2.1 Tapered devices

Waveguides, devices and sensors

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Summary of previous lectures

- Each waveguide has properties which are material dependent and design dependent: attenuation, loss, dispersion, mode degeneracy.
- In a perfect optical fibre some of these modes are degenerate
- Because of cylindrical symmetry, polarization modes are degenerate.
- High intensities induce nonlinear optical effects

Outline

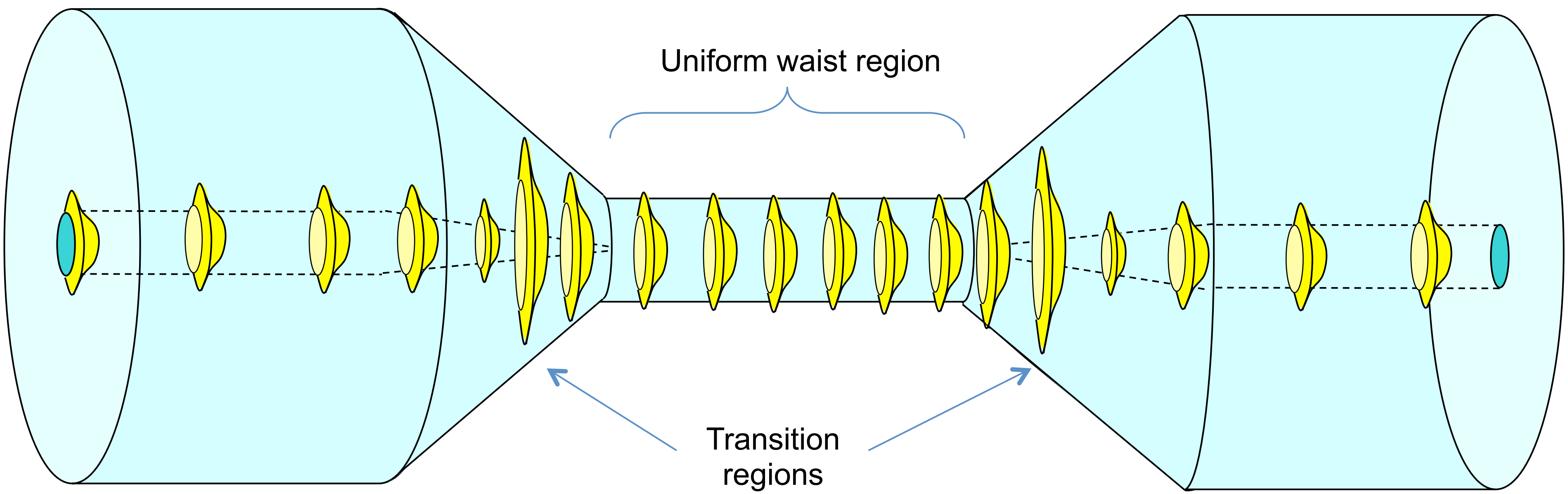
- Optical fibre tapers
- Optical fibre couplers
- Coupled Wave Equations

Learning Outcome

- Assess coupling between different modes
- Describe the working principle of fiberised devices (Coupler, Tapers)
- Design optical devices

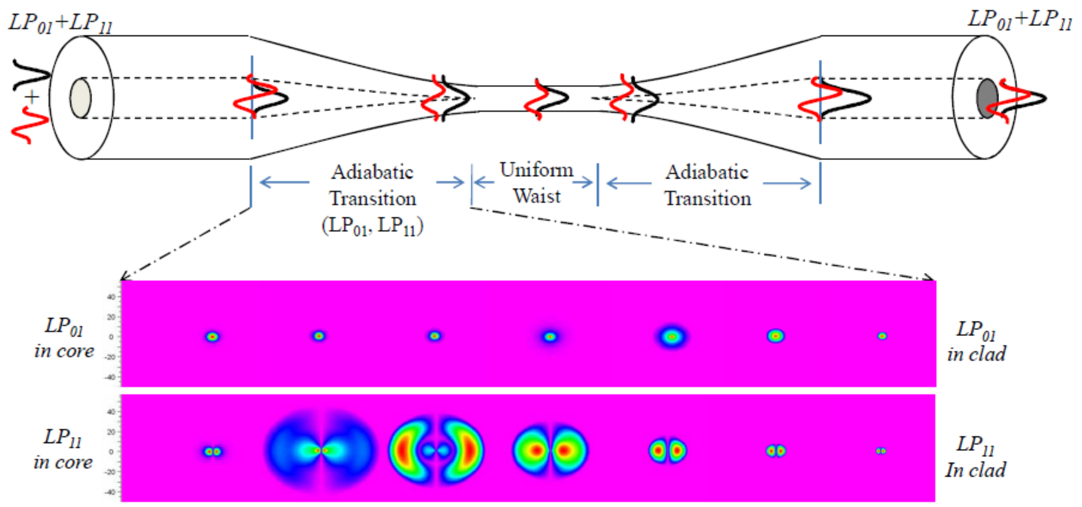
Tapers

It is the simplest device. It is a section of waveguide with reduced diameter. In the **transition regions** the diameter decreases, V decreases, the mode overlap with the core *h* decreases. For very small V, the mode is guided by the cladding/air interface. In the **uniform waist region** the evanescent field is OUTSIDE the glass. Core dopants diffuse over the whole taper cross section in the UWR

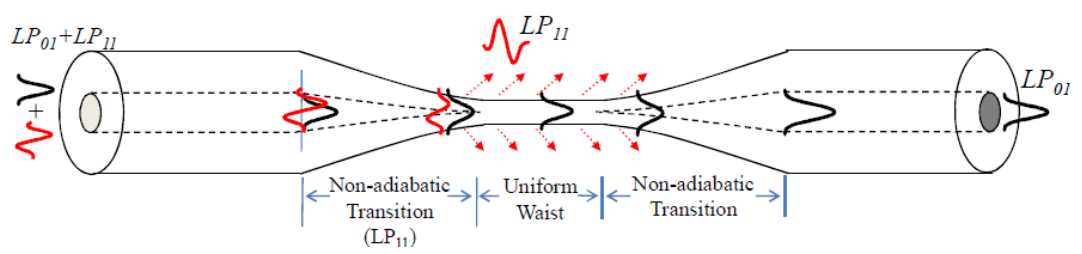


Tapers

In the transition regions the diameter changes: coupling between different modes can occur. The taper is called adiabatic if no power exchange occurs.



