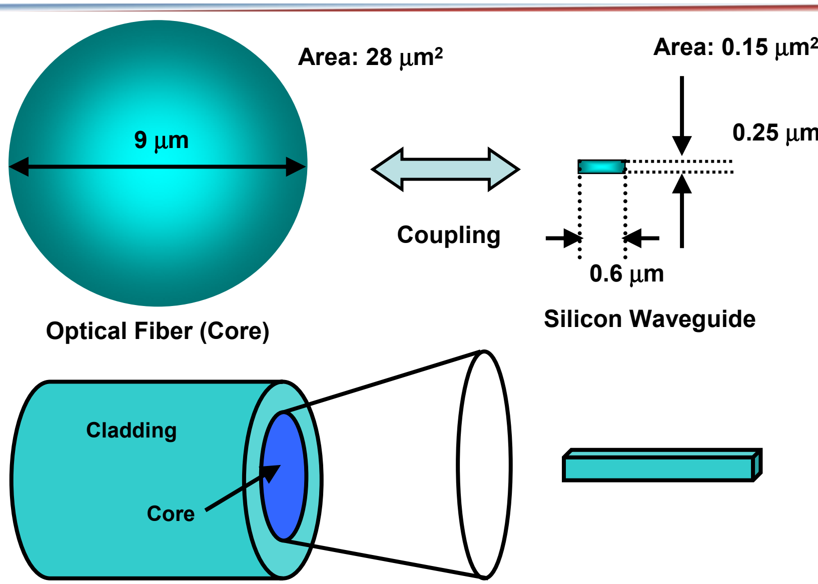
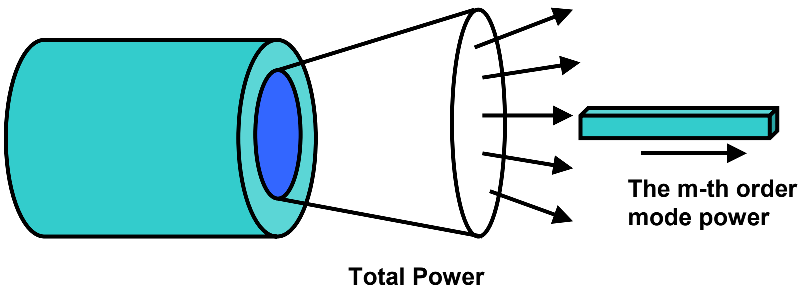
I/O Coupler

Class: Integrated Photonic Devices
Time: Fri. 8:00am ~ 11:00am.
Classroom: 資電206
Lecturer: Prof. 李明昌(Ming-Chang Lee)

I/O Fibre and Waveguide Coupling



Definition of Coupling Efficient



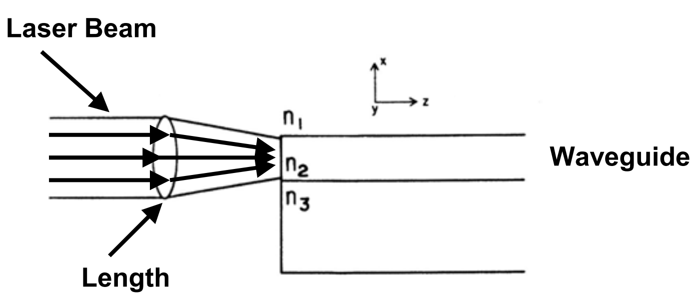
Coupling efficient **is defined as**

$$\eta_{cm} \equiv \frac{\text{Power coupled into (out of) the m-th order mode}}{\text{Total power in optical beam prior to coupling}}$$

Coupling loss (dB) is defined as

$$Loss_{cm} \equiv 10 \cdot \log \frac{\text{Power coupled into (out of) the m-th order mode}}{\text{Total power in optical beam prior to coupling}}$$

