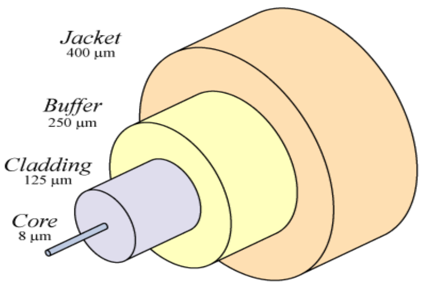
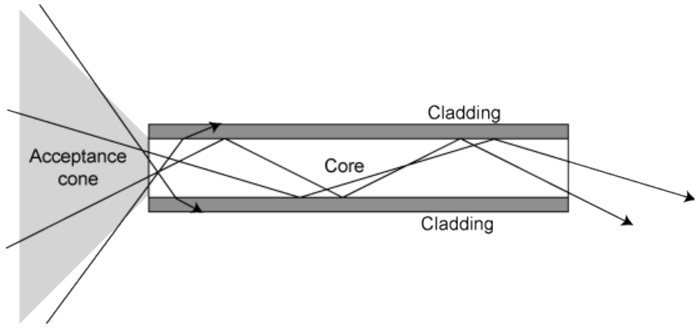
2×2 Fiber Coupler Components in Communication and Sensing

Basic structure





All-fiber Components

- The necessary function of signal processing/ manipulation is performed whilst the signal is still guided by fiber
- Components can be readily spliced to signal carrying circuit with a common fiber handling tool
- Components realized from fiber in the from of fiber
- No significant insertion loss due to geometry mismatch or mismatch in overlap of modal fields

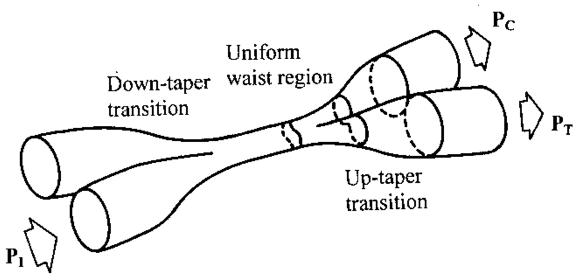
Major Devices

- Fused Fiber Couplers: FFC
- Fiber Amplifier: EDFA
- Fiber Bragg Grating: FBG

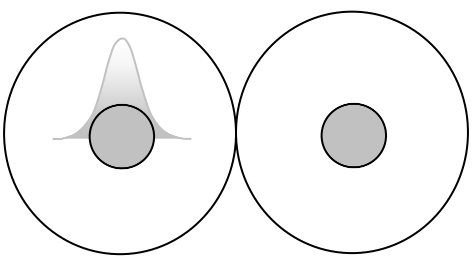
Fused Fiber Coupler

A 2×2 fused biconical tapered (FBT) coupler

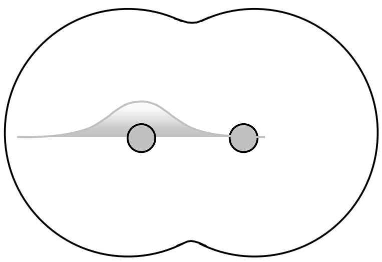
- A 4-port device: 2 input ports P_I & P_R and 2 output ports P_T & P_C
- Light injected into one of the input ports
- appears at either of the out ports or both in some ratio
- Power splitting ratio depends on design parameters: operating wavelength and this is the key to realise many devices