If the transition is sharp, modes exchange power and experience loss.



Jung, Opt. Express 16(19) (2008): 14661-14667

Taper adiabaticity

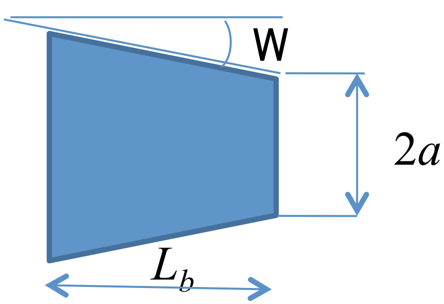
In an adiabatic transition, the taper angle is small enough so that the LP_{01}, LP_{11} core modes can be considered unperturbed as they evolve from being core-guided to cladding-guided.

The beat length L_b between two modes with propagation constants b_1 and b_2 has been considered the defining factor for adiabaticity.

$$L_b = \frac{2\pi}{\beta_1 - \beta_2}$$

Two modes do not exchange power for distances longer than the beating length: thus the transition region angle W is limited by:

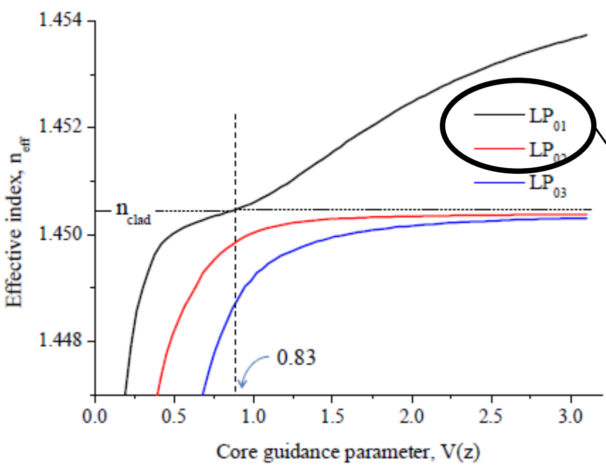
$$\Omega \leq \frac{\Delta a}{L_b} < \frac{a(\beta_1 - \beta_2)}{2\pi}$$



Adiabatic Taper Design

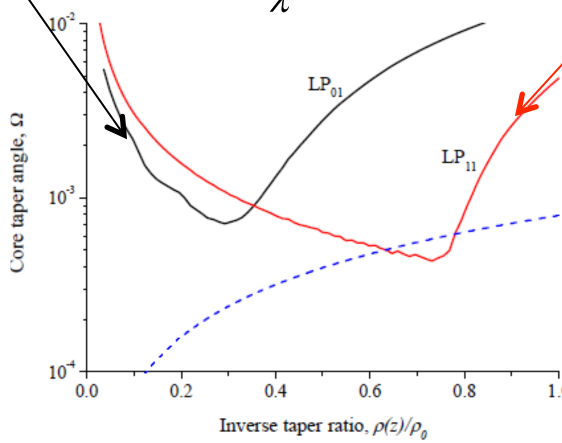
In non-adiabatic transition, modes couple to high order modes with the same symmetry. Amongst those, the most efficient is the next high order mode ($LP_{01} \rightarrow LP_{02}$; $LP_{11} \rightarrow LP_{12}$; $LP_{21} \rightarrow LP_{22}$)

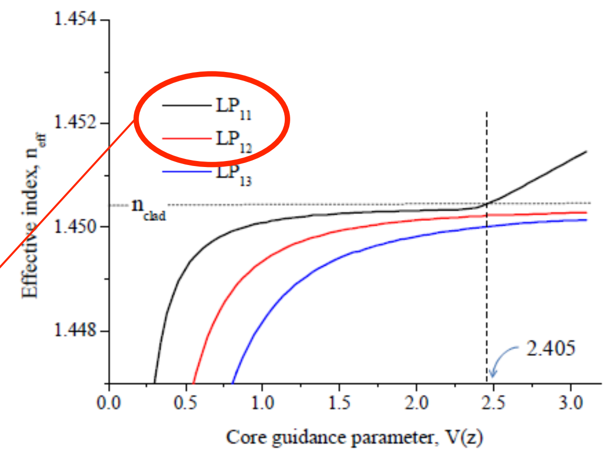
b_1 and b_2 are calculated for unperturbed waveguides at different waveguide size a, then W is calculated:



