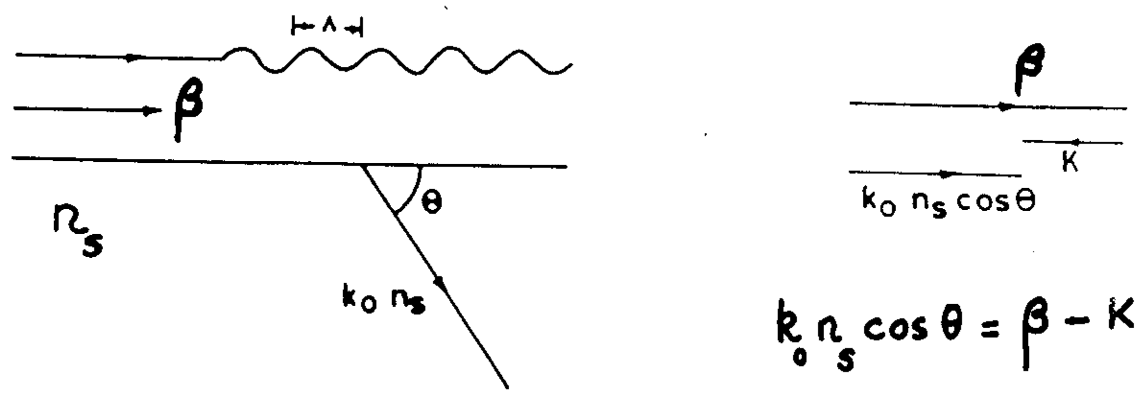


Phase Matching Condition :

