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Fibre Optic Sensors:
basic principles and most common applications

(PART 2)

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devices

"OFS technology is really about ~~modulation~~ – about making light interact with the environment in a controlled repeatable and, finally, useful fashion. The stimulus was originally scientific curiosity coupled to the glimmer of application."

Brian Culshaw, 1998

Outline

- Fibre Optics Sensors: General Aspects
- More on Components and Devices
- Detection Techniques
- Applications

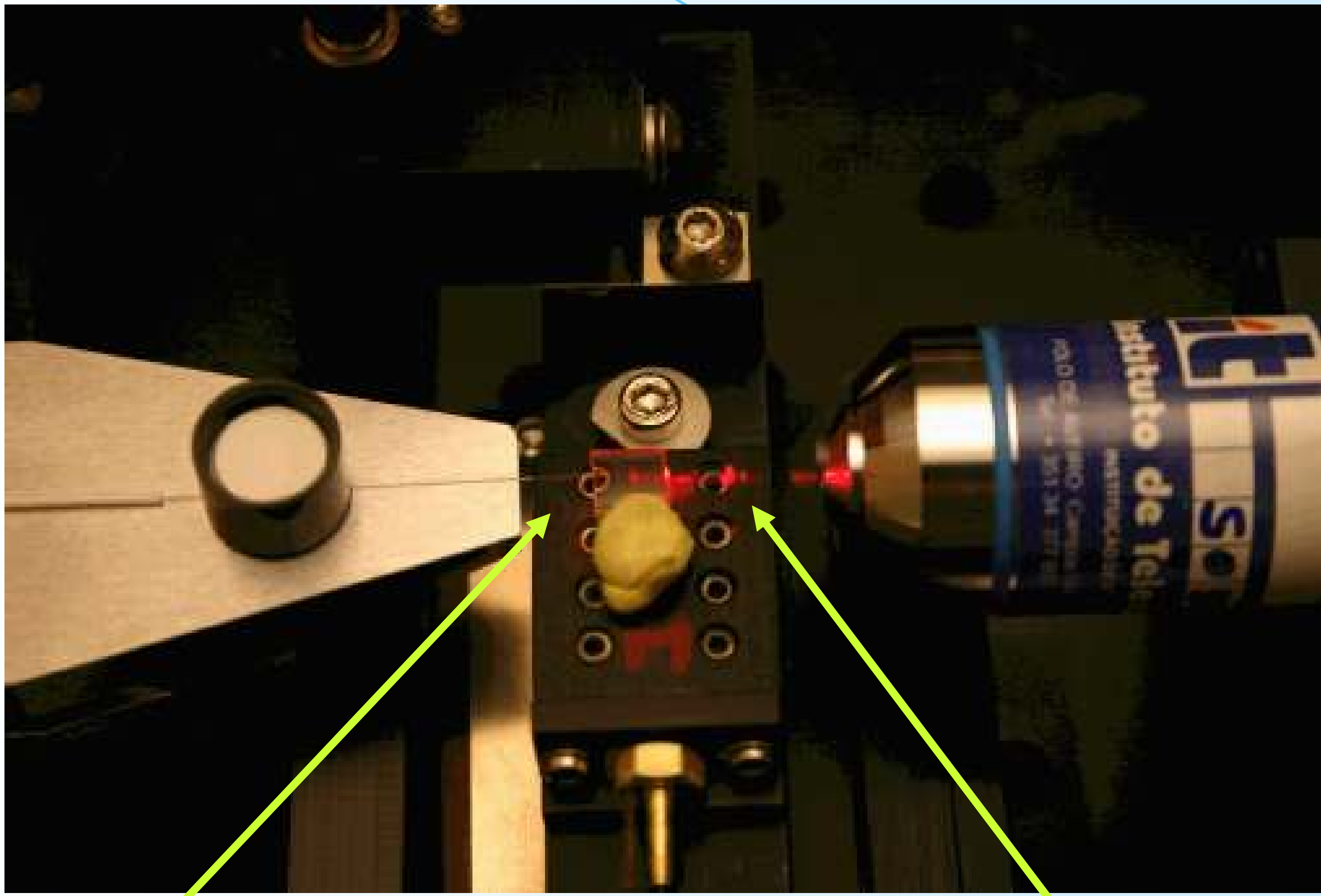
Devices

- Fibre based devices:
  - Couplers
  - Wavelength Multiplexers
- Hybrid devices (have fibre transition):
  - Isolators
  - Polarisers
  - Modulators
  - …

Fibre / Devices Coupling

- Light must be coupled between different fibre and/or integrated optics devices and/or discrete components.
- Low Loss (Insertion Loss) required to preserve optical power for sensing interaction and detection.
- Coupling Types
  - Fibre – Fibre (splices, connectors, butt-coupled)
  - Fibre – waveguide (usually butt-coupled)
  - Open air (lens focusing)
- Power dividers or combiners: fibre couplers