$$\Omega \le \frac{a}{z} = \frac{a(\beta_1 - \beta_2)}{2\pi}$$

$$\beta = \frac{2\pi}{\lambda} n_{eff}$$

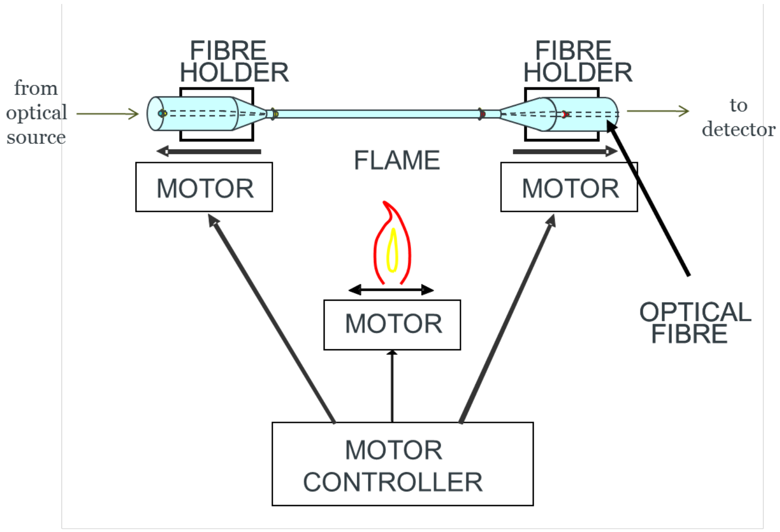


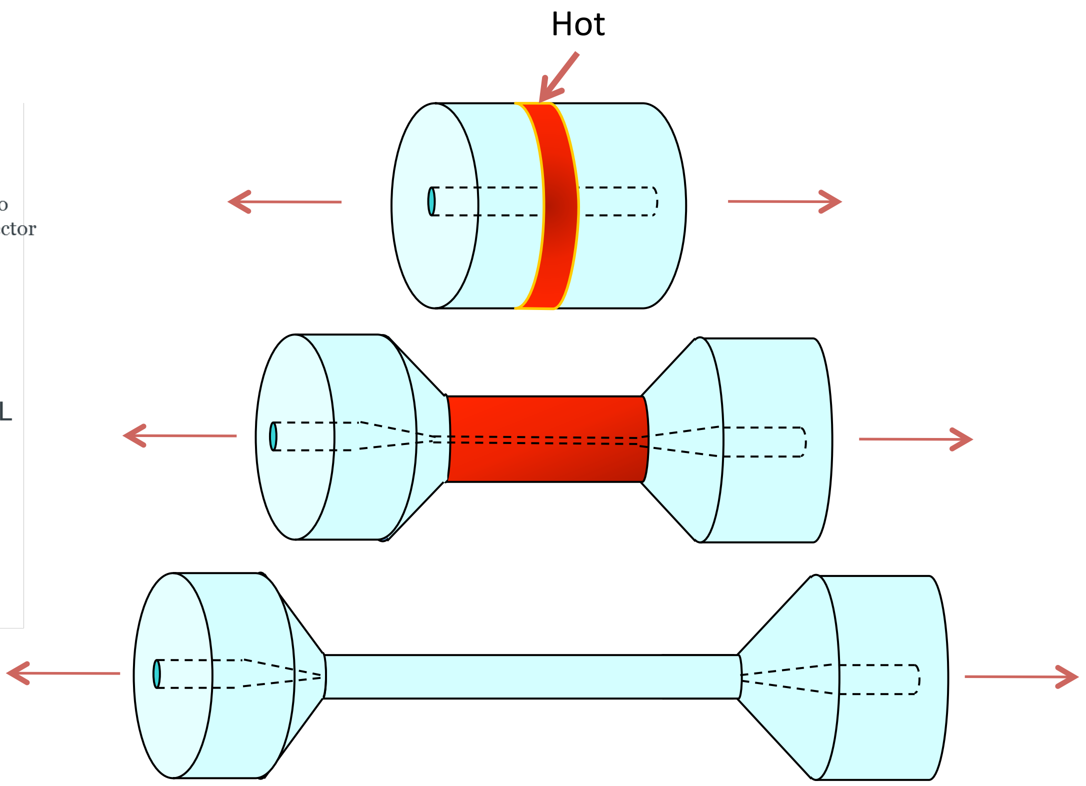


Jung, Opt. Express 16(19) (2008): 14661-14667

Taper manufacture (fibres)

Optical fibre tapers are made by stretching fibres which are being heated above the softening temperature (h_s=$10^{7.6}$poise). The mass conservation law allows to calculate the diameter of tapered fibres for each elongation.





Taper manufacture (silica fibres)

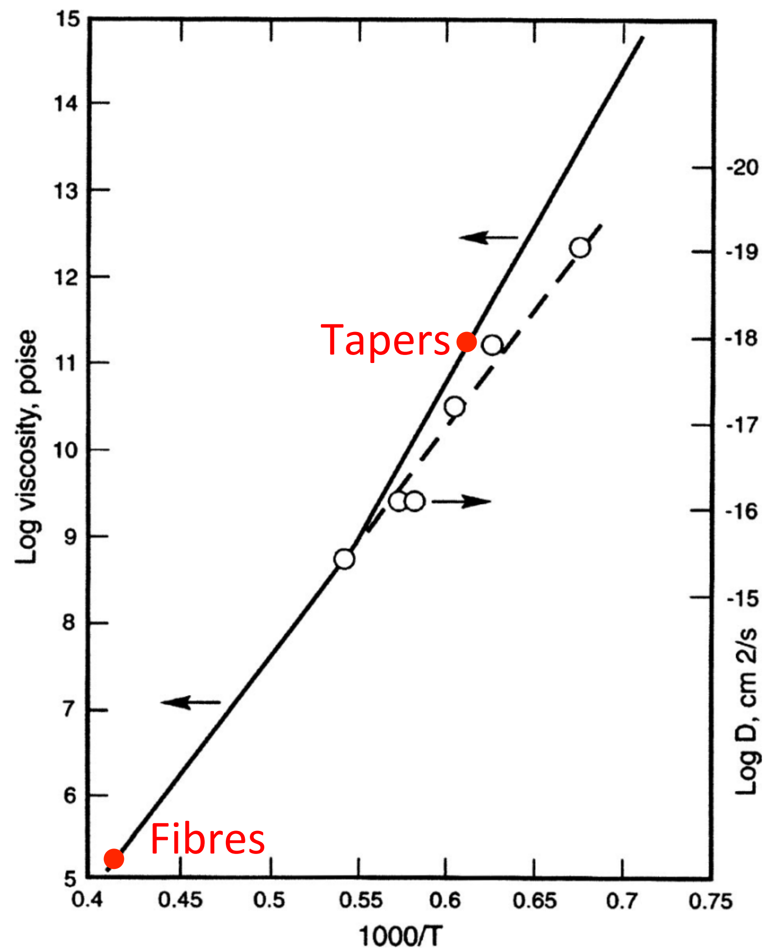
Processing temperature is strongly dependent on the processing speed.