Principle of Coupling: Overlap of modes



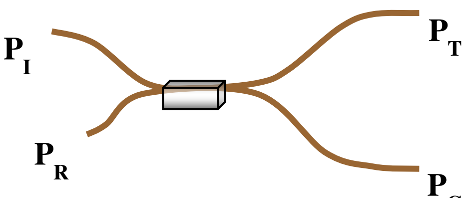
Optically isolated fiber-pair



Fused tapered waist

Coupling is due

- to cladding-mode coupling



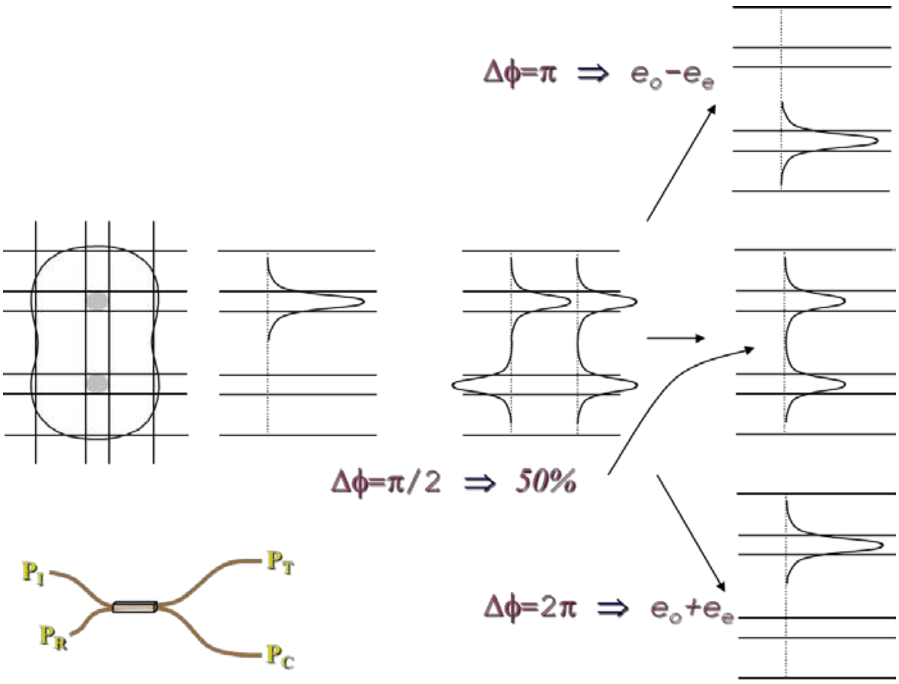
- to supermodes' beating

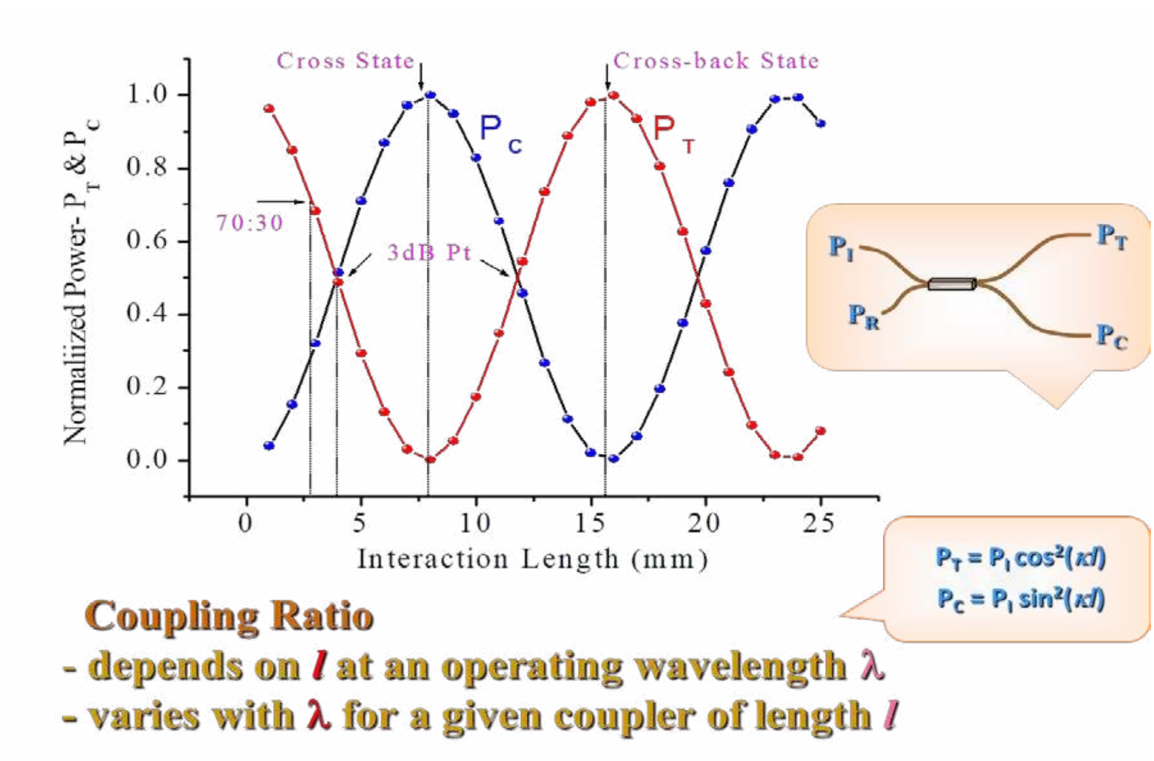
Power transfer

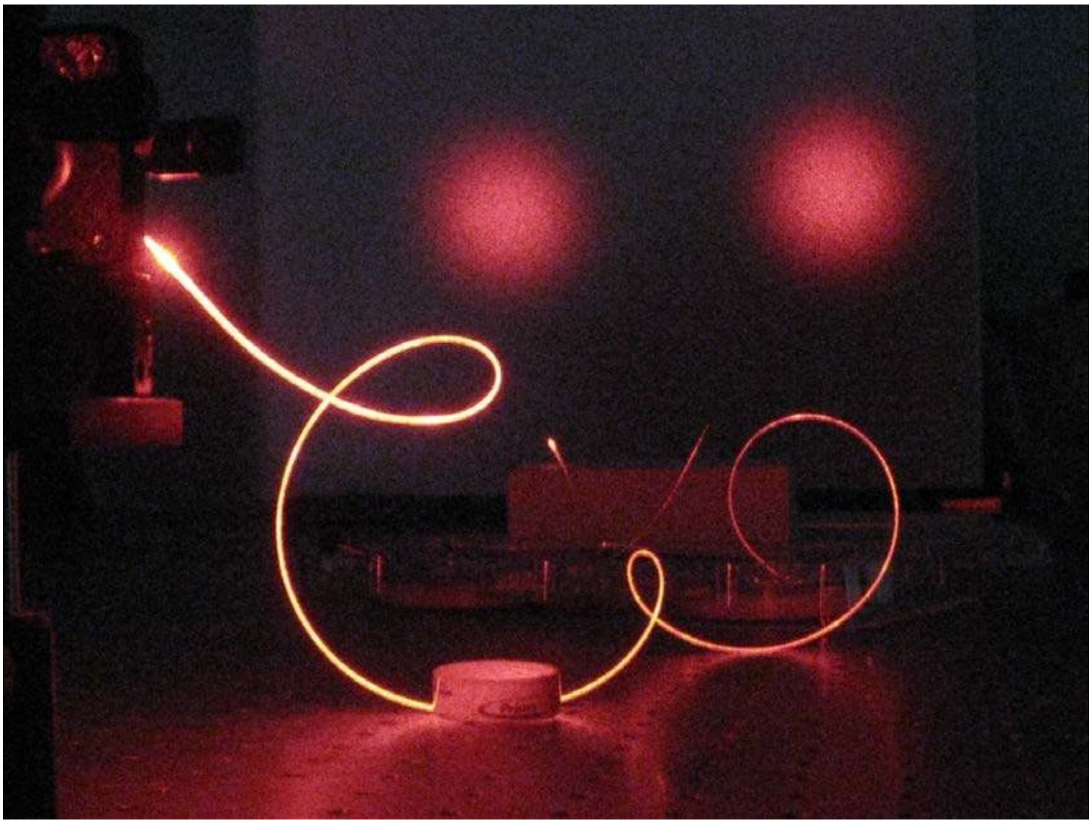
$P_T = P_I \, Cos^2(\kappa l)$ κ = Coupling Coefficient