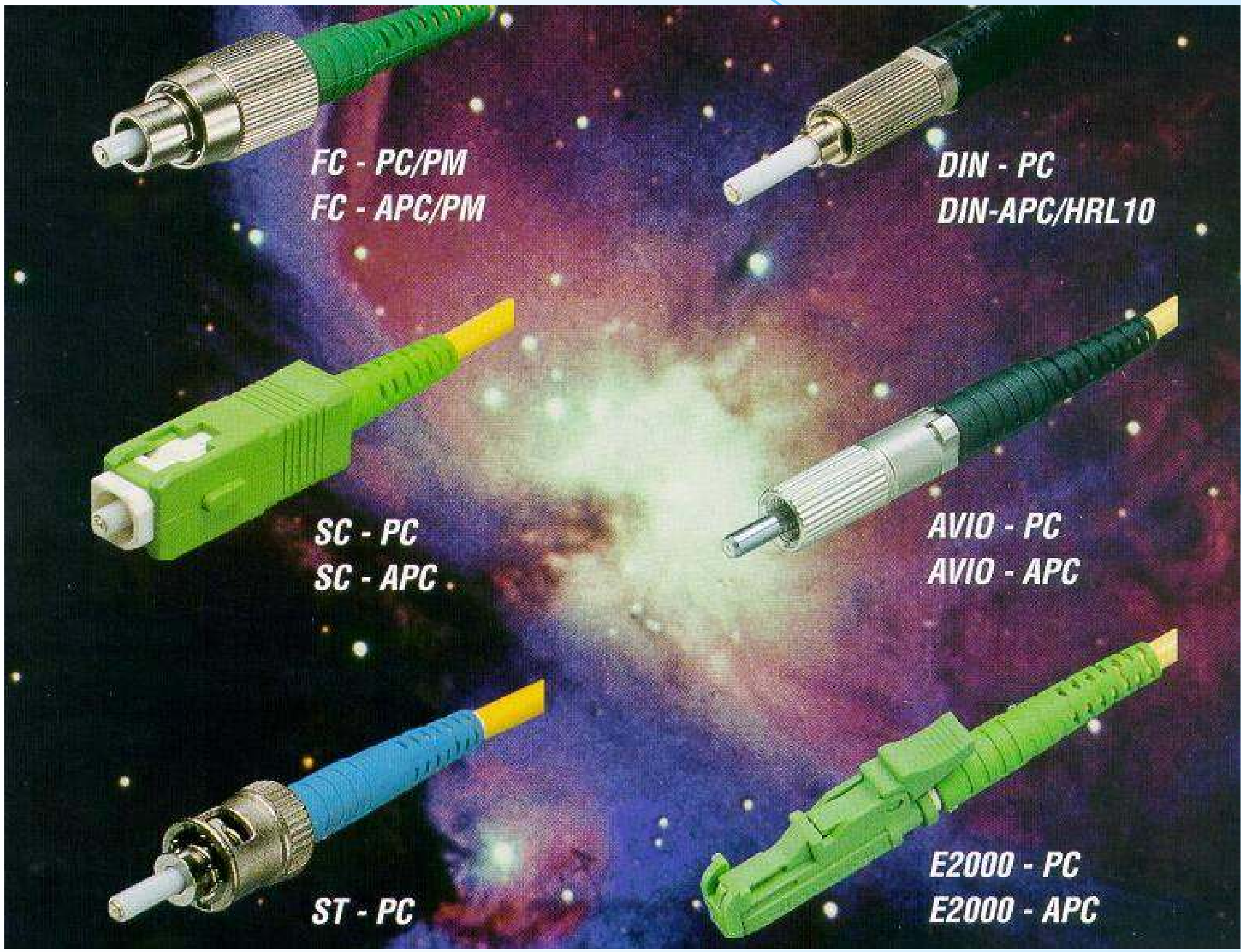
Laboratory Use



Fibre – Device butt coupling

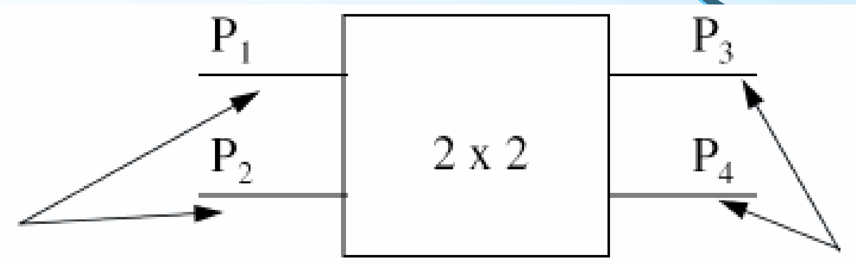
Lens (open air) coupling

Prototypes, Products: Optical Connectors



Couplers - Characteristics

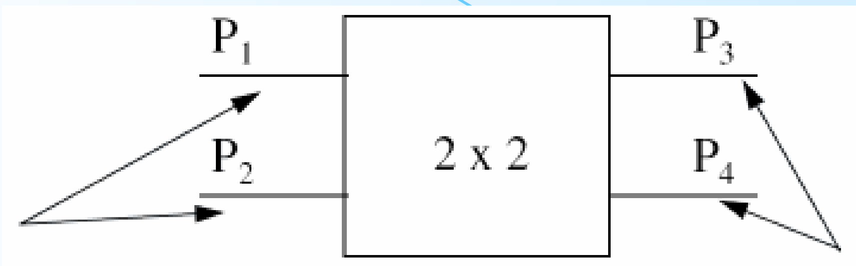
input



output

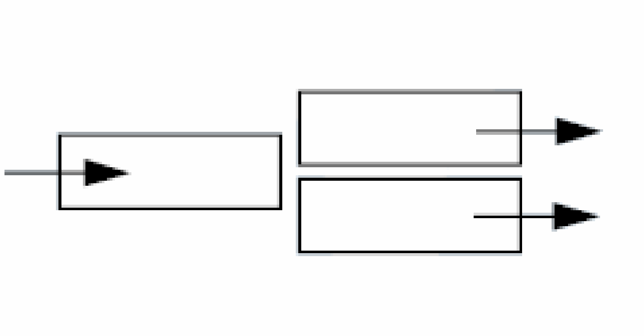
- **Characteristics to take into account:**
- **Number of ports**
- **Insertion loss** and **division ratio**
- **Insertion loss**: attenuation of a signal at one port from another input port
  - Insertion loss (dB) = 10 log (P_1/P_3)
- **Division** (or splitting) **ratio**: % of the input power at each of the output ports
  - 100 . P_3/(P_3 + P_4) % , 100 . P_4/(P_3 + P_4) %
- **Directivity**
- **Wavelength dependency**
- **Fiber type (single-mode or multi-mode)**
- **Cost**

Couplers - Characteristics

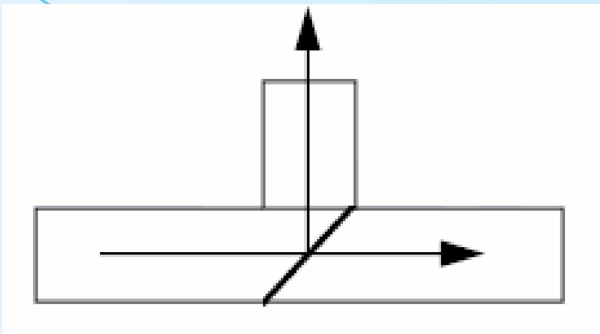


- **Excess loss**: signal attenuation above the minimum one required for the achieved splitting ratio.
  - Excess loss (dB)= 10 log P_in/(∑P_out)
- **Directivity** (aka **isolation**): signal attenuation at one of the input ports different from the one at which signal is being injected
  - Directivity (dB) = 10 log P_1/P_2

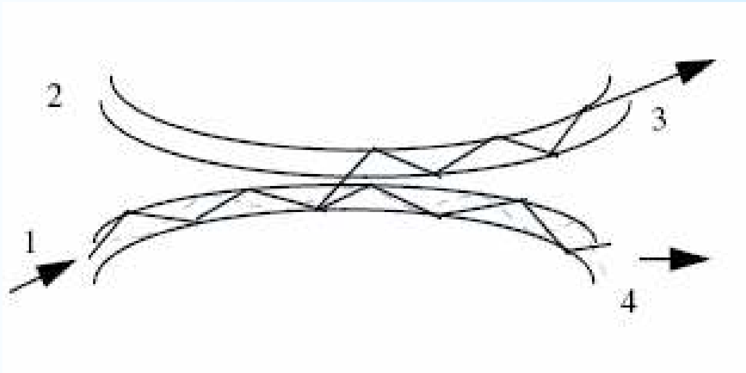
Couplers – Working Principle



Lateral displacement



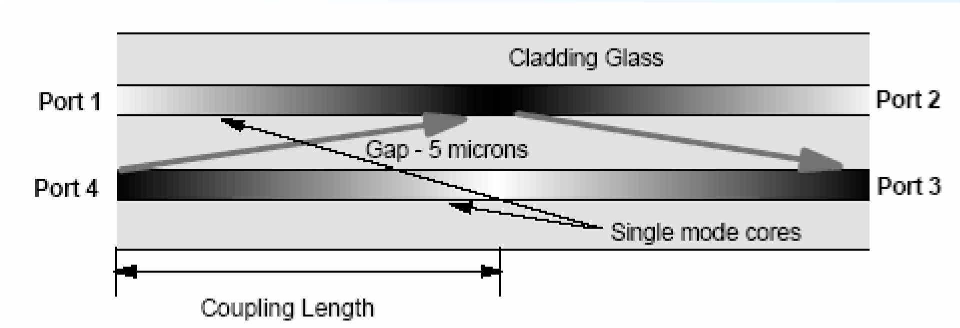
Beam Splitter

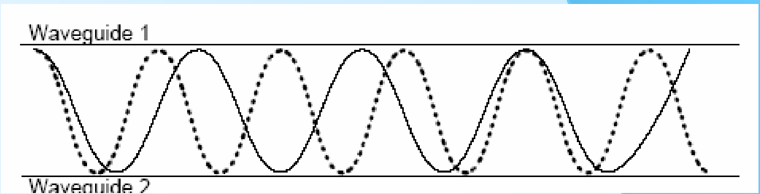


Coupled fibres

Resonant Coupling

- Two fibre cores are closely placed
- A resonant coupling is created and optical power is transferred from one core to the other (dipole model, evanescent field from core 1 induces field on core 2), it progressively builds up





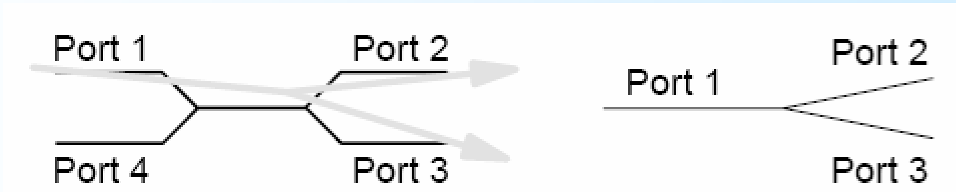
-- λ_1 ___ λ_2

Resonant Couplers

- The coupling length increases with the distance between cores
- The coupling length strongly depends on the wavelength
- From the exciting to induced fields (cores), there is phase change

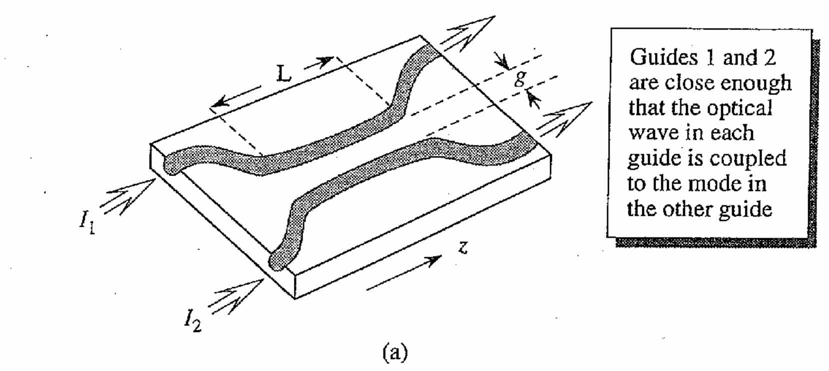
$$\begin{pmatrix} \mathbf{E}_{1,\,out} \\ \mathbf{E}_{2,\,out} \end{pmatrix} = \begin{pmatrix} \sqrt{1-\alpha} & j\sqrt{\alpha} \\ j\sqrt{\alpha} & \sqrt{1-\alpha} \end{pmatrix} \cdot \begin{pmatrix} \mathbf{E}_{1,\,in} \\ \mathbf{E}_{2,\,in} \end{pmatrix}$$