Stress in silica fibres should be smaller than a critical value, otherwise fibre will break.

Viscous force: F α µv
µ = viscosity
v= pulling speed

Fibres are pulled at 2km/min, tapers at 1mm/min:
6 orders of magnitude difference in v
6 orders of magnitude in µ

T from 2200^{o}C can be decreased to 1400 ^{o}C:
Use inexpensive butane flame instead of expensive graphite furnace

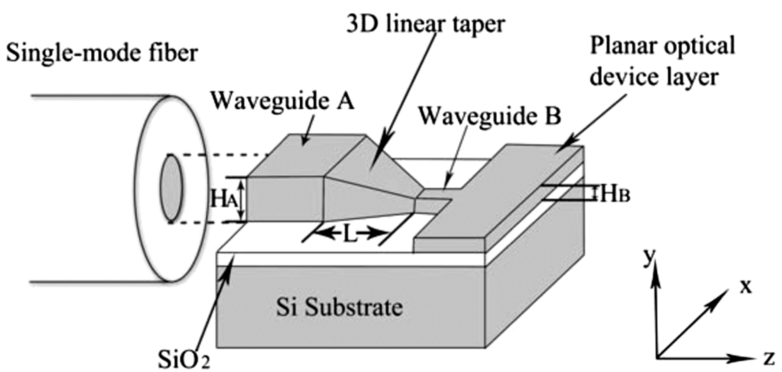


R.H. Doremus, J. Appl. Phys. 92(12), (2002) 7619

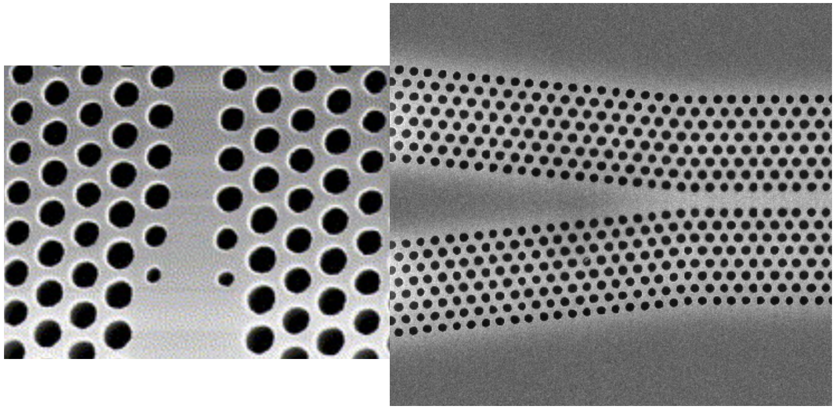
Taper manufacture (planar)

Planar waveguides are manufactured by photolithographic means. Tapers cannot be made after fabrication. They are designed together with the waveguide.

Tapers can have constant waveguide size and changing refractive index or changing waveguide size and constant refractive index. In practice the second is more convenient in solid planar waveguides.



Z. Yang, Opt. Eng. 48(3), (2009) 030503

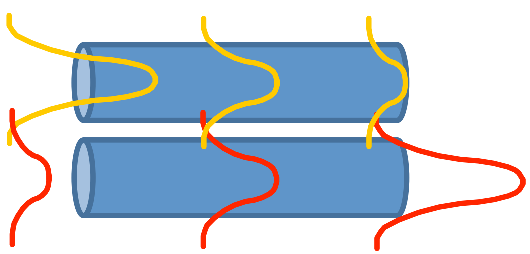


Couplers

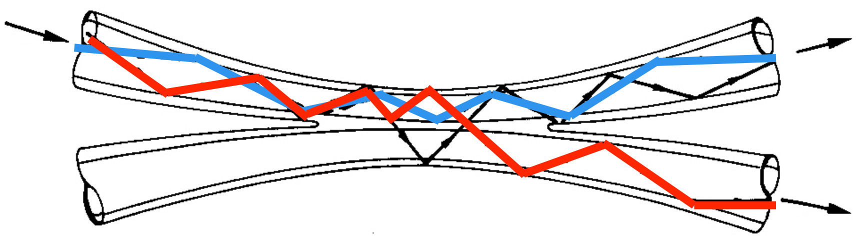
Couplers are multi waveguide devices that allow to exchange power in a controlled manner.

In waveguides a fraction of the power is propagating in the evanescent field outside the core. If this overlaps with another field, it exchanges power → Coupling.