$P_C = P_I \, Sin^2(\kappa l)$ l = Length of Interaction

Coupling of Modes







Measured Characteristics of Fabricated Splitters/ WDMs (Some Typical Results)

Characteristics of Power Splitters

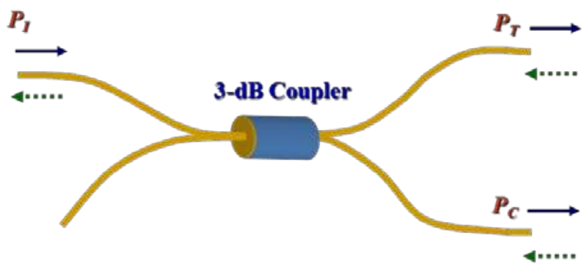
Characteristics	SMF @ 1310 nm	SMF @ 1550 nm	SMF @ 632.8 nm
Splitting Ratio	10% – 90%	10% – 90%	20% – 80%
Excess Loss	0.1dB – 0.3dB	0.1dB – 0.5dB	0.6dB – 1.1dB
Return Loss	40dB – 60dB	40dB – 60dB	50dB – 60dB

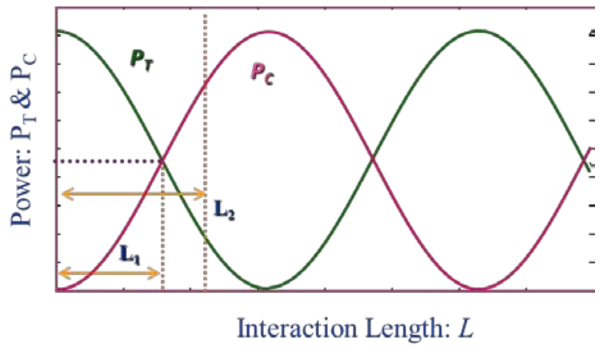
A typical WDM @ 1310/1550 nm

Characteristics	@ 1310 nm	@ 1550 nm
Wavelength Isolation	16.4dB	14.7dB
16dB Isolation Bandwidth	60nm	50nm
Excess Loss	0.61dB	0.37dB

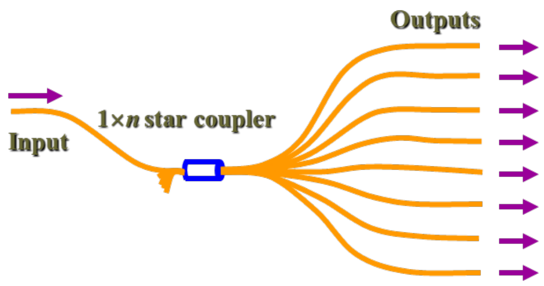
o Beam Splitter/Combiners
3-dB Couplers
Tap/Access Couplers
Tree Couplers
o Classical Wavelength Division Multiplexer/Demultiplexer (WDM/WDDM)
o Wavelength Interleaver
o Fiber Loop Mirror Reflector