Direct Focusing



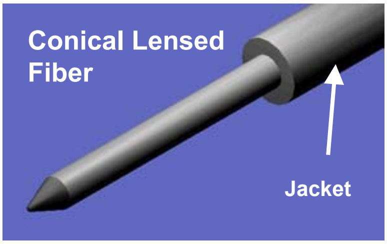
$$\eta_{cm} \equiv \frac{\left[\int\int A(x,y)B_m^*(x,y)dxdy\right]^2}{\int\int A(x,y)A^*(x,y)dxdy \cdot \int\int B_m(x,y)B_m^*(x,y)dxdy}$$

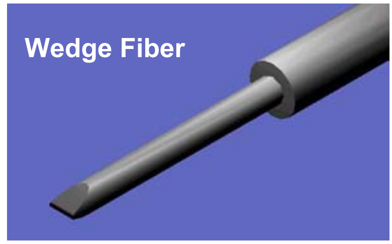
A(x,y) amplitude distribution of incident beam at facet

B(x,y) amplitude distribution of the m-th order waveguide mode

- **The coupling efficient depends on mode size matching.**
- **The coupling efficient depends on mode profile matching. (Gaussian beam is easy to be coupled to waveguide's fundamental mode)**

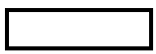
Lensed Fibers

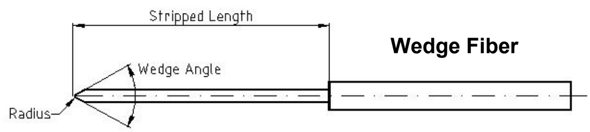




O/E Land

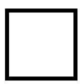
Rectangular Waveguide

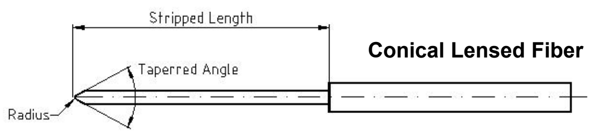




Wedge Fiber

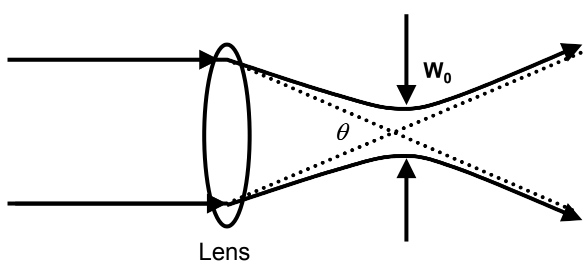
Square Waveguide





Conical Lensed Fiber

Diffraction Limit of Beam Spot

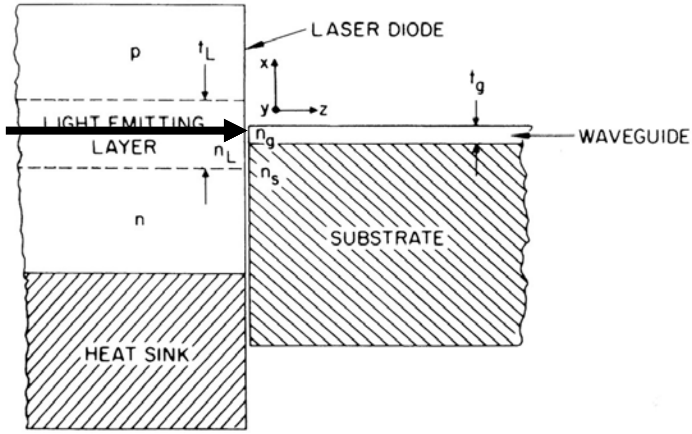


$$NA = \sin(\theta)$$

$$W_0 = \frac{2.44\lambda}{2NA} = 1.22\lambda / NA$$

- **The smallest beam spot size is limited by the NA (numerical aperture) and wavelength**

End-Butt Coupling



- **It is usually used for laser diode coupling light to waveguide (mode size is similar)**