Output and input waveguides are called PORTS



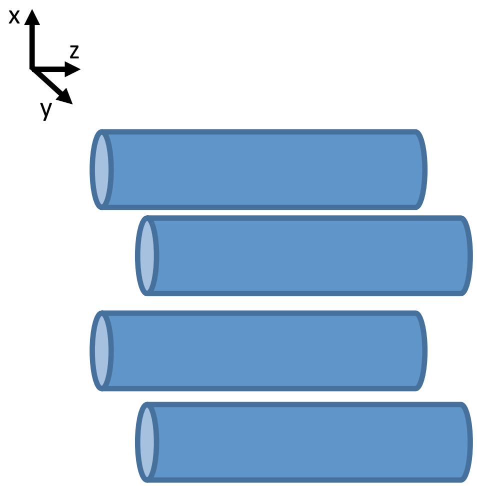
Working mechanism (Wave theory)

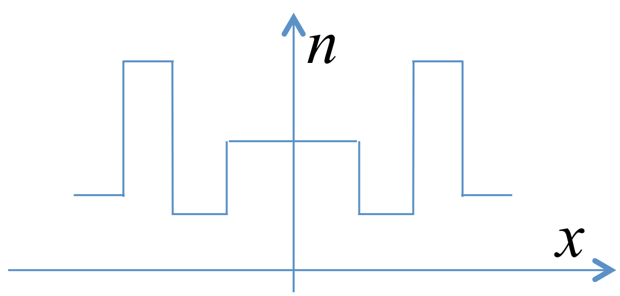


Working mechanism (Ray theory)

Couplers: mode coupling

Coupling between different waveguides can be calculated solving Maxwell equation for the whole structure (i.e. considering the complex refractive index profile given by different waveguides)



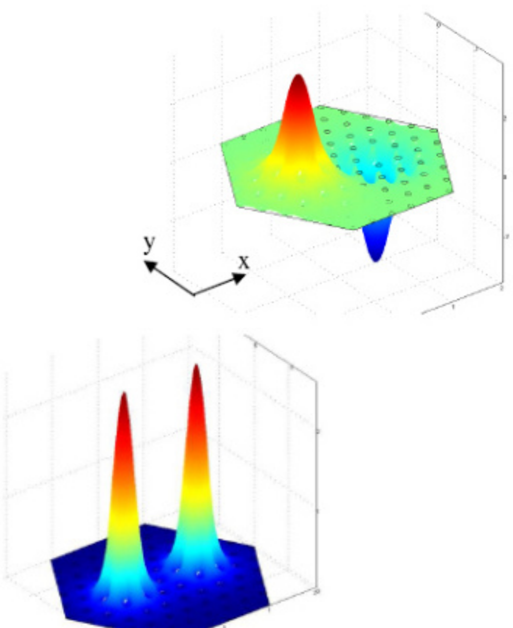


It is challenging for fibres as cylindrical symmetry is broken

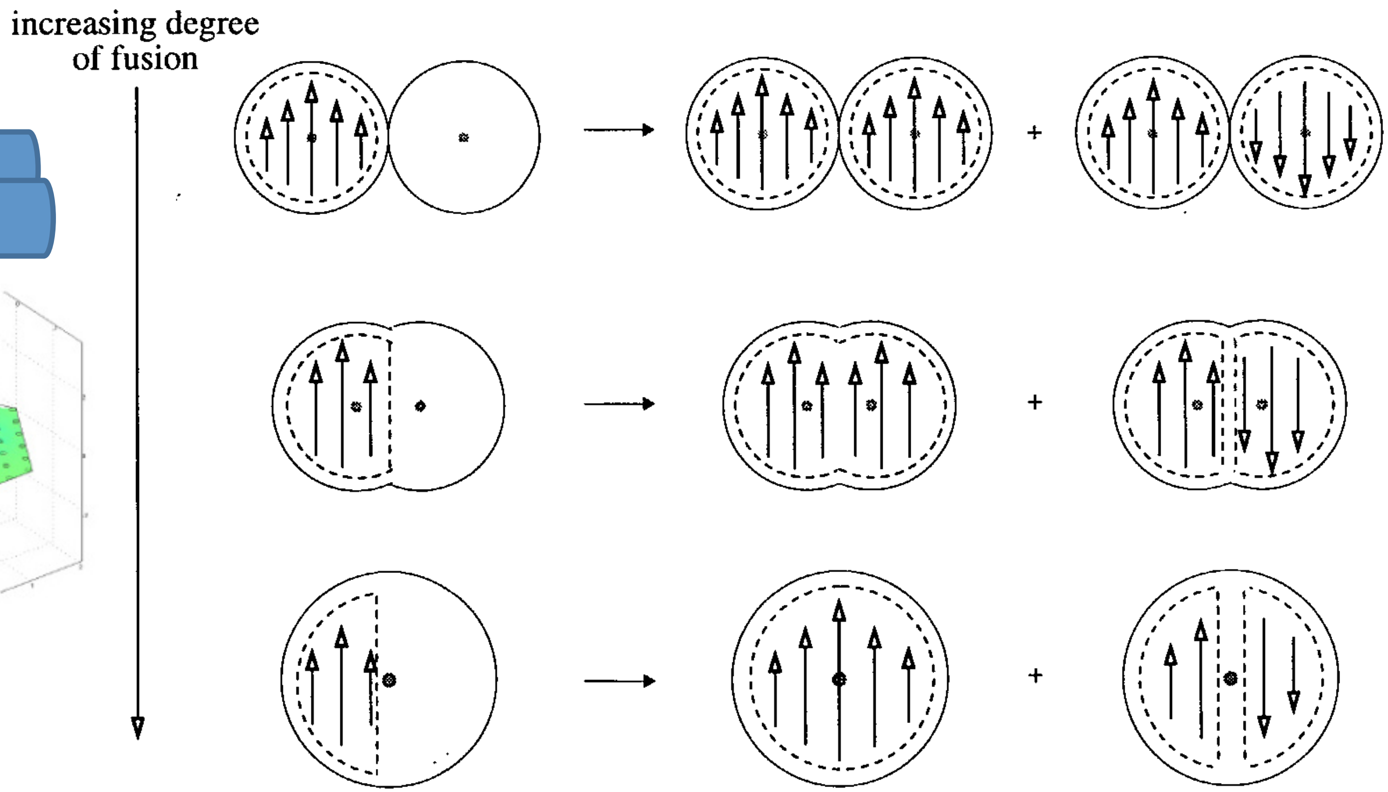
Slab waveguides are 1D case: easier to solve