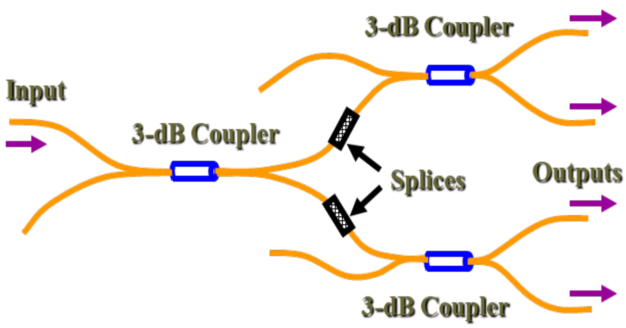
<u>3-dB Couplers</u>



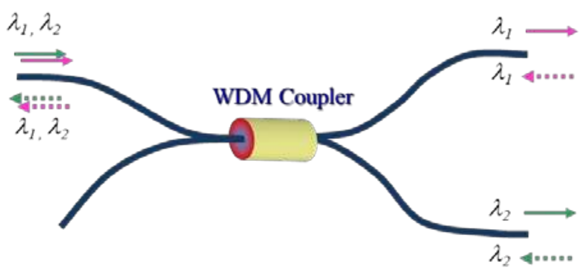


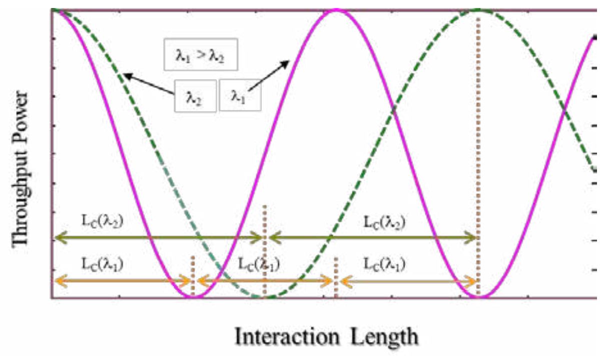
<u>Tree Coupler</u>





<u>Classical WDM/WDDM</u>

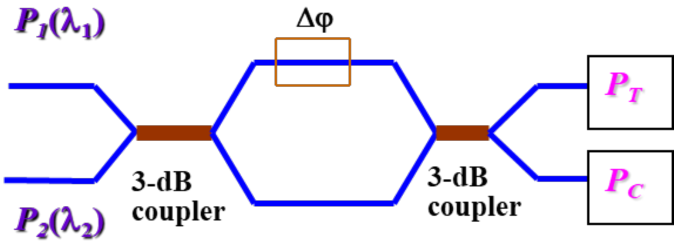




<u>Wavelength Interleaver</u>

$$P_T = P_1(\lambda_1)\sin^2\frac{\Delta\varphi(\lambda_1)}{2} + P_2(\lambda_2)\cos^2\frac{\Delta\varphi(\lambda_2)}{2}$$

$$P_C = P_1(\lambda_1)\cos^2\frac{\Delta\phi(\lambda_1)}{2} + P_2(\lambda_2)\sin^2\frac{\Delta\phi(\lambda_2)}{2}$$



- if $\Delta\varphi(\lambda_1)= 2\pi$ & $\Delta\varphi(\lambda_2)= \pi$, then $P_T = 0$ and $P_C = P_1(\lambda_1)+P_2(\lambda_2)$

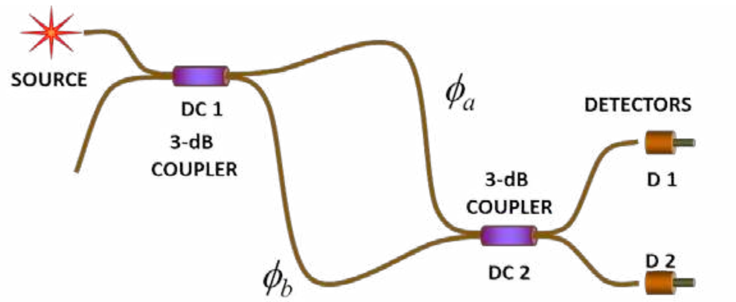
  i.e., power at both wavelengths now appear at the coupled port

- $\Delta\varphi$ satisfies the condition that $\Delta\varphi(\lambda_1)- \Delta\varphi(\lambda_2)= \pi$, both wavelengths can be combined into the coupled arm