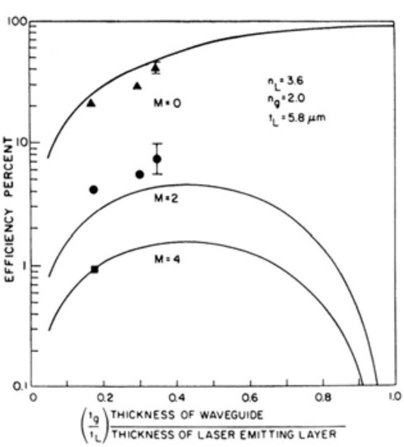
Efficiency of End-Butt Coupling

Suppose the light source is fundamental mode

$$\eta_{cm} \equiv \underbrace{\frac{64}{(m+1)^2\pi^2}}_{normalization}\cdot\underbrace{\frac{n_l n_g}{(n_l+n_g)^2}}_{reflection}\cdot$$

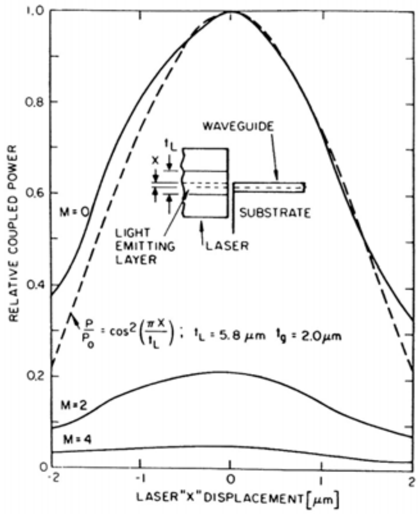
$$\underbrace{\cos^2\left(\frac{\pi t_g}{2t_l}\right)\cdot\frac{1}{\left[1-\left(\frac{t_g}{(m+1)t_l}\right)^2\right]^2}}_{Overlap}\cdot\underbrace{\frac{t_g}{t_l}}_{area\ mismatch}\cdot\underbrace{\cos^2\left(\frac{m\pi}{2}\right)}_{even\ or\ odd}$$

m: mode No. (waveguide)



- **Coupling efficiency decrease with index contrast. (Most power is reflected)**
- **There is no coupling between symmetric modes (even modes) and anti-symmetric modes (odd modes)**
- **Coupling efficient is maximal as the mode profile is matched**

Misalignment of End-Butt Coupling



Suppose $t_g < t_L$ and $X \leq (t_L - t_g)/2$

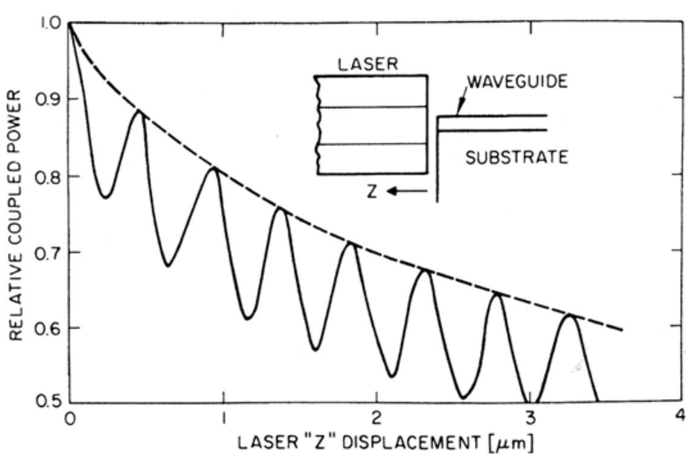
$$P = P_0 \cos^2(\frac{\pi X}{t_L})$$

X: vertical misalignment

P_0: the coupled power for X = 0

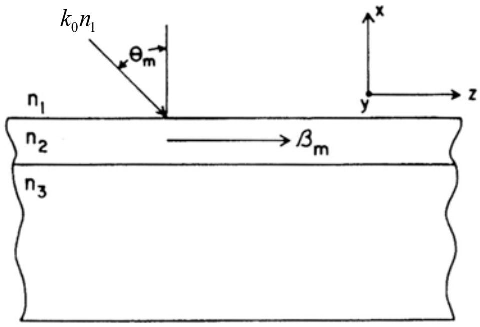
- Coupling efficiency is very sensitive to the misalignment in vertical direction

Space Variation of End-Butt Coupling



- The power decay is due to diffraction loss
- The oscillation is due to Fabry-Perot etalon (discussed in the following section)

Surface Coupling



To couple light into the waveguide, phase-matching condition has to be satisfied.