Solutions

Maxwell equations solutions are called supermodes



Di Bin, Opt. Express 17 (2009) 15778-89



Excitation | Fundamental Supermode | High order Supermode

S. Farwell, PhD thesis (1997)

Field

Modes are orthonormal solutions of Maxwell equations.

Each propagating field can be expressed as linear combination of modes $E_i\,(z)$ with a weight coefficient $A_i(z)$:

$$E(z) = \sum_j A_j(z) E_j(z) e^{-i(\beta_j z - \omega t)}$$

where $A_j(z)$ are position dependent if there is power exchange with other modes.

It is possible to approximate the exact solution as linear combination of modes of ALL waveguides

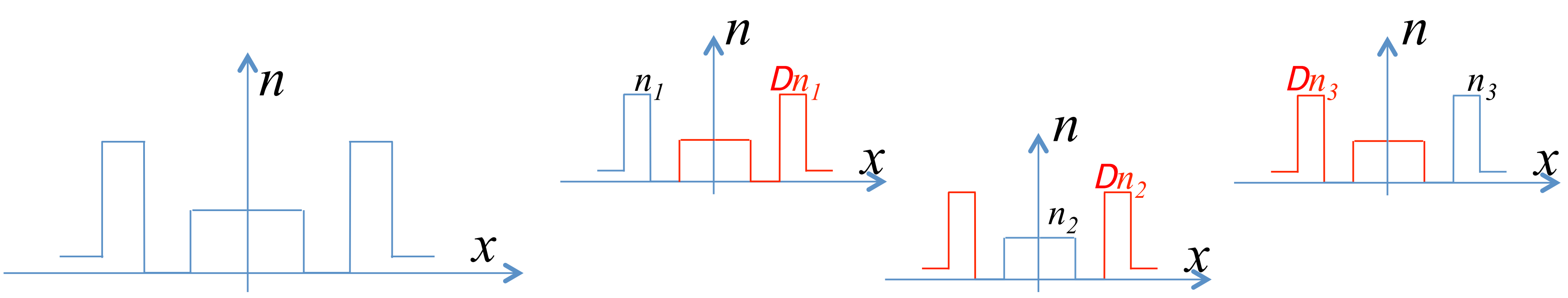
How to calculate A_j??

Perturbation

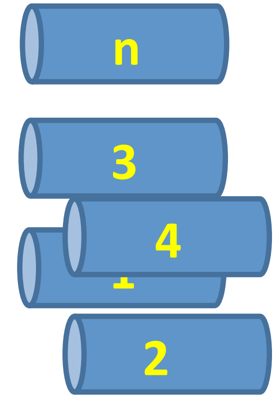
An easy approach is to divide the system with a refractive index profile $n(x,y)$ in individual waveguides (i=1…N) with $n_i(x,y)$ and expand the mode of the system in series of the modes of each waveguide.

Each individual waveguide has know solutions if taken singularly.

In the entire structure each individual waveguide experience its local $n_i(x,y)$ plus a perturbation D$n_i(x,y) = n(x,y) - n_i(x,y)$.



Coupled wave equations



Coupling between different waveguides is described by:

$$
\begin{cases}
\dfrac{dA_1}{dz} = i\kappa_{12}A_2 e^{i(\beta_1-\beta_2)z} + i\kappa_{13}A_3 e^{i(\beta_1-\beta_3)z} + \ldots + i\kappa_{1n}A_n e^{i(\beta_1-\beta_n)z} \\
\dfrac{dA_2}{dz} = i\kappa_{21}A_2 e^{i(\beta_2-\beta_1)z} + i\kappa_{23}A_3 e^{i(\beta_2-\beta_3)z} + \ldots + i\kappa_{2n}A_n e^{i(\beta_2-\beta_n)z} \\
\ldots \\
\dfrac{dA_n}{dz} = i\kappa_{n1}A_2 e^{i(\beta_n-\beta_1)z} + i\kappa_{n3}A_3 e^{i(\beta_n-\beta_3)z} + \ldots + i\kappa_{nn-1}A_{n-1} e^{i(\beta_n-\beta_{n-1})z}
\end{cases}
$$

where k_{nm} are coupling coefficients between waveguides *n* and *m*.

Coupling coefficients

The coupling between different waveguides can be calculated from the perturbation of the refractive index:

$$\kappa_{\nu\mu} = \omega c_{\nu\mu} \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} \left(E_\nu^* \cdot \Delta n_\mu^2 \cdot E_\mu \right) dxdy$$

where c_{nm} are the overlap integrals between modes of different waveguides n and m:

$$c_{\nu\mu}^{-1} = \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} \left(E_\nu^* \times H_\mu + E_\mu^* \times H_\nu \right) \cdot z dxdy$$

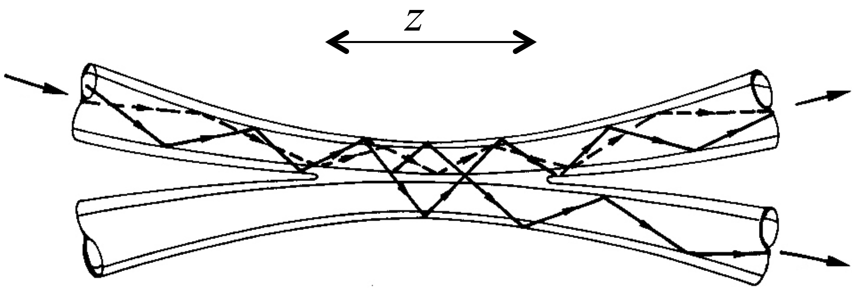
If the modes are far apart, their overlap is negligible, thus $c_{nm} \sim 0$.