$$\Delta\beta = \beta_m - \beta_n = \pm K = \pm \frac{2\pi}{\Lambda}$$

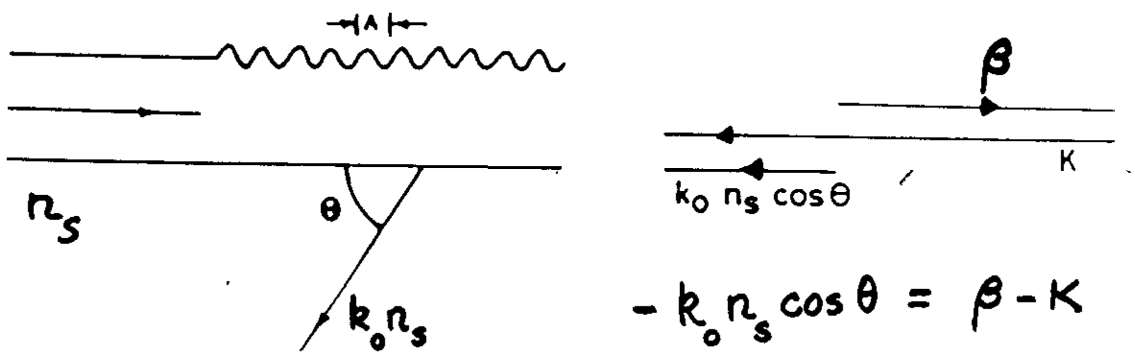


Phase Matching Condition



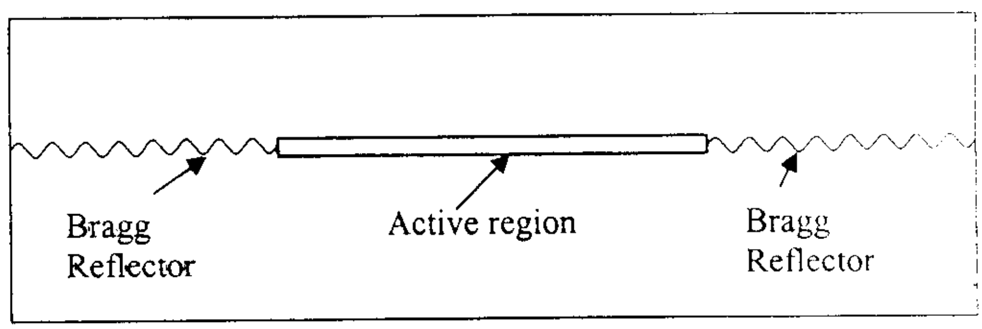
$$k_0 n_s \cos\theta = \beta - K$$

$$K = \frac{2\pi}{\Lambda}$$

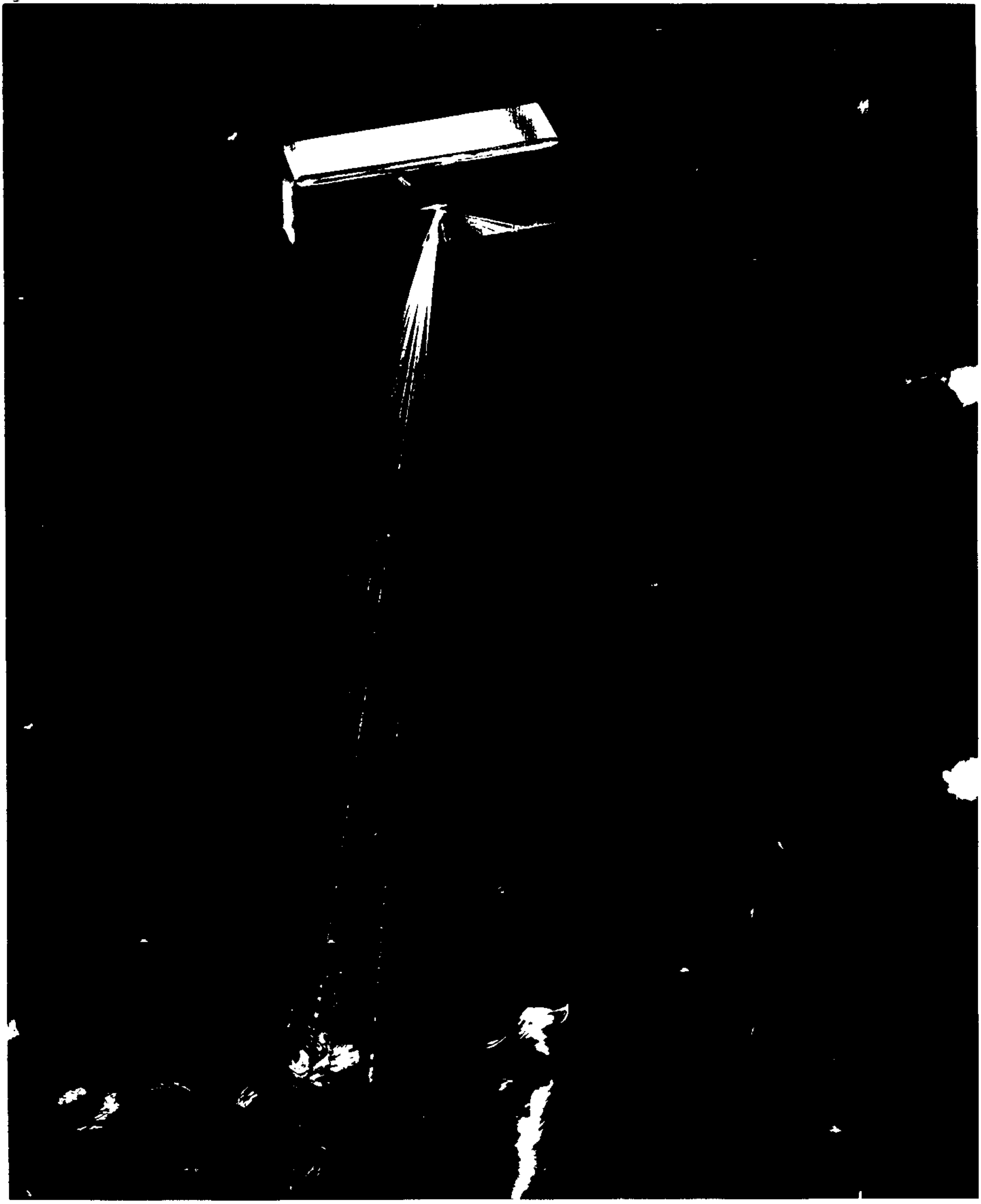


$$-k_0 n_s \cos\theta = \beta - K$$

Efficient method to achieve single longitudinal mode emission



DBR (Distributed Bragg Reflector) Laser



$$\Psi(x,z) = A\,\psi_0(x)\,e^{-i\beta_0 z} + B\,\psi_1(x)\,e^{-i\beta_1 z}$$

$$\frac{dA}{dz} = \kappa\, B\, e^{i\Gamma z}$$

$$\frac{dB}{dz} = -\kappa\, A\, e^{-i\Gamma z} \quad ; \quad \Gamma = \beta_1 - \beta_2 - K$$

κ depends on waveguide parameters, extend of periodic perturbation & λ_0.