Thus,

$$\beta_m = k_0 n_1 \sin\theta_m = \frac{2\pi}{\lambda_0} n_1 \sin\theta_m$$

However, to guide wave

$$\beta_m > \frac{2\pi}{\lambda_0} n_1$$

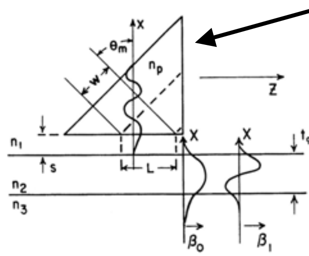
$\longrightarrow$ $\sin\theta_m > 1$ **(?)**

- **What is the advantage of surface coupling?**
- **Is it possible that the light is coupled from the surface to the waveguide?**

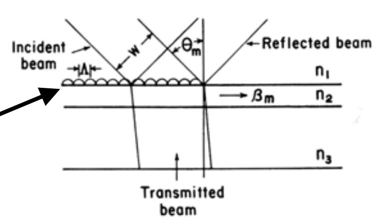
Two Types of Surface Coupling

- **Prism Couplers**

Prism

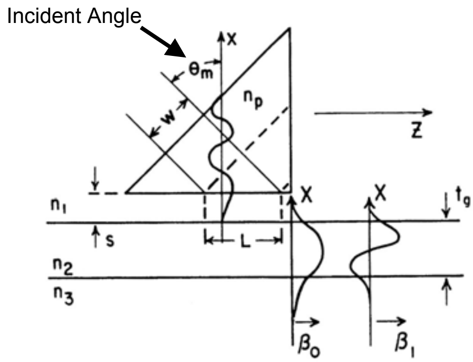


- **Grating Couplers**



Grating

Prism Couplers



To satisfy phase matching,

$$\frac{2\pi n_p}{\lambda_0}\sin\theta_m = \beta_m$$ **(true only if** $n_p > n_1$ **)**

$$\theta_m > \theta_c = \sin^{-1}\left(\frac{n_1}{n_p}\right)$$ **(total reflection)**

To achieve a complete power transfer

$$\kappa L = \frac{\pi}{2}$$ **(Recall** $\cos^2(\kappa L)$ **)**

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

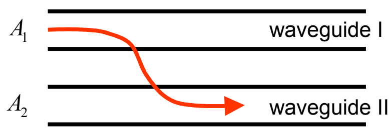
- **θ_m have to be larger than the critical angle θ_c (what's happen if not?)**
- **The coupling coefficient depends on the n_p, n_1, n_2 and gap s.**
- **Each waveguide mode corresponds to a specific angle.**
- **In fact, the coupling efficient also depends on the beam profile**

Prism Couplers

- **Disadvantage: the input light should be highly collimated**
- **It is difficult to make a high index prism for semiconductor waveguide**

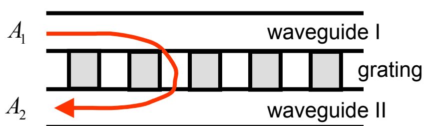
Coupling by Grating

<u>Codirectional coupling</u> (β_1 and β_2 have the same propagation direction)



$$\begin{cases} \dfrac{dA_1}{dz} = j\kappa_{12} A_2 \exp[j(\beta_2 - \beta_1)z] \\ \dfrac{dA_2}{dz} = j\kappa_{21} A_1 \exp[-j(\beta_2 - \beta_1)z] \end{cases}$$

<u>Contradirectional coupling</u> (β_1 and β_2 have different propagation direction)