- in reverse direction thus it separates these wavelengths

- in practice a flattop response needed; obtained by cascading MZs

Fiber MACH-ZEHNDER



a phase shift of $\pi/2$ across DCs

$$E_1 = \frac{1}{2}E_0\left[\exp(i\varphi_a) + \exp(i\varphi_b + \pi)\right]$$

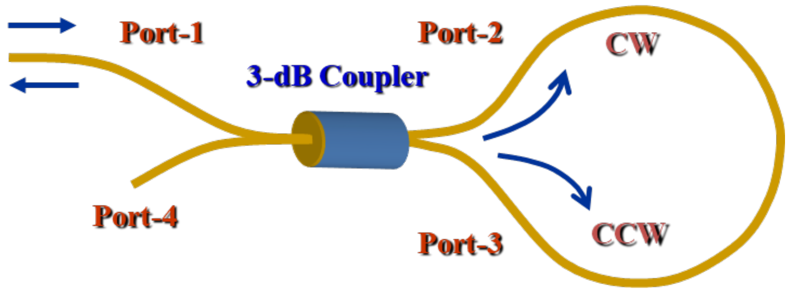
$$E_2 = \frac{1}{2}E_0\left[\exp\left(i\varphi_a + \frac{\pi}{2}\right) + \exp\left(i\varphi_b + \frac{\pi}{2}\right)\right]$$

$$I \propto \left\langle E.E^* \right\rangle$$

$$I_1 = \frac{1}{2}I_0\left[1 - \cos(\varphi_a - \varphi_b)\right]$$

$$I_2 = \frac{1}{2}I_0\left[1 + \cos(\varphi_a - \varphi_b)\right]$$

Fiber Loop Mirror



- resonator cavity in fiber laser
- passive fiber based FP devices
- duplex transmission using single light source at one end
- non-linear loop mirror, add-drop/switch

port-4:

$$E_4 = \underbrace{\frac{E_0}{\sqrt{2}} e^{i.0} \times e^{i\varphi} \times \frac{1}{\sqrt{2}} e^{i.0}}_{\text{CW}} + \underbrace{\frac{E_0}{\sqrt{2}} e^{i\pi/2} \times e^{i\varphi} \times \frac{1}{\sqrt{2}} e^{i\pi/2}}_{\text{CCW}}$$

$$I \propto \left\langle E_4 . E_4^* \right\rangle = 0$$

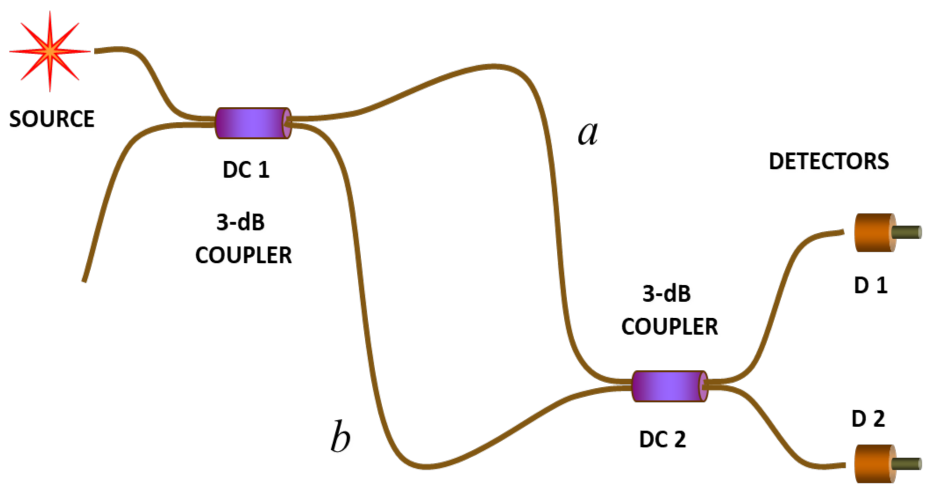
$$E_1 = \underbrace{\frac{E_0}{\sqrt{2}} e^{i.0} \times e^{i\varphi} \times \frac{1}{\sqrt{2}} e^{i\pi/2}}_{\text{CW}} + \underbrace{\frac{E_0}{\sqrt{2}} e^{i\pi/2} \times e^{i\varphi} \times \frac{1}{\sqrt{2}} e^{i.0}}_{\text{CCW}}$$

port-1:

$$I \propto \left\langle E_1 . E_1^* \right\rangle = E_0^2 = I_0$$

INTERFERROMETERS

Two-beam Interferometer: Fiber MACH-ZEHNDER

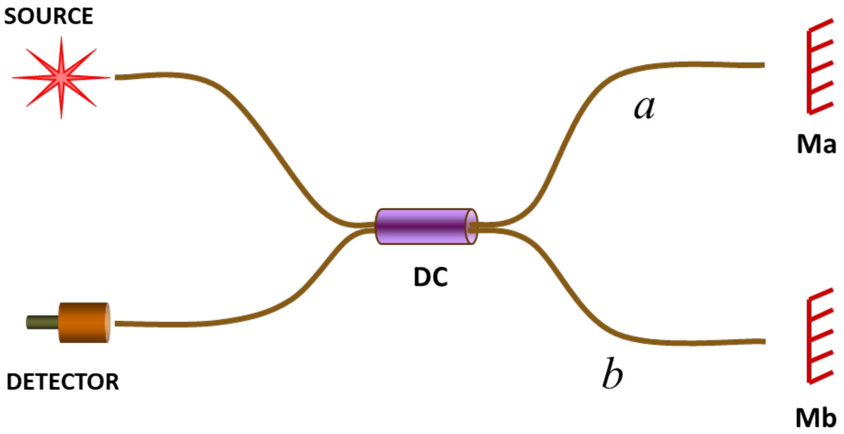


Transfer Function

$$I_1 = \frac{1}{2} I_0 \left[1 - \cos\left(\varphi_a - \varphi_b\right)\right]$$

$$I_2 = \frac{1}{2} I_0 \left[1 + \cos\left(\varphi_a - \varphi_b\right)\right]$$

<u>Two-beam Interferometer: Fiber MICHELSON</u>



Transfer Function

$$I_1 = \frac{1}{2} I_0 \left[1 - \cos\left(\varphi_a - \varphi_b\right)\right]$$

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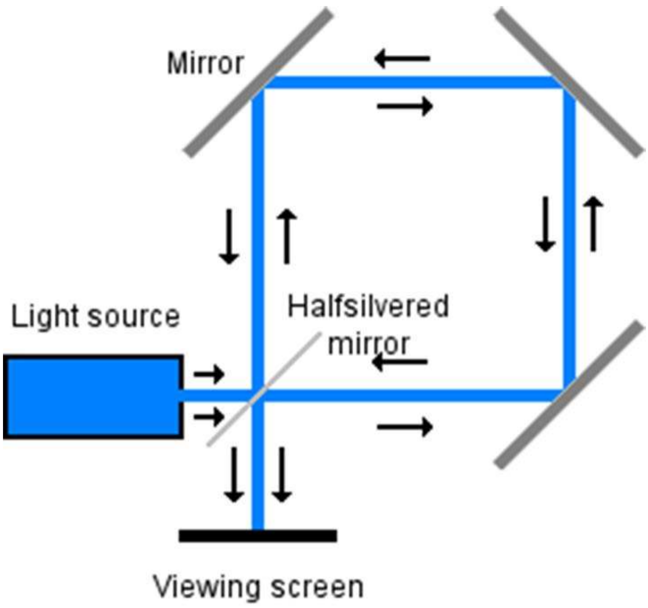
<u>Sagnac Interferometer</u>



Assume Circular Cavity

$\tau = 2\pi r/c$

τ = propagation time

r = cavity radius

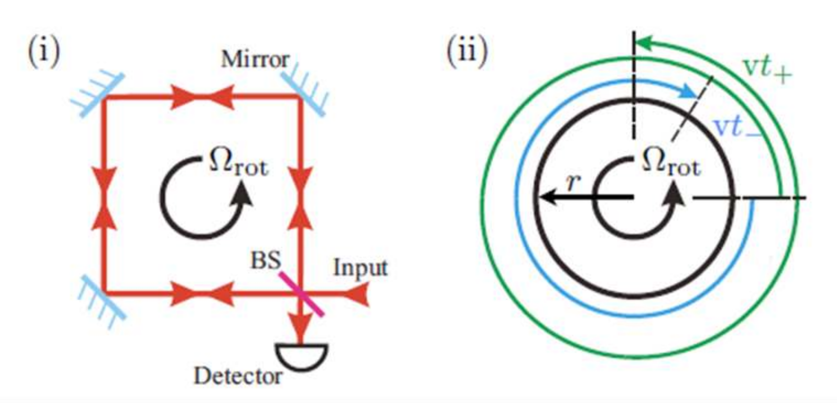
$\Delta\tau = (2\pi + \Omega\tau)(r/c) - (2\pi - \Omega\tau)(r/c)$