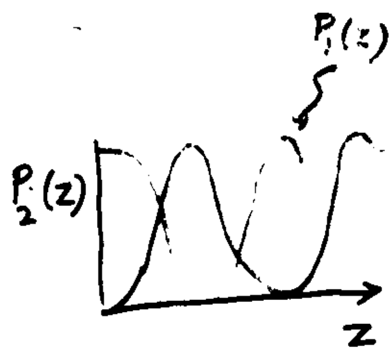
If $\Gamma = 0$ $(\beta_1 - \beta_2 = K)$ Phase Matching

$$\frac{d^2 A}{dz^2} = \kappa \frac{dB}{dz} = -\kappa^2 A(z)$$

$\Rightarrow$

$$P_1 = |A(z)|^2 = \cos^2 \kappa z$$

$$P_2 = |B(z)|^2 = \sin^2 \kappa z$$



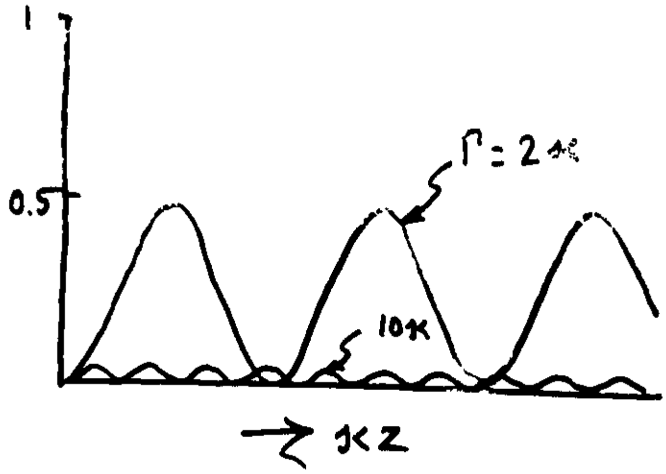
$\Gamma \neq 0$

$$\frac{d^2 B}{dz^2} + i\Gamma \frac{dB}{dz} + \kappa^2 B(z) = 0$$

$$P_1(z) = \cos^2 \gamma z + \frac{\Gamma^2}{4\gamma^2} \sin^2 \gamma z$$

$$P_2(z) = \frac{\kappa^2}{\gamma^2} \sin^2 \gamma z$$

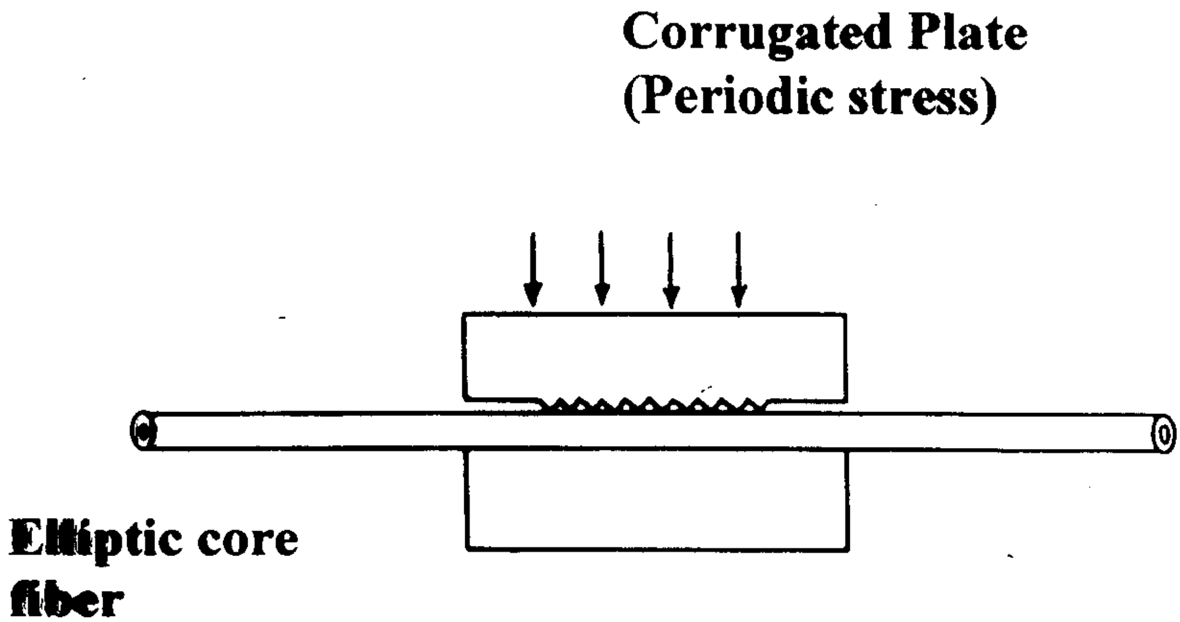
$$\gamma^2 = \kappa^2 + \frac{\Gamma}{4}^2$$