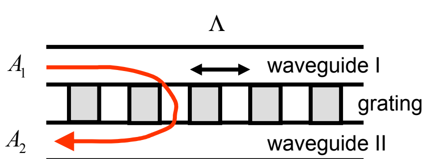


$$\begin{cases} \dfrac{dA_1}{dz} = j\kappa_{12}(z) A_2 \exp[j(\beta_2 - \beta_1)z] \\ \dfrac{dA_2}{dz} = -j\kappa_{21}(z) A_1 \exp[-j(\beta_2 - \beta_1)z] \end{cases}$$

minus

Coupling by Grating

<u>Contradirectional coupling</u> (β_1 and β_2 have different propagation direction)



$$\begin{cases} \dfrac{dA_1}{dz} = j\kappa_{12} A_2 \exp[j(\beta_2 - \beta_1)z] \\ \dfrac{dA_2}{dz} = -j\kappa_{21} A_1 \exp[-j(\beta_2 - \beta_1)z] \end{cases}$$

Remind

$$\kappa_{pq}(z) \propto \omega\varepsilon_0 \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} (N^2 - N_q^{\,2}) \mathbf{E}_p^{\,*} \cdot \mathbf{E}_q \, dxdy = \omega\varepsilon_0 \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \underbrace{\Delta\varepsilon(z)}_{\text{periodic function}} \cdot \mathbf{E}_p^{\,*} \cdot \mathbf{E}_q \, dxdy$$

periodic function

→ $\kappa_{pq}(z) \propto \sum_m \kappa_{pq}(m) \exp(jm\mathrm{K}z)$ (Fourier Series)

where $\mathrm{K} = \dfrac{2\pi}{\Lambda}$ and $\kappa_{pq}(m) = \dfrac{1}{\Lambda}\displaystyle\int_0^{\Lambda} \kappa_{pq}(z) \exp(-jm\mathrm{K}z)\, dz$

Coupling by Grating

$$\kappa_{qp}(z) = \kappa_{pq}^{*}(z) = \sum_{m} \kappa_{pq}^{*}(m)\exp(-jmKz) \longrightarrow \kappa_{qp}(m) = \kappa_{pq}^{*}(-m)$$

The first order mode coupling (m=1):

$$\begin{cases} \dfrac{dA_1}{dz} = j\kappa_{12}A_2\exp[j(\beta_2-\beta_1)z] \\ \dfrac{dA_2}{dz} = -j\kappa_{21}A_1\exp[-j(\beta_2-\beta_1)z] \end{cases} \longrightarrow \begin{cases} \dfrac{dA_1}{dz} = j\kappa_{12}(1)A_2\exp[j(\beta_2-\beta_1+\dfrac{2\pi}{\Lambda})z] \\ \dfrac{dA_2}{dz} = -j\kappa_{12}(1)A_1\exp[-j(\beta_2-\beta_1+\dfrac{2\pi}{\Lambda})z] \end{cases}$$

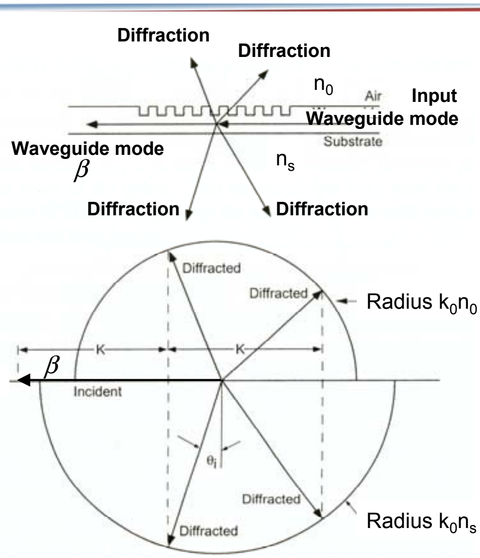
$$\beta_1 = \beta_2 + \frac{2\pi}{\Lambda}$$ (Phase-matched)