$E_{i,out}$ are the output fields, $E_{i,in}$ are the input fields
α is the coupling factor

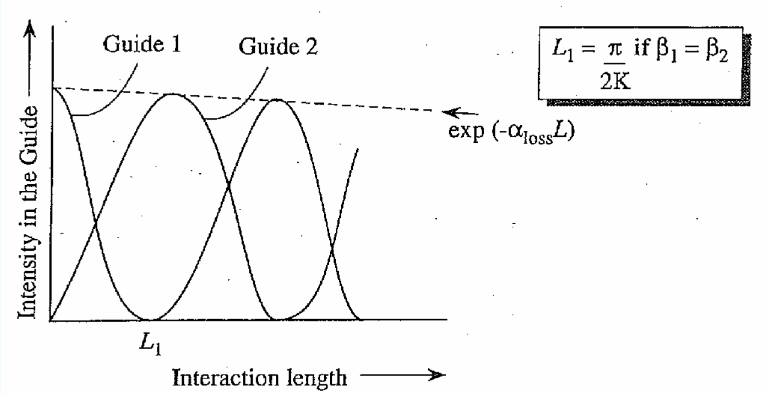


The couplers are symmetrical , such as in the direction 1->2,3 there is an equivalence between schemes; however, in the opposite direction, joining 2 similar signals in 2 and 3, will only result in 1 signal of amplitude equal to the mean of both their amplitudes!!!

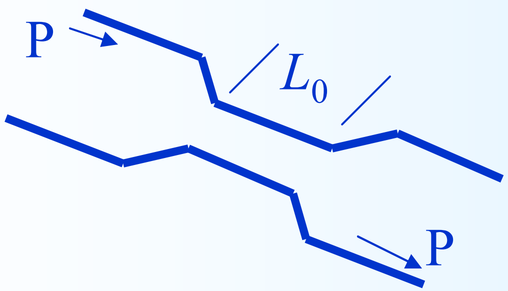
$$P_1(z) = A_1A_1^* = cos^2(Kz)e^{-\alpha_{loss}z}$$
$$P_2(z) = A_2A_2^* = sin^2(Kz)e^{-\alpha_{loss}z}$$

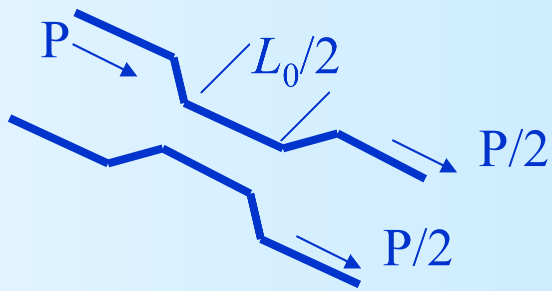


(a)



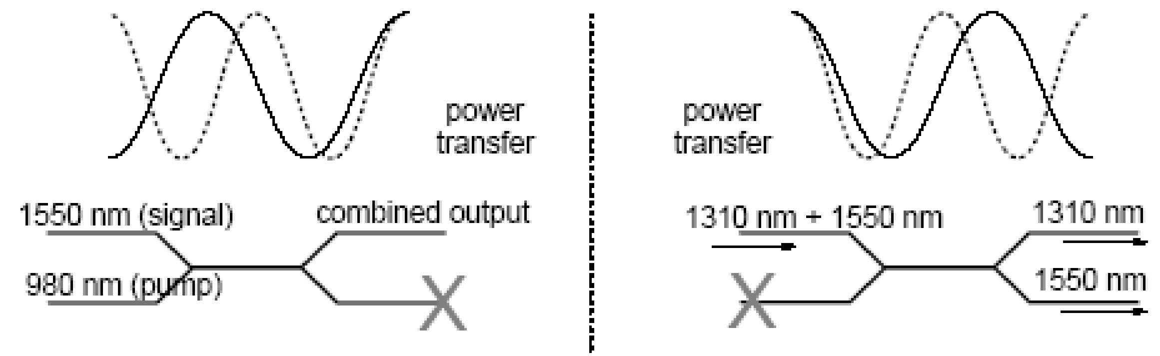
- **By the end of the coupling length, all energy is coupled to other guide**
- **It carries on like this periodically**
- **In this way a 3dB coupler is defined with half of the coupling length, and there on successively**



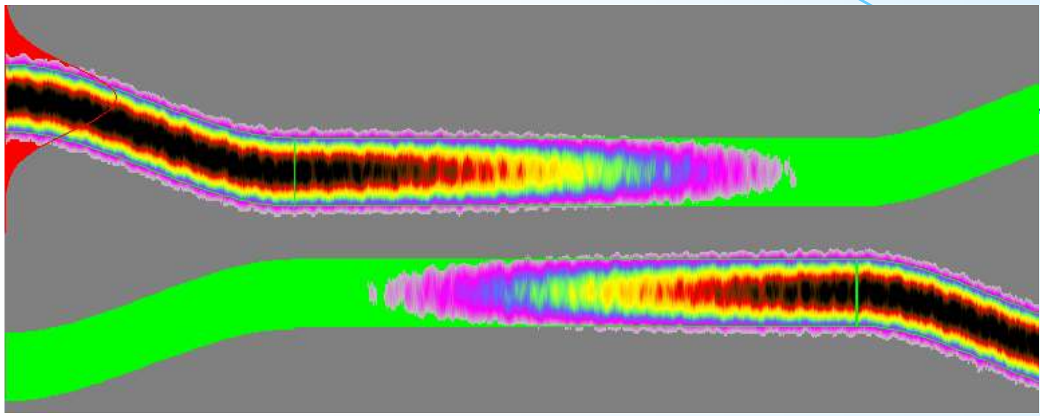


λ-selective Couplers

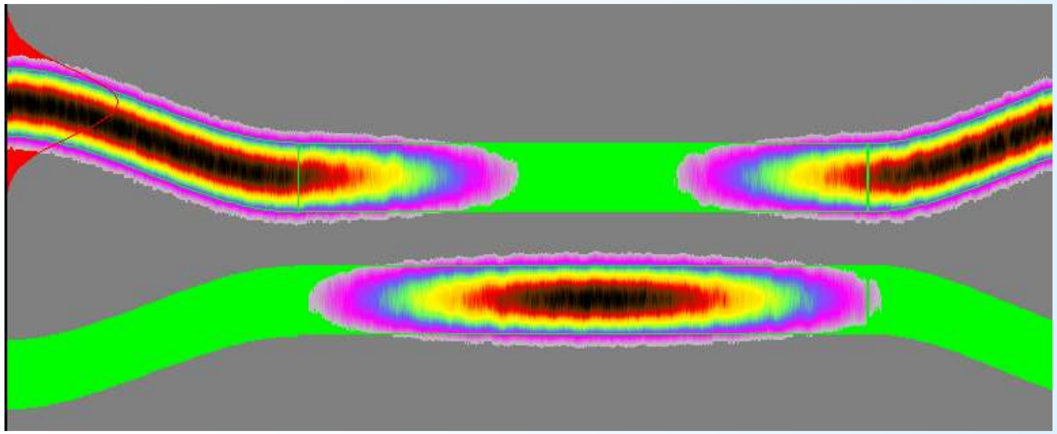
- By correctly drawing the coupler's length, a ~100% light coupling, coming from different λs, can be achieved.
  - Typical insertion losses are < 1.5dB
  - High bandwidths: 30-50nm
  - Common Operational Bands : 980-1550, 1300-1500, 1550-1600, ... (telecommunications windows)



λ - Selective Coupling (DeMUX)