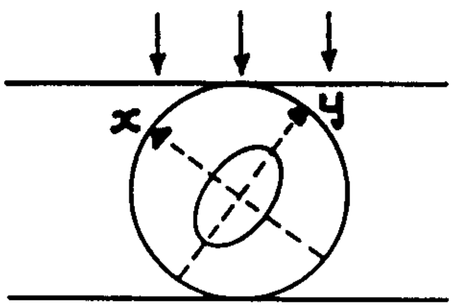


For more details see

Introduction to Fiber Optics.

Pressure Sensor





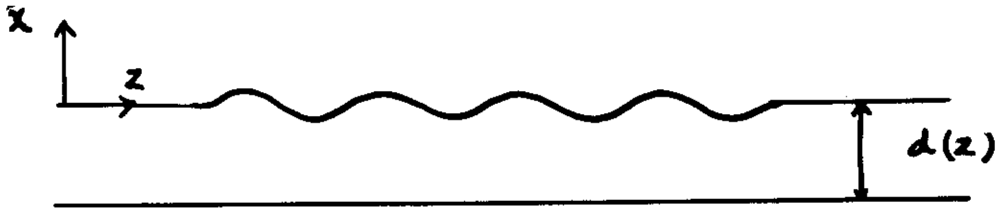
Beat Length $L_b = \dfrac{2\pi}{\beta_y - \beta_x} \approx$ few mm

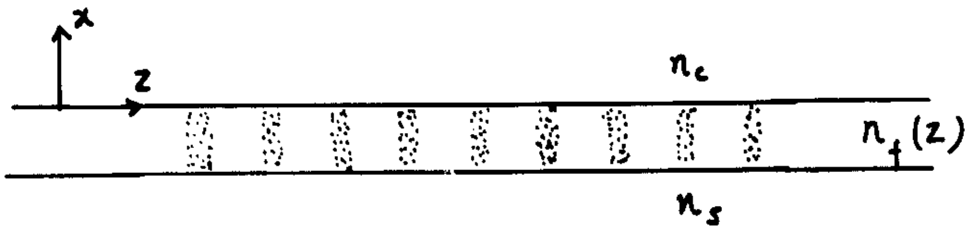
We must have

$$\Lambda \approx L_b$$

to induce coupling among the $x-$ and $y-$ polarized modes.