Couplers

Fibre coupler coefficients are difficult to calculate because fibres are tapered and it is difficult to control the length over which two co-propagating modes overlap.

Solution of coupled equations for the outputs is a sine function for single polarized light:

$$\begin{cases} I_3 = \frac{I_0}{2}(1+\cos\kappa z) \\ I_4 = \frac{I_0}{2}(1-\cos\kappa z) \end{cases}$$



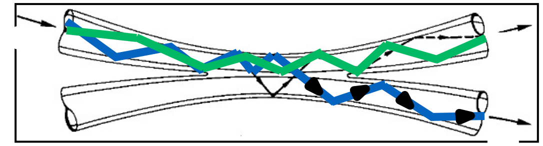
And for unpolarized light:

$$\begin{cases} I_3 = \dfrac{I_0}{2}\left\{1+\cos\left[\left(\kappa_x+\kappa_y\right)z\right]\cos\left[\left(\kappa_x-\kappa_y\right)z\right]\right\} \\ I_4 = \dfrac{I_0}{2}\left\{1-\cos\left[\left(\kappa_x+\kappa_y\right)z\right]\cos\left[\left(\kappa_x-\kappa_y\right)z\right]\right\} \end{cases}$$

$$\kappa_x = \frac{2^{3/2}\sqrt{n_{core}^2-n_{clad}^2}\cdot 2.405^2\cdot\left(2n_{core}^2V+1\right)}{n_{core}^3 a\sqrt{\pi}V^{7/2}} \qquad \kappa_y = \frac{2^{3/2}\sqrt{n_{core}^2-n_{clad}^2}\cdot 2.405^2\cdot\left(2n_{core}^2V-1\right)}{n_{core}^3 a\sqrt{\pi}V^{7/2}}$$

F. P. Payne, Electron. Lett. **21**, (1985) 561-563

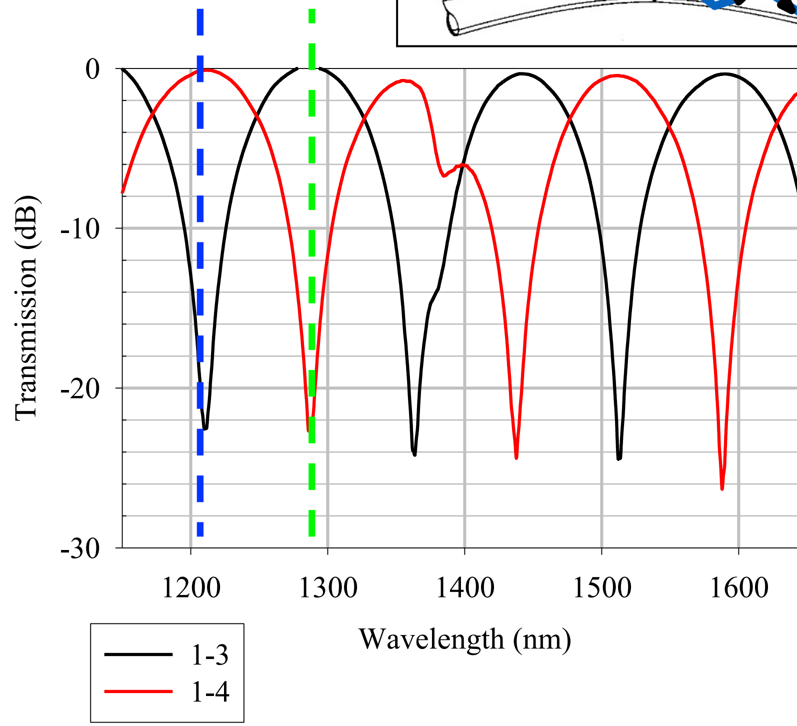
Couplers



At l=1280nm, $P_{1\text{-}3}$~0 and $P_{1\text{-}4}$~-22dB.

The fraction of power launched in port 1 which can be extracted from port 4 is -22dB (=0.006 or 0.6%). The remaining fraction (99.4%) leaves from port 3.

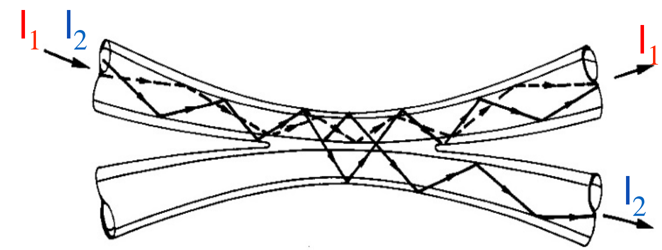
At l=1210nm, $P_{1\text{-}3}$~-22dB and $P_{1\text{-}4}$~0dB. Nearly all the power is extracted from port 4.



The spectral properties of couplers are strongly dependent on the coupler geometry: it is possible to tailor power splitting at specific wavelengths.