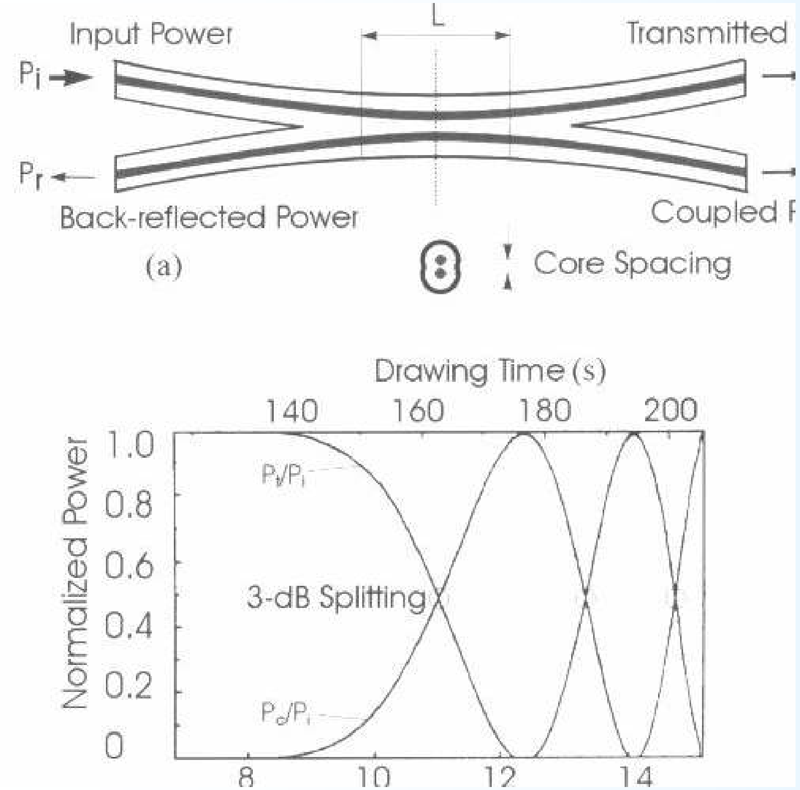
1310 nm

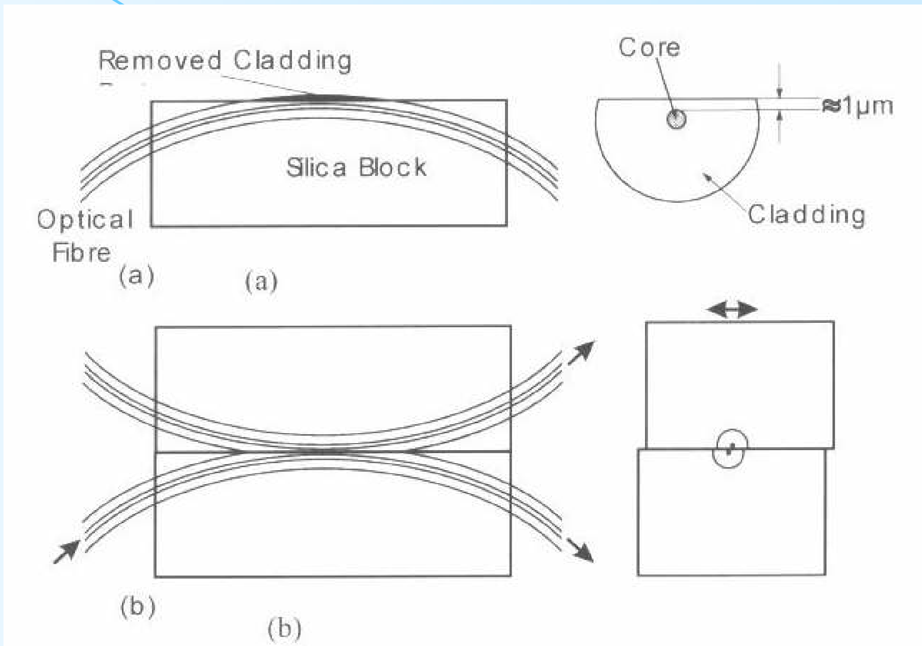


1550 nm

http://www.cem2.univ-montp2.fr/~moreau/

Coupler Technology





Fused fibres

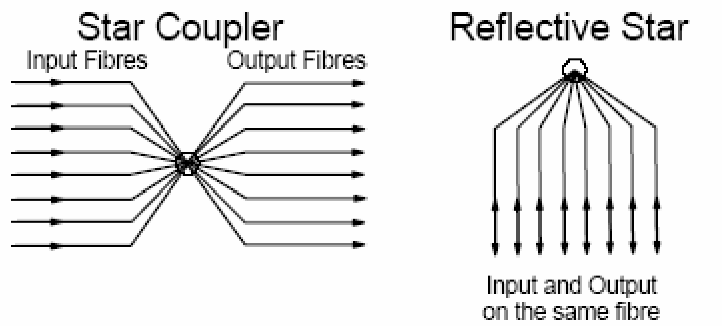
Polished half-block

Low cost, mass production, fixed coupling ratio

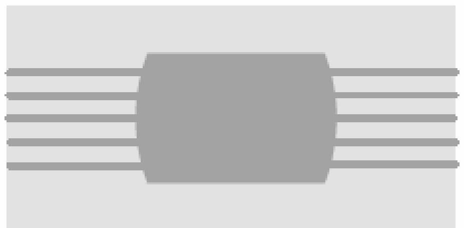
Can have better characteristics, variable coupling ratio

Star Couplers

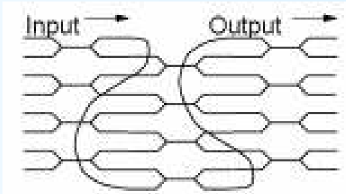
- It's simply a coupler where each input is partially presented on each output
- Main drawback: power division by 2^n
- Fused fibre technology or sequential concatenation