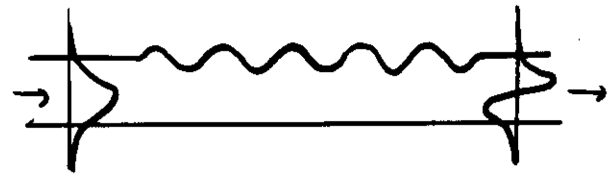
PERIODIC WAVEGUIDES



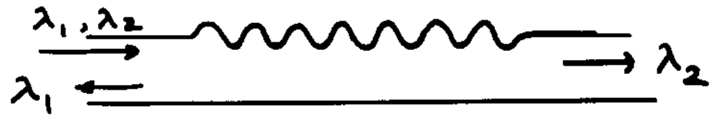


Applications in

- Mode converters

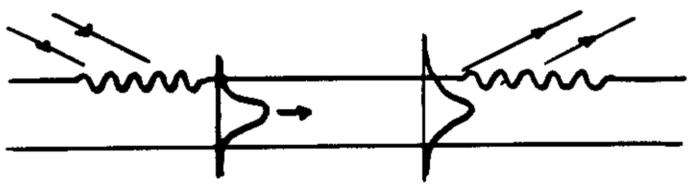


- λ filters

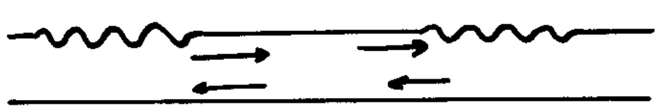


- Polarization transformers

- Input, output couplers



- DFB & DBR Lasers



Contradirectional Coupling

$$E(x,z) = A(z)\, E_1(x)\, e^{-i\beta_1 z} + B(z)\, E_2(x)\, e^{i\beta_2 z}$$

$$\frac{dA}{dz} = \kappa\, B(z)\, e^{i\Gamma z}$$

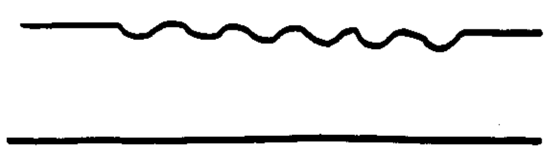
$$\frac{dB}{dz} = \kappa\, A(z)\, e^{-i\Gamma z} \qquad \Gamma = \beta_1 + \beta_2 - K$$

$\underline{\Gamma = 0}$ $\Rightarrow$ Say $\beta_1 = \beta_2$ $\Rightarrow$ $K = \frac{2\pi}{\Lambda} = 2\beta$

$$\Rightarrow \frac{2\pi}{\Lambda} = 2\, n_{eff} \cdot \frac{2\pi}{\lambda_0} \Rightarrow \boxed{\Lambda = \frac{\lambda_0}{2 n_{eff}}}$$