Ω = rotation per τ

$\Delta\tau = 4\pi r^2\Omega/c^2$

for ω, $\Delta\varphi = \omega\Delta\tau = 4\pi r^2\omega\Omega/c^2$

Fresnel-Fizeau Drag Effect



$$t_\pm = \frac{2\pi r \pm r\,\Omega_{\rm rot} t_\pm}{\rm v}$$

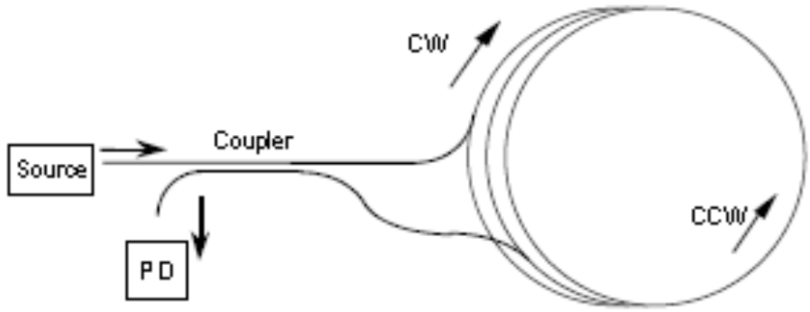
$$t_\pm \left(\frac{{\rm v} \mp r\,\Omega_{\rm rot}}{\rm v}\right) = \frac{2\pi r}{\rm v}$$

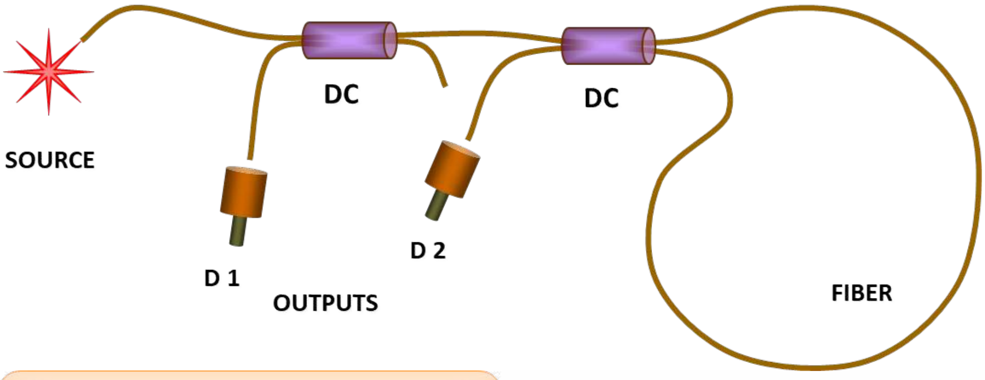
$$t_\pm = \frac{2\pi r}{{\rm v} \mp r\,\Omega_{\rm rot}}$$

$$\begin{aligned} \delta t &= t_+ - t_- \,, \\ &= \frac{2\pi r}{{\rm v} - r\,\Omega_{\rm rot}} - \frac{2\pi r}{{\rm v} + r\,\Omega_{\rm rot}} \\ \Longrightarrow \quad \delta t &= \frac{4\pi r^2\,\Omega_{\rm rot}}{{\rm v}^2 - (r\,\Omega_{\rm rot})^2} \,. \end{aligned}$$

$$\Delta\phi = \frac{4\boldsymbol{A}\cdot\boldsymbol{\Omega}_{\rm rot}}{\lambda_0 {\rm v}}$$

<u>Closed Cavity Defined by Optical Fiber</u>





loop rotated in its plane
with angular velocity Ω

phase shift between the two
counter propagating beams

$$\varphi_\Omega = 4\Omega\omega A / c^2$$