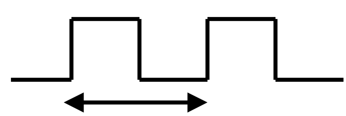
The second order mode coupling (m=2):

$$\begin{cases} \dfrac{dA_1}{dz} = j\kappa_{12}A_2\exp[j(\beta_2-\beta_1)z] \\ \dfrac{dA_2}{dz} = -j\kappa_{21}A_1\exp[-j(\beta_2-\beta_1)z] \end{cases} \longrightarrow \begin{cases} \dfrac{dA_1}{dz} = j\kappa_{12}(2)A_2\exp[j(\beta_2-\beta_1+\dfrac{4\pi}{\Lambda})z] \\ \dfrac{dA_2}{dz} = -j\kappa_{12}(2)A_1\exp[-j(\beta_2-\beta_1+\dfrac{4\pi}{\Lambda})z] \end{cases}$$

$$\beta_1 = \beta_2 + 2\cdot\frac{2\pi}{\Lambda}$$ (Phase-matched)

Grating Coupler (Output)





Λ : **period of grating**

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

The horizontal k vector (propagation constant β) is shifted by

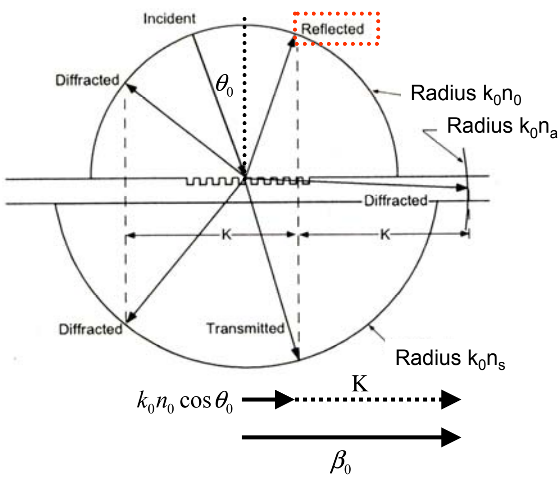
$$\beta_n = \beta_0 + nK$$

where $n = 0, \pm1, \pm2, \cdots$

$$\theta_n = \cos^{-1}\left(\frac{\beta_n}{k_0 n_{0,s}}\right)$$

Grating Coupler (Input)

Because the propagation constant can be shifted by grating, it can be used for surface coupling.



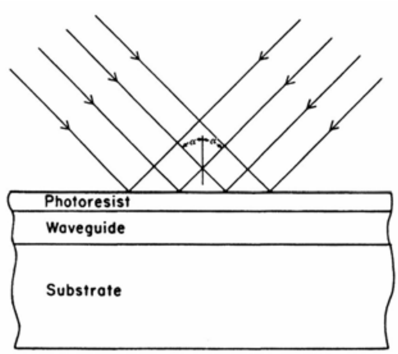
To couple light to the waveguide mode β_0, the incident angle θ_0 has to be designed as:

$$k_0 n_0 \cos\theta_0 + \mathrm{K} = \beta_0$$

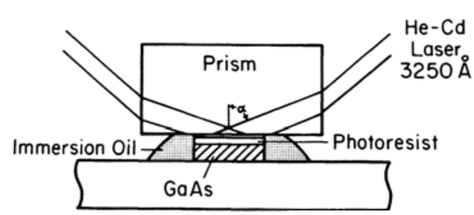
$$\theta_0 = \cos^{-1}\left(\frac{\beta_0 - \mathrm{K}}{k_0 n_0}\right)$$

Q: Is it better for large K or small K?