Bragg Condition

$$\frac{d^2 B}{dz^2} = \kappa \frac{dA}{dz} = \kappa^2 B(z)$$

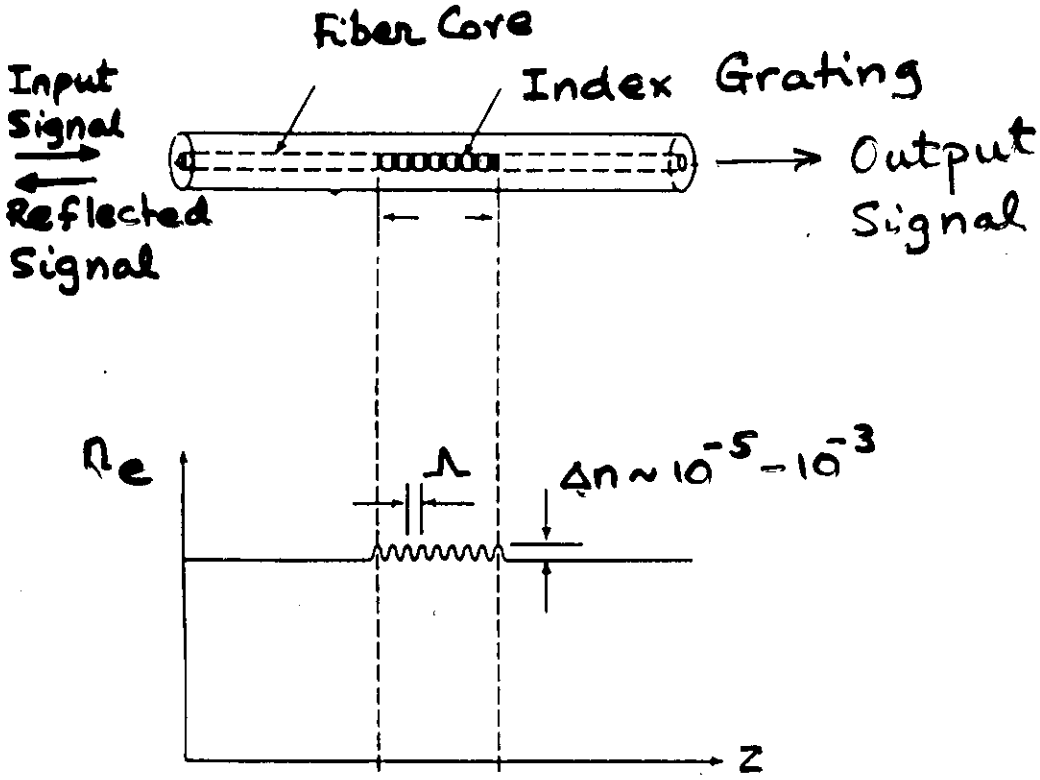


$$B(z) = \frac{\sinh \kappa (z-L)}{\cosh \kappa L}$$

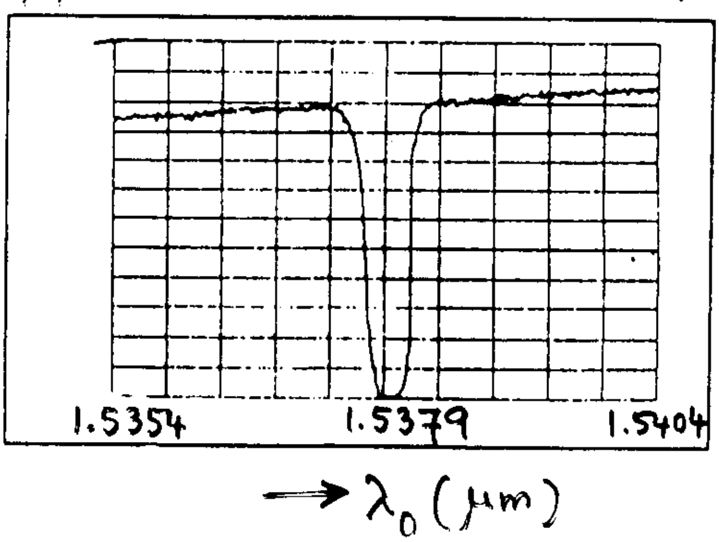
$$A(z) = \frac{\cosh \kappa (z-L)}{\cosh \kappa L}$$

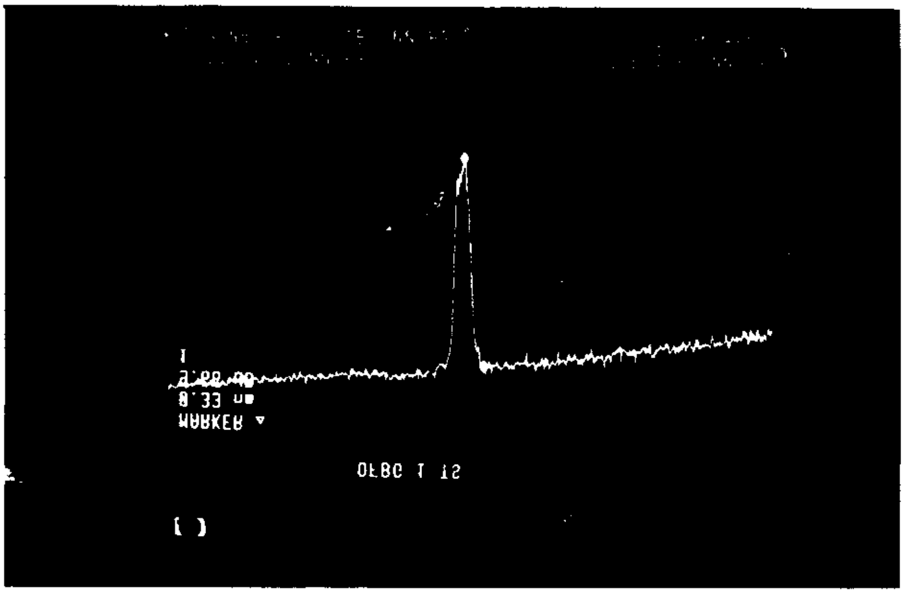
$$R = \tanh^2\left(\frac{\pi\, \Delta n\, L}{\lambda_0}\right) \qquad \text{for } n = n_0 + \Delta n \sin Kz$$