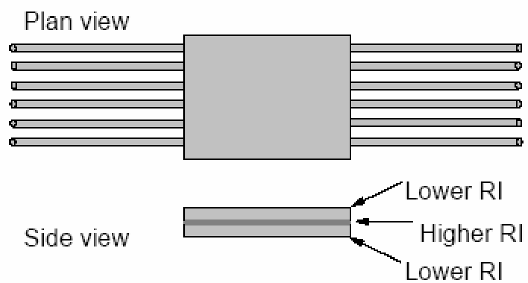


Fused Fibre Star Coupler



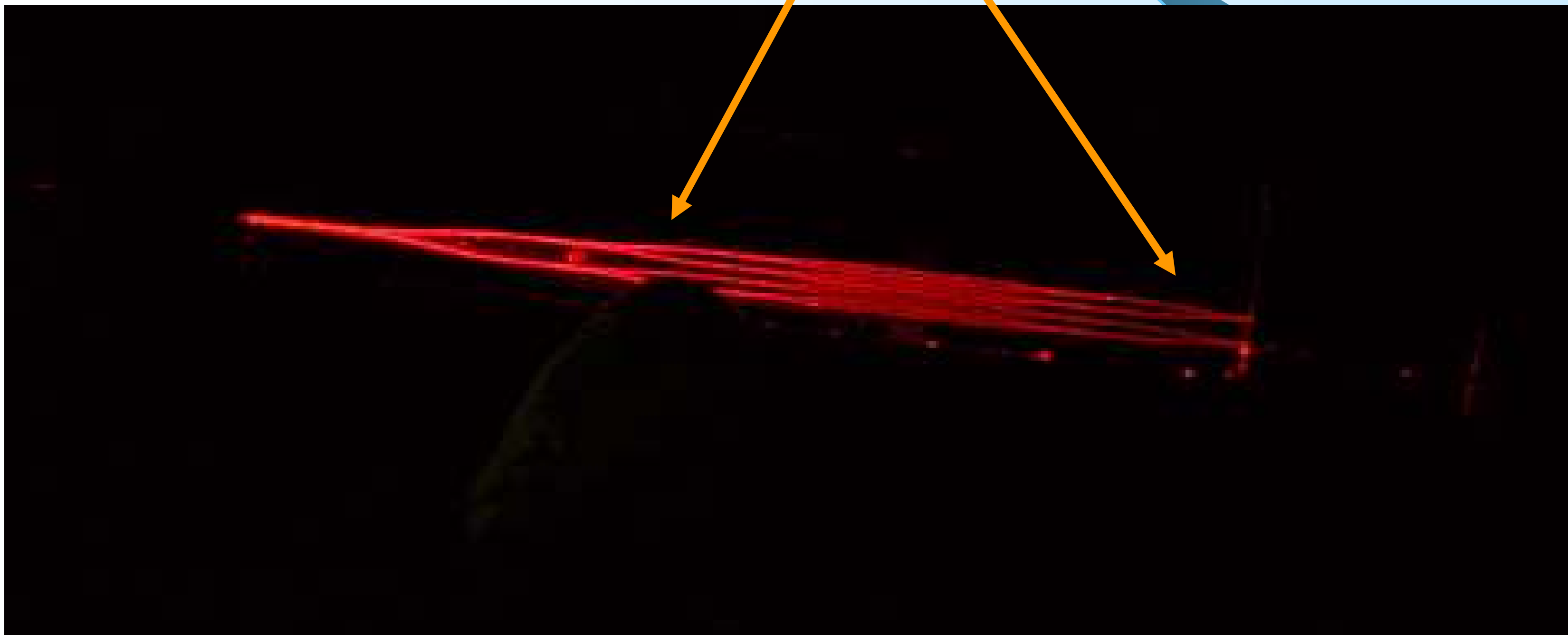
Planar (Free Space) Star Coupler





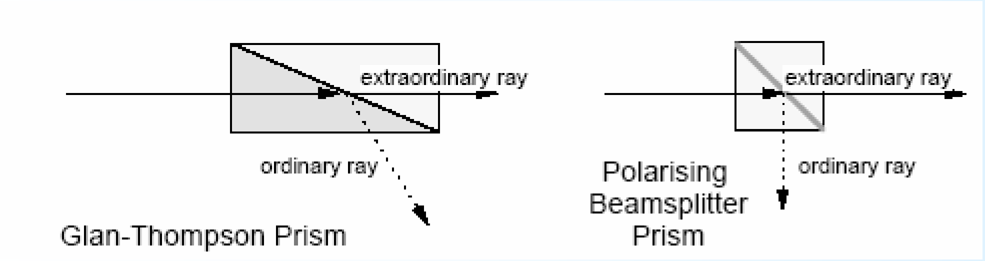
Mixing Plate Coupler

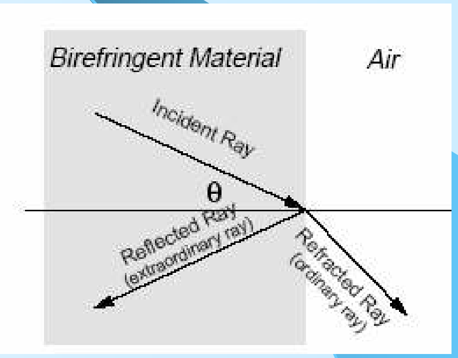
Intrinsic loss causes power (scattering)
drop at same division level



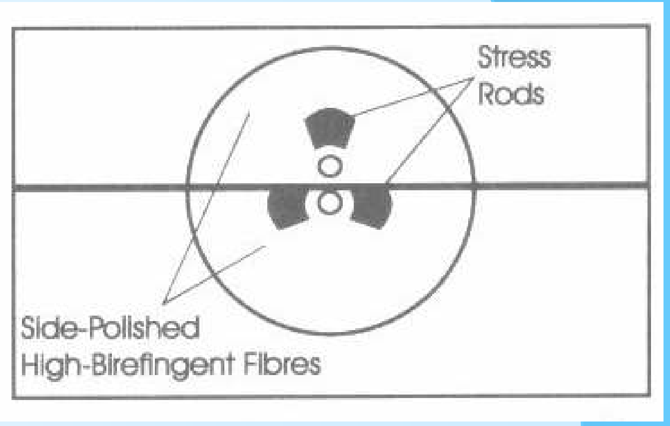
Polarisation Beam-splitters

- Sometimes it's needed to split two polarisations from a beam of light
  - Based on birefringent materials, devices whose total internal reflection angle is different for both polarisations can be designed
    - Calcite ($CaCO2$), Rutile ($TiO2$) are examples of materials of this type

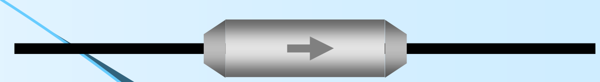




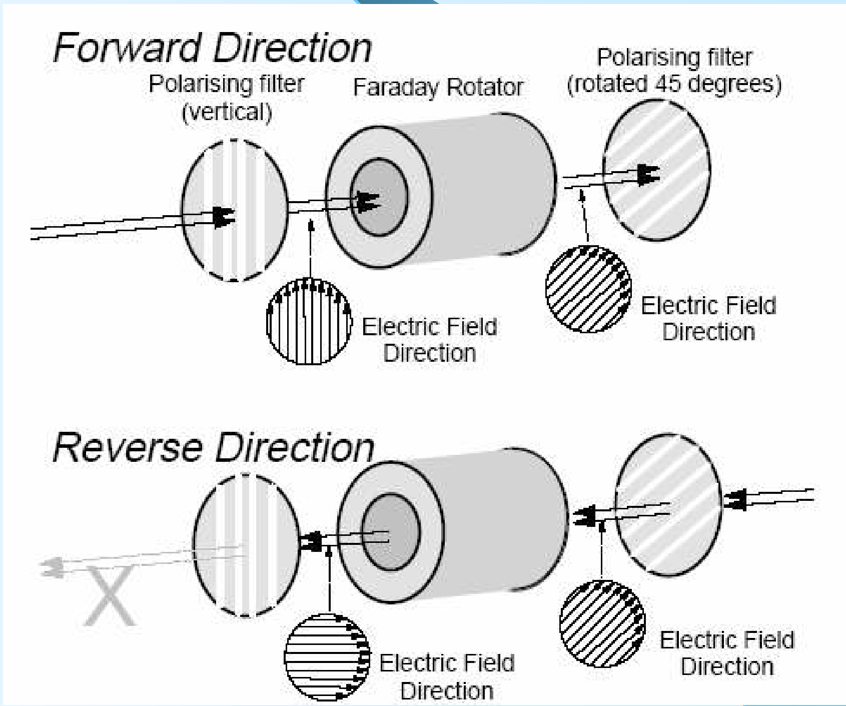
  - Also made with fused (lapped) coupler technology using high birefringence fibres



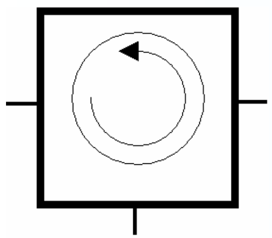
Isolators



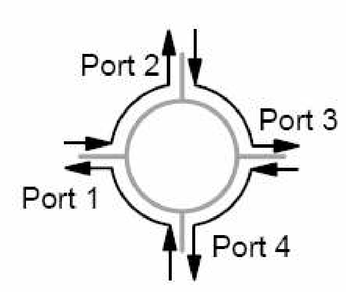
- Faraday effect
  - Some materials can rotate the polarisation of incoming light.
  - With two linear polarisers, it can block light transmission coming in the counter-propagating direction.
  - Insertion losses ~1dB

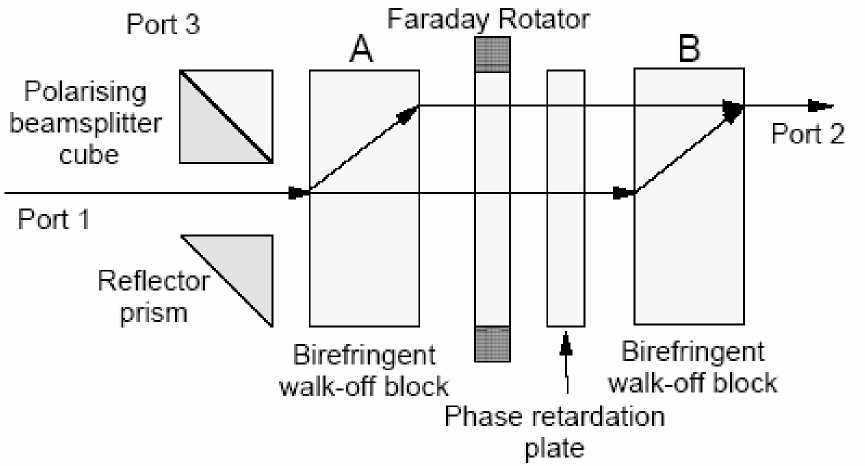


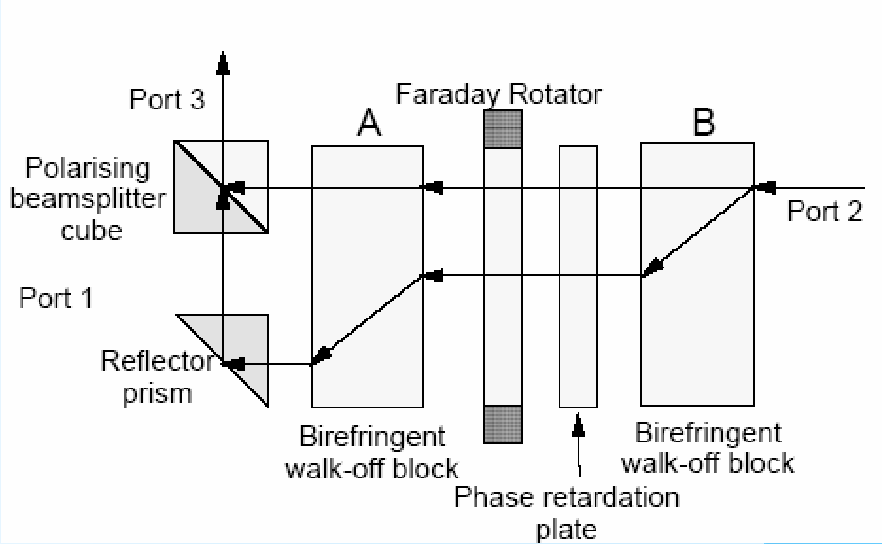
Circulators



- Many applications for directing light (e.g.: reflective sensors, fibre Bragg grating sensors)
  - Better handling of available power as compared to two optical couplers
- Can be built based on isolators, are usually micro-optical based devices
- Low Insertion Losses <1.5dB

