Universidad Carlos III de Madrid
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Electronic Instrumentation

Chapter 5

Optical and Optoelectronic Sensors and Measurements

Module 5. Optical and Optoelectronic Sensors and Measurements

- Introduction
- Basic components and signal conditioning
- Position, Displacement and Rangefinders
- Laser interferometry
- Fiber Optic sensors
- Gyroscopes

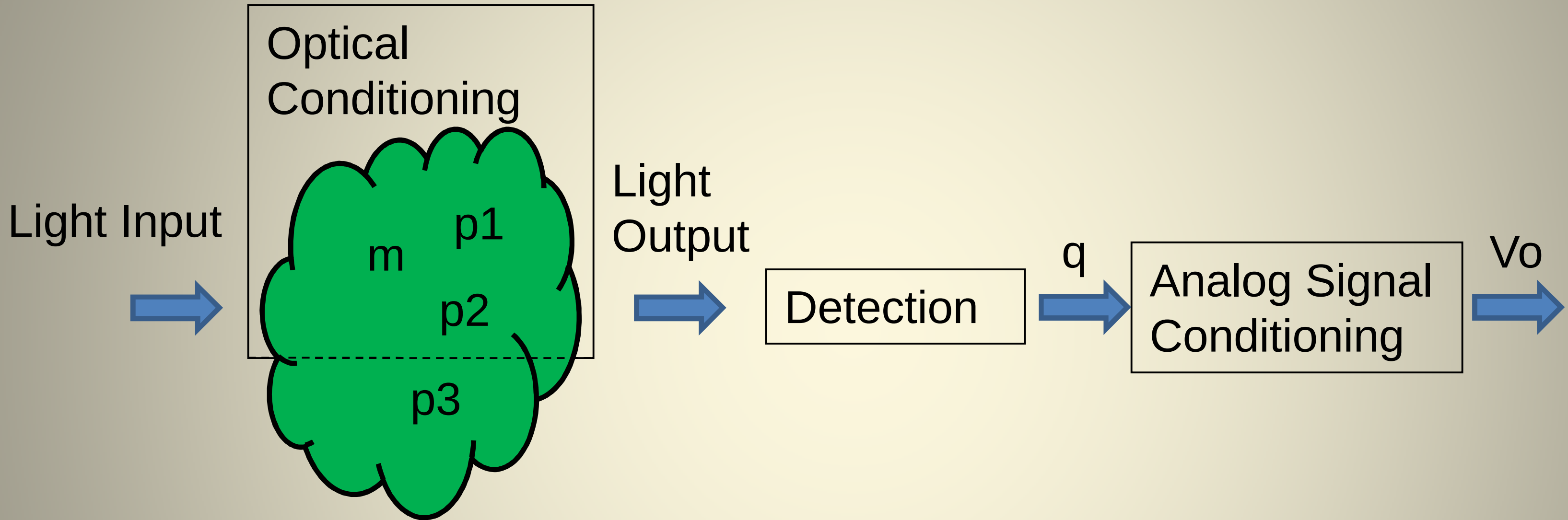
Introduction

- In this chapter we will focus on the principles of measurement used in optical and optoelectronic sensors .
- A survey of input sensor mechanisms will be addressed but only some applications will be described in more detail.
- In this case the classification of the sensors is due to the characteristics of the light (electromagnetic wave) that are changed by the measured physical phenomena:
  - Amplitude (Intensity)
  - Polarization (Polarimetry)
  - Optical phase (Interferometry)
  - Frequency of emission / wavelength (Spectroscopy / Gratings)

Introduction

- Some advantages of optical and optoelectronic measurements:
  - Non-contact and non-invasive approaches
  - EMI inmunity
  - High precission measurements (e.g. interferometry)
  - Withstanding harsh environments and preserving electro-magnetic isolation (e.g. optical fiber)