WDM

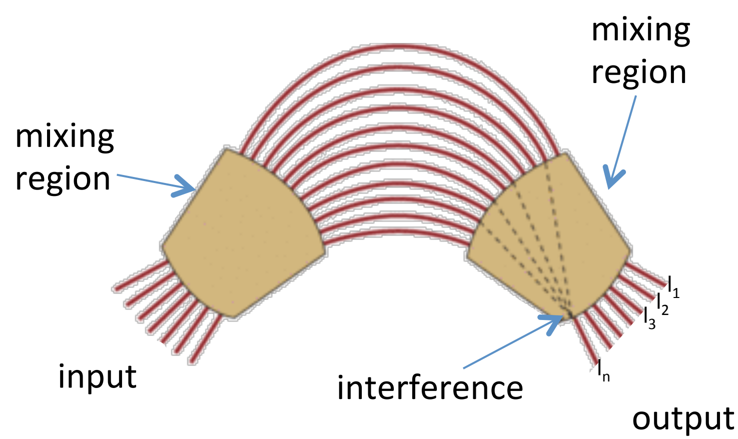
Wavelength Division Multiplexing (WDM) devices enable light from 2 or more inputs with different wavelengths (l) to be injected in a single waveguide



A demultiplexer splits different wavelengths propagating in a single waveguides into many different waveguides.

A coupler is the simplest WDM device and it is widely used in fibre lasers/amplifiers to inject pump and seed in the same fibre.

In multiple wavelengths WDM, when spacing between different wavelengths is small, arrayed waveguides (AWG) are used



WDM vs WFC

Couplers can split power in different ratios: Wavelength Division Multiplexers (WDM) separate physically inputs with different wavelengths (l). Wavelength flattening couplers (WFC) split equally the input at any l in two equal outputs.

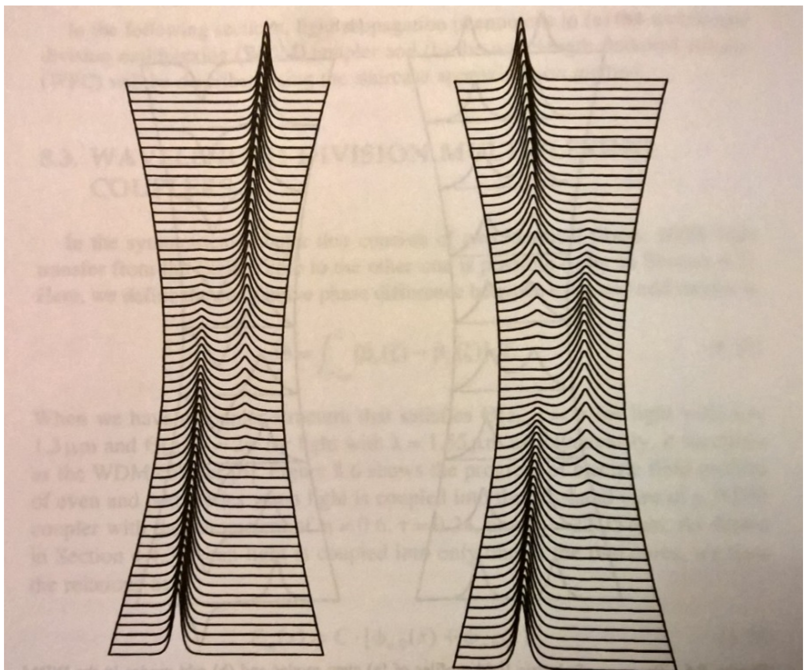


Figure 8.8 Light intensity waveforms in the WDM coupler for (a) $\lambda = 1.3\,\mu m$ and (b) $\lambda = 1.55\,\mu m$.

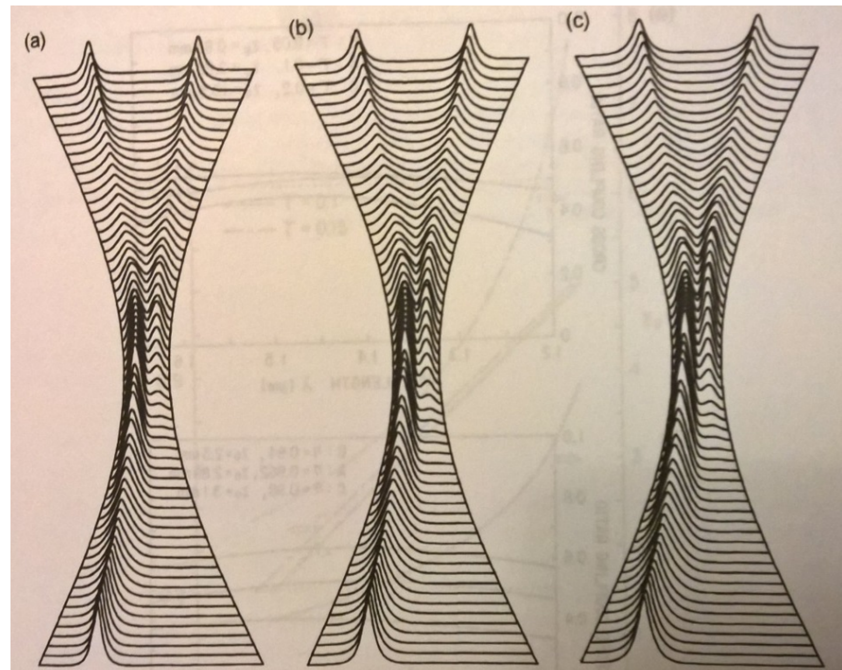


Figure 8.12 Light intensity transients at (a) $\lambda = 1.3\,\mu m$, (b) $\lambda = 1.425\,\mu m$, and (c) $\lambda = 1.55\,\mu m$ in the wavelength-flattened coupler.

Okamoto, Fundamentals of Optical Waveguides, Academic Press