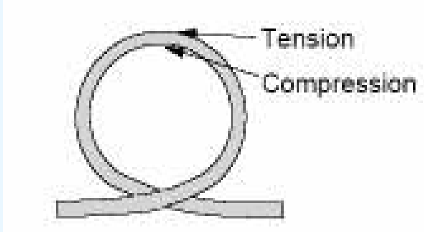


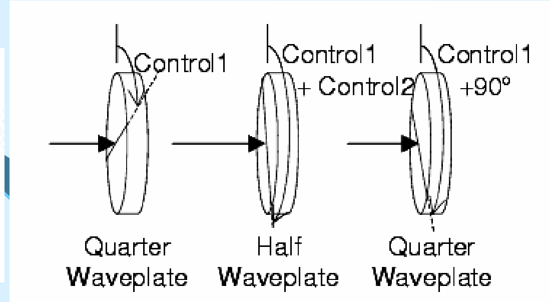


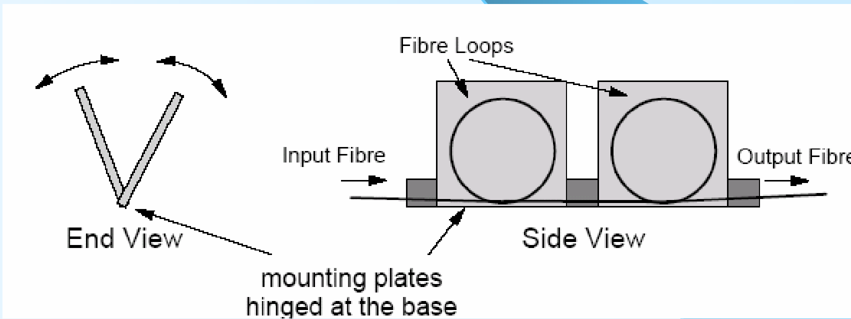


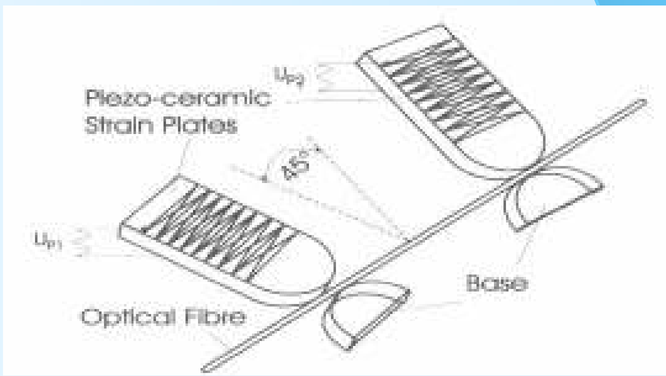
Polarisation Controllers

- In many cases it's necessary to control a field's polarization
  - Line up with the main axis in a birefringent fibre, etc.
- We can build such device, based on a birefringent fibre loop
  - In a fibre loop, the suffered tensions and compressions by the fibre bending, are in many cases enough to cause birefringence
  - By rotating the axis, we can get changes on the electrical field orientation
- Typical devices have two or three loops
- Piezo-electric devices can squeeze the fibre on some points, altering its birefringence









Modulators

- Necessary to change dynamically the intensity or phase of light.
- Signal Processing (trigger, lock-in, synchronisation, …)

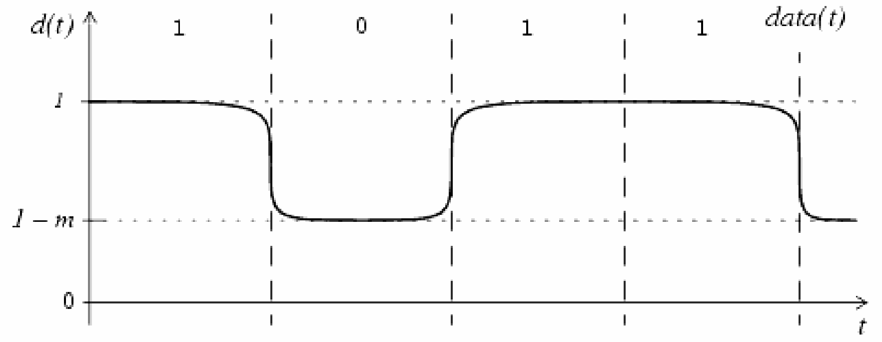
Modulator Types - Working Principles

- Electro Absorption Modulators
- Acoustic-Optic Modulators
- Electro-Optic Phase Modulators
  - Mach Zehnder
  - 2 x 2 Couplers
- Pockels Effect
- Piezoelectric
- Faraday Effect

Electro-absorption modulators

- A p-n junction when inversely polarized, absorbs light (receiver principle); when not polarized, it presents minimal absorption.
  - depends on the used material's gap (defines cut-off frequency)
  - only absorbs wavelengths shorter than the cut-off wavelength (higher energies)
  - exhibits linear response (useful for analogical modulation)
  - "on-state" insertion losses in the order of 9 dB, as an isolated component
  - exhibits insignificant losses (1dB) when coupled to lasers or other devices.
- Electric field:

$$\mathbf{E}_{out}(t) = \mathbf{E}_{in}(t) \cdot \sqrt{d(t)} \cdot \exp\left(\frac{j\alpha}{2} \ln[d(t)]\right)$$



α chirp parameter, d(t) given by, for example, as an digital signal:

$$d(t) = (1-m) + m \cdot data(t)$$

$$P_{out}(t) = P_{in}(t) \cdot d(t) = P_{in}(t) \cdot ((1-m) + m \cdot data(t))$$

Acousto-Optic Modulator

- When an acoustic wave travels thru a material, it induces compression and expansion zones.
  - causes gratings
  - Controlling the sound’s frequency and intensity (easy, since the wave is electronically generated) the grating strength can be chosen
    - light and sound frequencies are very different (e.g. f_{light}=200THz >> f_{sound}=200MHz), so is their speed (for quartz, e.g. v_{light}~2E8 >> v_{sound}~6E3) which results in wavelengths one or two orders of magnitude apart (e.g. λ_{light}~1E-4m e Λ_{sound}~1/3E-5m =>$\lambda_{light}/\Lambda_{sound}$=30)
- Important Factors on Bragg refraction
    - the incidence angle is equal to the refraction angle
    - There must be constructive reflection between two optical waves
      - Λ acoustic wave, λ optical wave, θ incidence angle

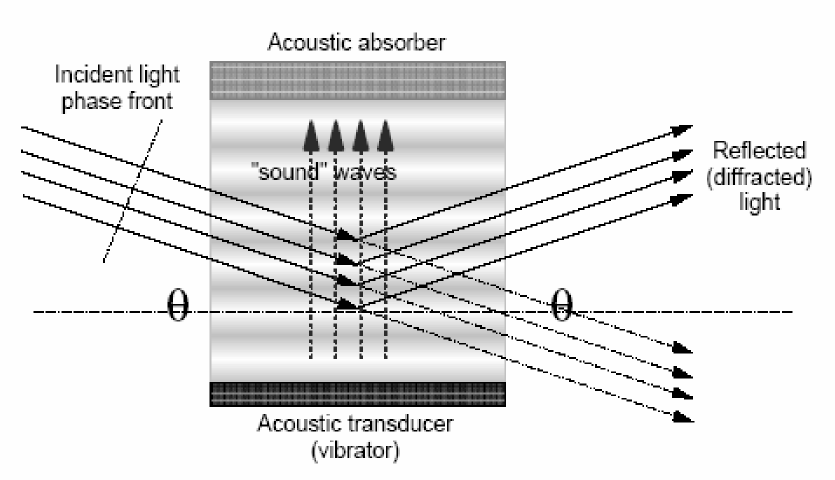
$$\sin \Theta = \frac{n\lambda}{2\Lambda}$$