Grating Fabrication



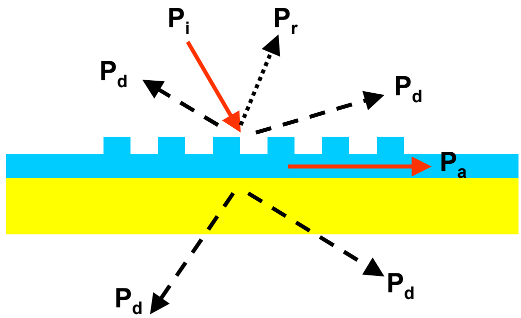
$$\Lambda = \frac{\lambda_0}{2\sin\alpha}$$



$$\Lambda = \frac{\lambda_0}{2n\sin\alpha}$$

- **A grating structure may be formed by either by masking and etching the waveguide surface**
- **Gratings are often patterned by holographic process (optical interference**

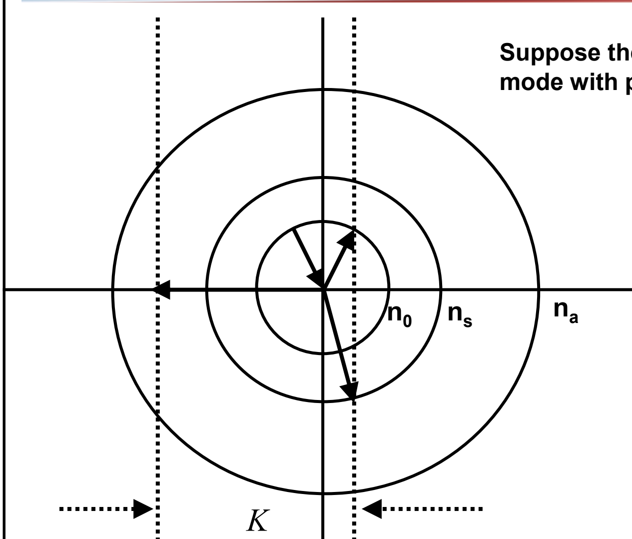
Coupling Efficient of Grating Coupler



$$\eta = \frac{P_a}{P_i}$$

- The coupling efficiency depends on the ratio of power transfer from the input light to the waveguide mode
- More diffraction modes decrease the coupling efficiency
- Polarization dependency.

Single Order Grating



Suppose the waveguide is single mode with propagation constant β

$$-k_0 n_0 < \beta - \mathrm{K} < 0$$

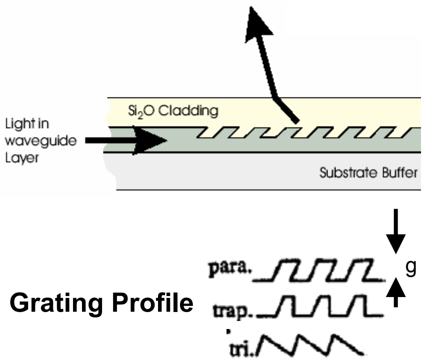
↓

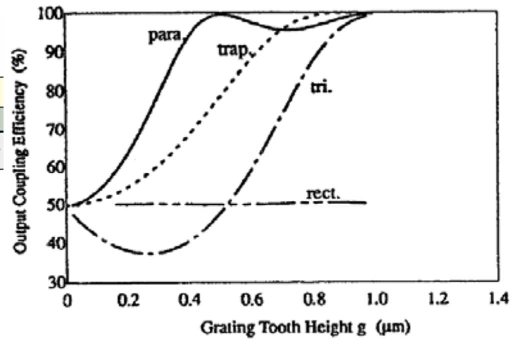
$$\beta < \mathrm{K} < \beta + k_0 n_0$$