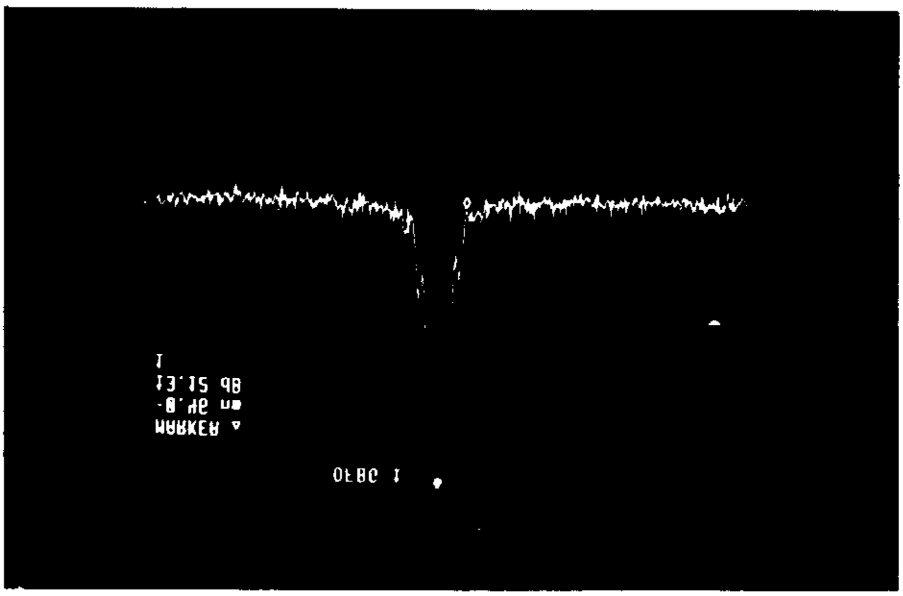
Fiber Bragg Gratings



Typical Transmission Spectrum

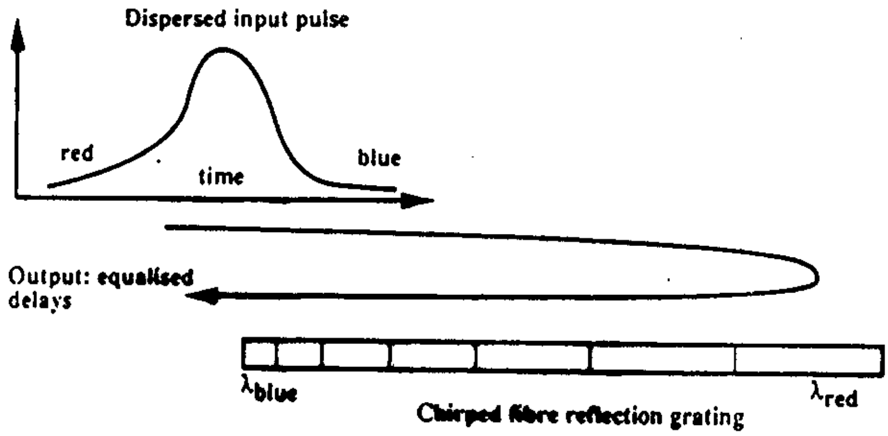




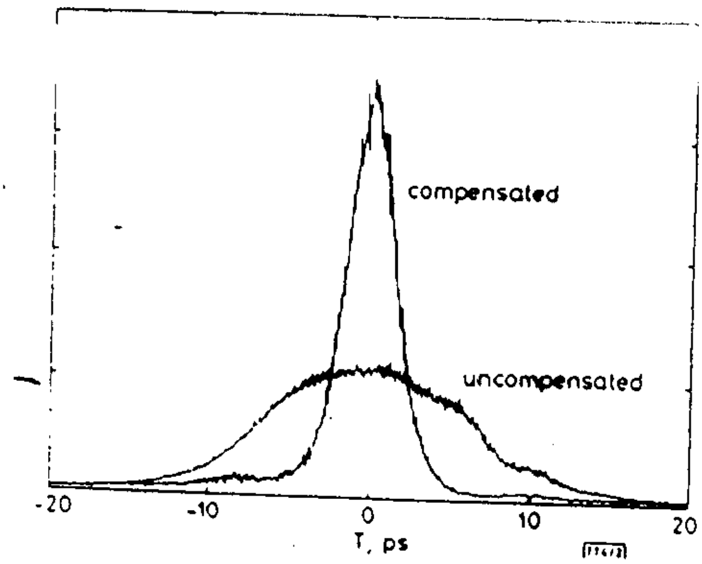


Dispersion Compensation:

Principle:



Typical Experimental Result:



*J.A.R. Williams et.al, Elect. Lett. 30, 12, 985 (1994).

FBGs are currently being exploited for applications in

- EDFA gain equalization,
- wavelength add/drop multiplexing,
- dispersion compensation,
- optical fiber sensor systems,
- routing, filtering, λ control in WDM systems

Advantages

- all fiber geometry
- have low insertion loss
- low back reflection
- potentially low cost
- flexibility in achieving a desired spectral characteristic