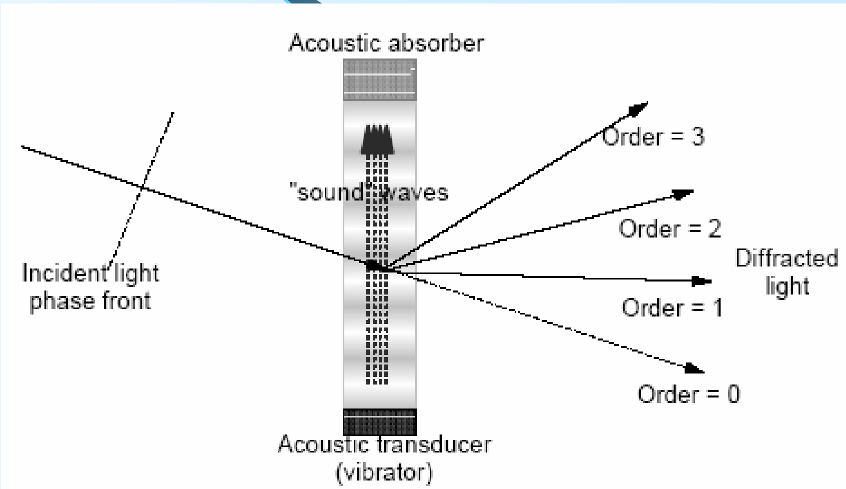
Acousto-Optic Modulator

Common Structures :

Bragg Modulator

Debye – Sears



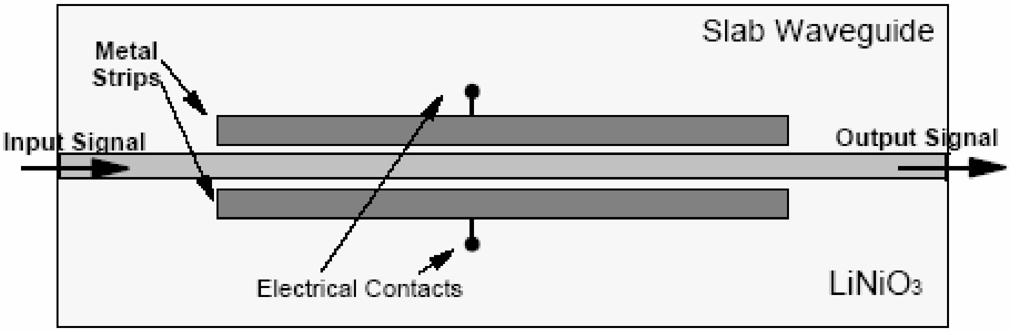


Advantages:
- can operate with high powers
- the refracted signal intensity is:
  - proportional to the acoustic wave intensity
- can modulate one or more different wavelengths at the same time
- the Doppler shift can be used to change the signal's wavelength

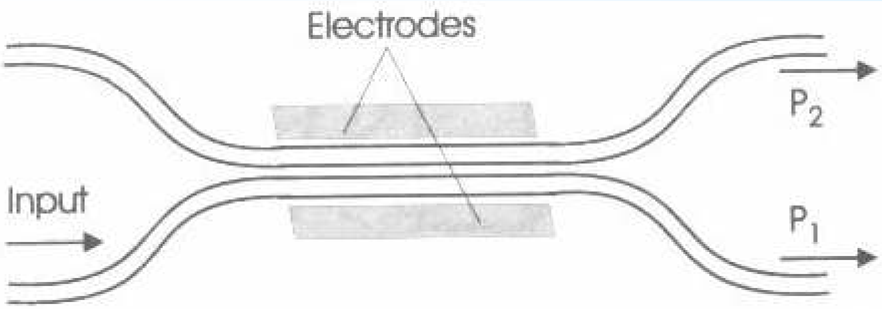
Disadvantages:
- relatively high insertion losses
- require a relatively high drive current
- the modulation frequency must be inferior to the acoustical wave frequency, therefore it has a low value

Electro-Optic Phase Modulators

- Applied electric field changes the refractive index
  - the index's variation is directly related with optical path through the media, and therefore with the signal's phase change
  - can also lead to an intensity modulator



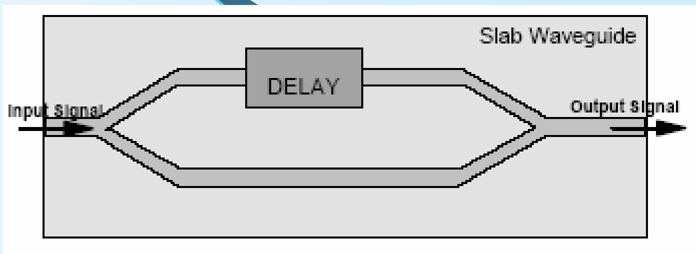
$$\mathbf{E}_{out}(t) = \mathbf{E}_{in}(t) \cdot \exp[j\Delta\varphi\, data(t)]$$

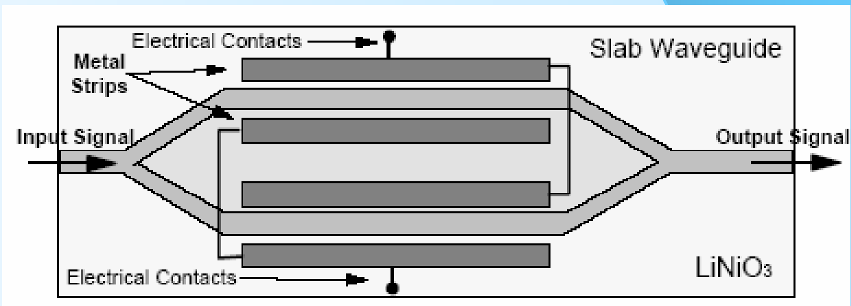


Coupling ration depends on the relative phase between field in each core -> Intensity modulation

Mach-Zehnder

- Most common modulator for telecommunications (available / low cost)
- Very high modulation frequencies ~10's GHz)
- Based on the delay between two arms that will induce phase rotations in the order of 180º
  - –If there's no delay, constructive interference will happen
  - –If there's 180º phase delay, there will be destructive interference
- Normally implemented on integrated technology due to the necessary precision on the guide length
- The more common material is $LiNiO_3$, but there are other materials





Mach-Zehnder

- The output power depends on the phase difference, $\Delta\Phi$, between the two arms of the modulator :

$$P_{out}(t) = P_{in}(t) \cdot d(t) = P_{in}(t) \cdot \cos^2[\Delta\Phi(t)]$$

$$\Delta\Phi(t) = \frac{\Delta\Phi_1(t) - \Delta\Phi_2(t)}{2}$$

$$\Delta\Phi = \frac{\pi}{2}\left(\frac{1}{2} - \mathrm{ext} \cdot \left(data(t) - \frac{1}{2}\right)\right) \quad \text{with } \mathrm{ext} = 1 - \frac{4}{\pi}\arctan(1/(\sqrt{f_{extinct}}))$$

considering $k=|\Delta\Phi 1|/\ |\Delta\Phi 2|$, we will have

k=-1 – ideal AM modulation (Phase opposition modulation)

k=0 - Chirp Modulation (only one of the arms is modulated)

k>-1 - Phase modulation (Both arms modulated with the same current)

extinction ratio

$$\varepsilon = 10 \ \log(f_{extinct})$$

Chirp Signal

$$\sigma \equiv \mathrm{sgn}\left(\frac{\Delta\Phi_1 + \Delta\Phi_2}{\Delta\Phi_1 - \Delta\Phi_2}\right)$$