↓

$$\frac{2\pi}{\beta + k_0 n_0} < \Lambda < \frac{2\pi}{\beta}$$

Asymmetric Grating Couplers

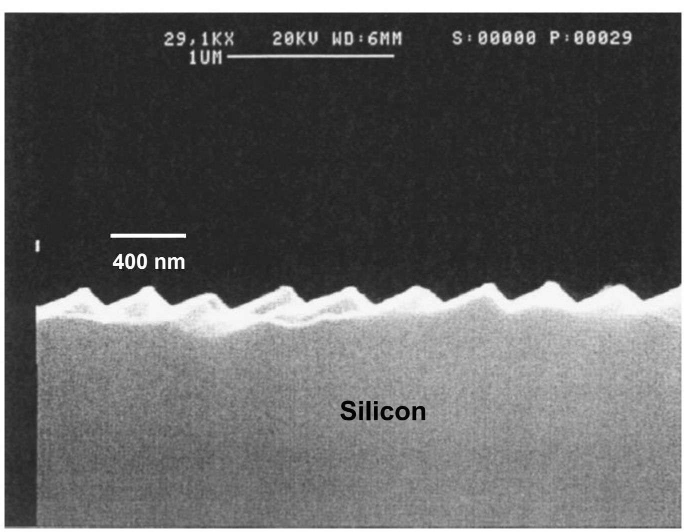




S.J. Sheard, JLT 1997

- **Asymmetric grating couplers are advantageous to single mode coupling**
- **Parallelogramic grating has the highest coupling coefficient**

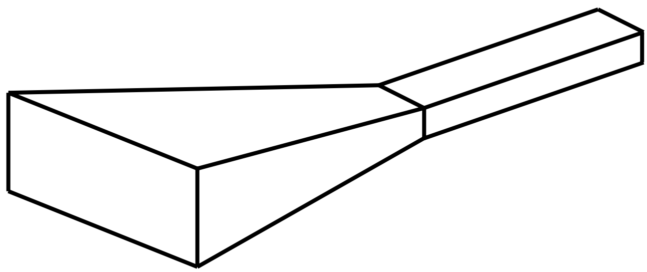
Blade Grating (Silicon)



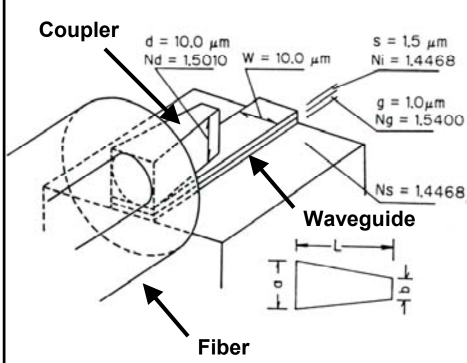
T. W. ANG, *Fiber and Integrated Optics, 2000*

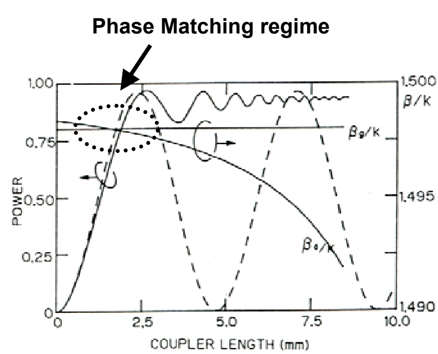
Tapered Mode Size Couplers

- **Adiabatic Tapered Waveguide**
  - **Lateral taper and vertical taper**
  - **With or without other index-matching material**



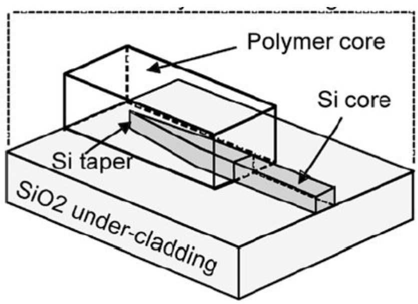
Tapered Mode Size Converters

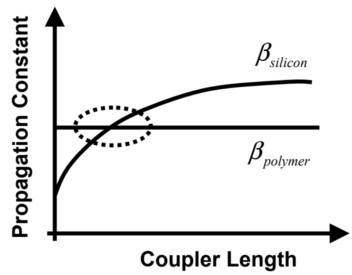


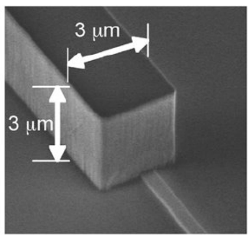


- **The coupler is tapered without changing the waveguide dimension**
- **The dimension of coupler interface is designed to match fiber core.**

Inverted Tapered Mode Size Converters







- **The waveguide is inverted tapered without changing the coupler dimension**
- **It is useful for high index-contrast waveguide**
- **The coupling length is usually small**