Mach Zehnder

- Alpha Factor : relation between the modulation's phase and intensity

$$\alpha \equiv 2\frac{\frac{d\Delta\Theta}{dt}}{\frac{1}{P_{out}}\frac{dP_{out}}{dt}}$$

$$\alpha = -\sigma\frac{1+k}{1-k}\frac{1}{\tan\Delta\Phi_{bias}}$$

If $\Delta\Phi_{bias} = \pi/4$

$$\alpha = -\sigma\frac{1+k}{1-k}$$

As an alternative, there are 2 other parameters:

$$k = \frac{\alpha + \sigma}{\alpha - \sigma}$$ symmetry factor

$$\sigma = -1.0\,sign(\alpha)$$ Chirp Signal

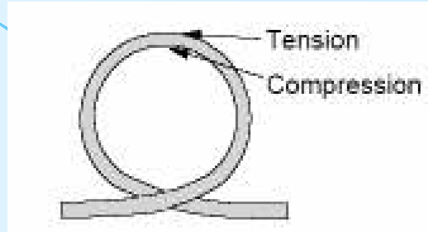
Piezoelectric Modulators

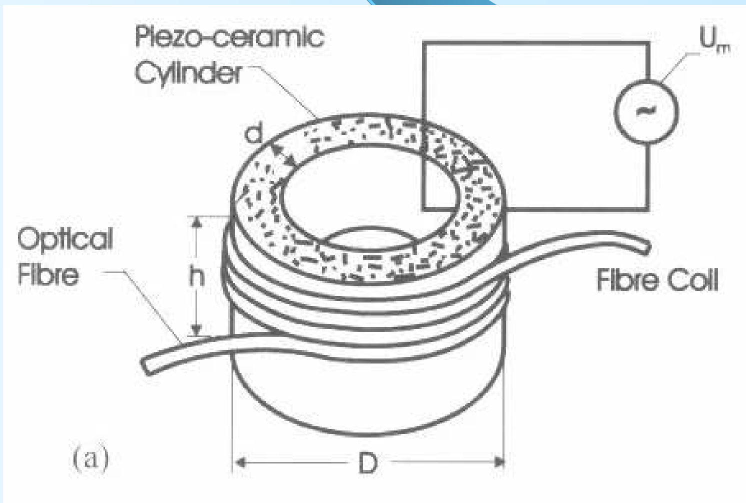
Mechanical uniaxial pressure changes the refractive index of the fibre

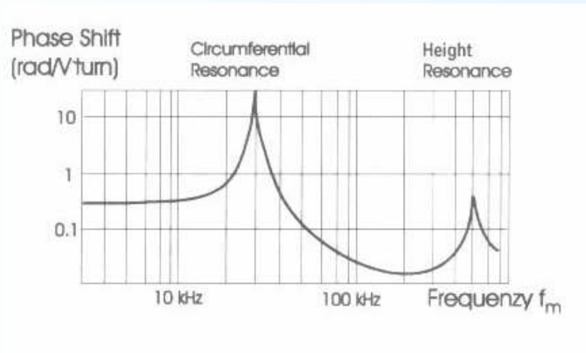
Phase changes between the two orthogonal components

Piezoelectric ceramics can modulate the phase of the optical signal on the fibre.

Usually frequency fixed devices, due to mechanical resonances

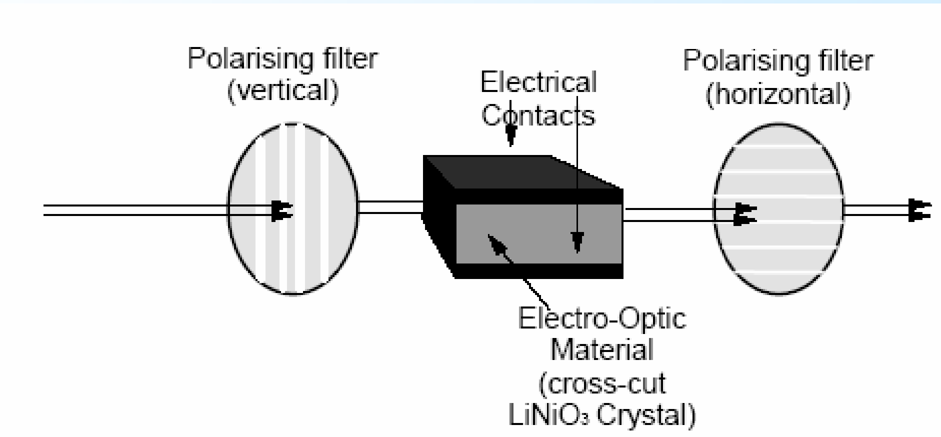






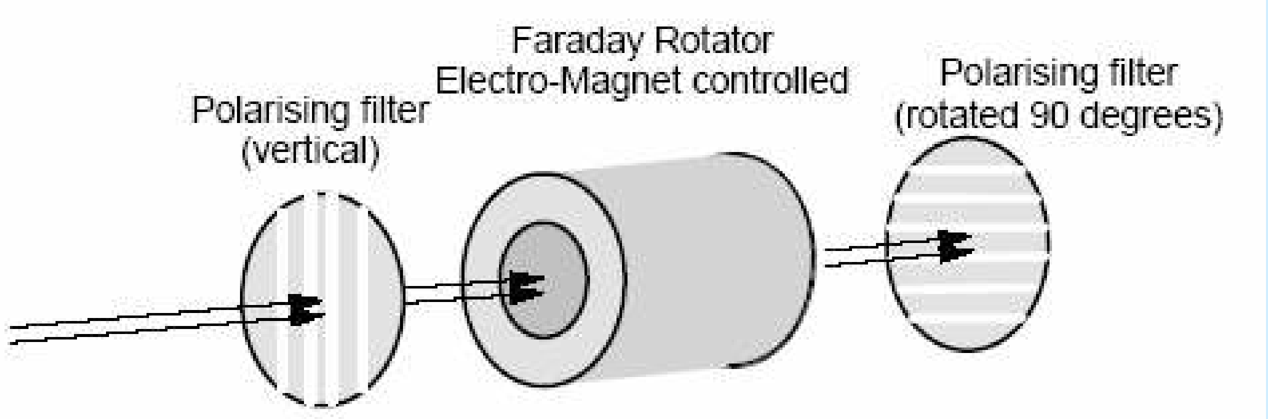
Pockels Cells Modulator

- Crystals with electrically controlled birefringence
  - LiNiO3, KDP (NH4H2PO4), ADP (KH2PO4)
  - Require high modulation tensions (1000V)
  - High loss, at least ½ of the power

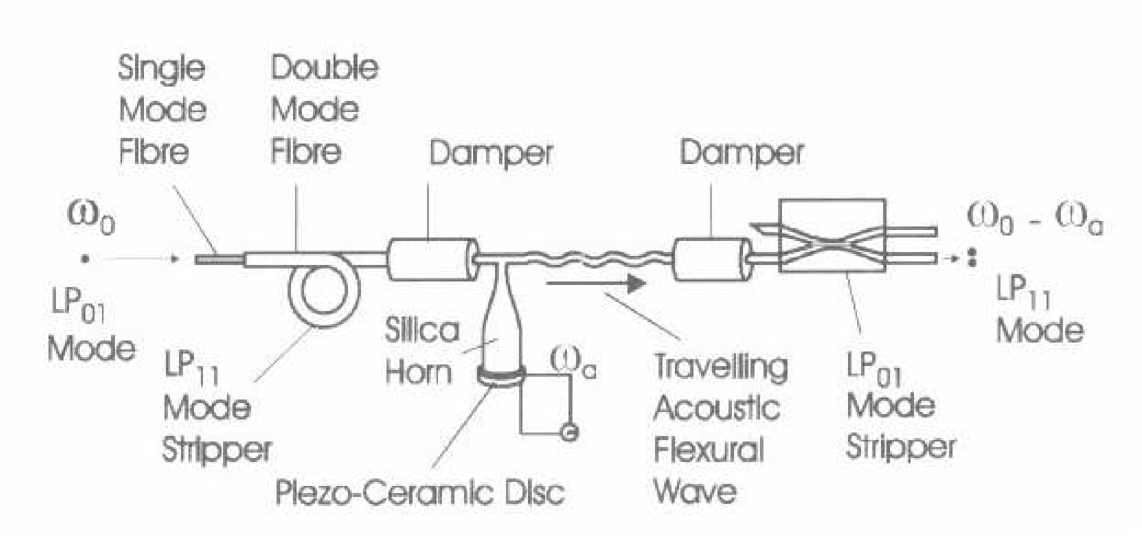


Faraday Effect Based Modulators

- The modulator is based on the Faraday effect
  - The used material causes variable polarization rotations
  - Slow and expensive



Mode Couplers



- Flexural acoustic wave couples core and cladding modes
- Re-coupling to core mode after given length
  - Modal intensity (phase) modulation
  - Pass over a Bragg grating
- Dynamic control of the reflected optical channel
- $L_{interaction} = 28$ mm,
  $\phi = 46\mu m$, RF = 2 MHz