Basic Architecture for an Opto-Electronic Instrumentation Measurement System



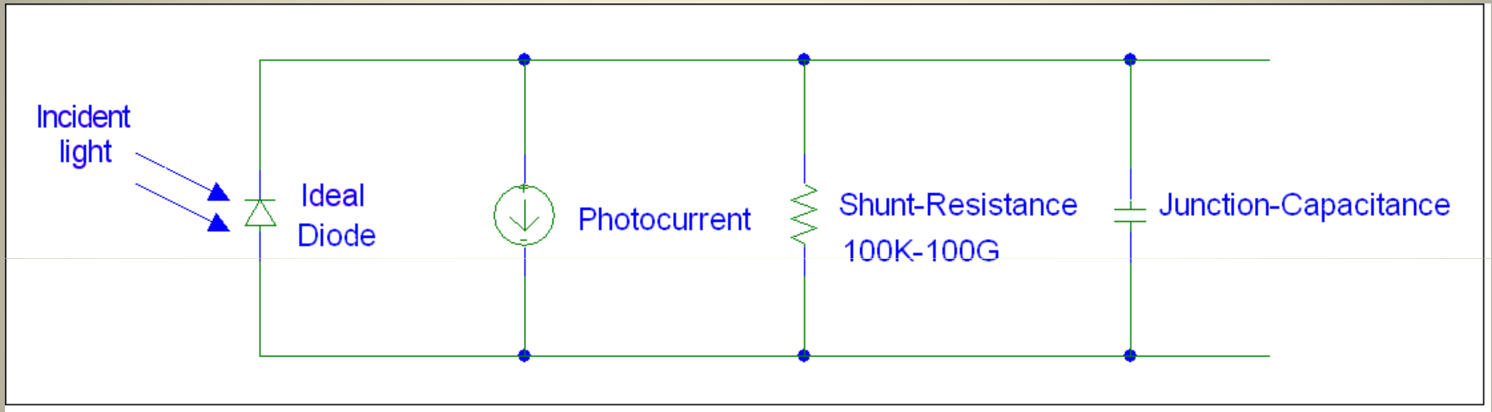
- Light Input from a light source (LASER, LED), but sometimes is not necessary.
- Output from the detector can be either a current (photodiode) an impedance change (photoconductor) or a voltage (photovoltaic sensor).
- Optical conditioning and lead-in/ lead-out of the light sometimes present (e.g. optical fiber) .
- The optical conditioning frequently converts the information from an optical magnitude to another (eg. Interferometer: optical phase to intensity) .

Analog signal conditioning of optoelectronic sensors

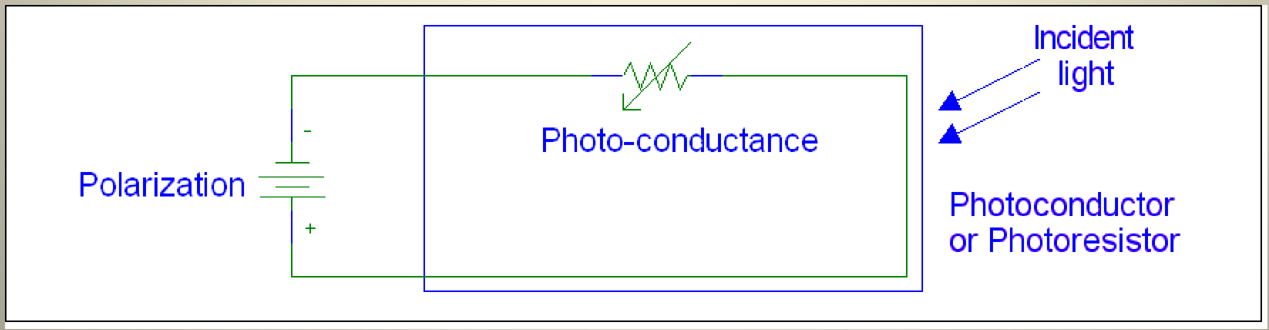
- Primarily light is detected by photodiodes, APDs, photoconductors.
- Current output with high impedance or variable high impedance is mainly obtained.
- Current to voltage circuits are basically used.
- Light may be externally injected into optoelectronic measurement systems by means of Lamps, LEDs and LASERs biased by a current source or voltage to current conversion circuit.

Equivalent of photo-detectors

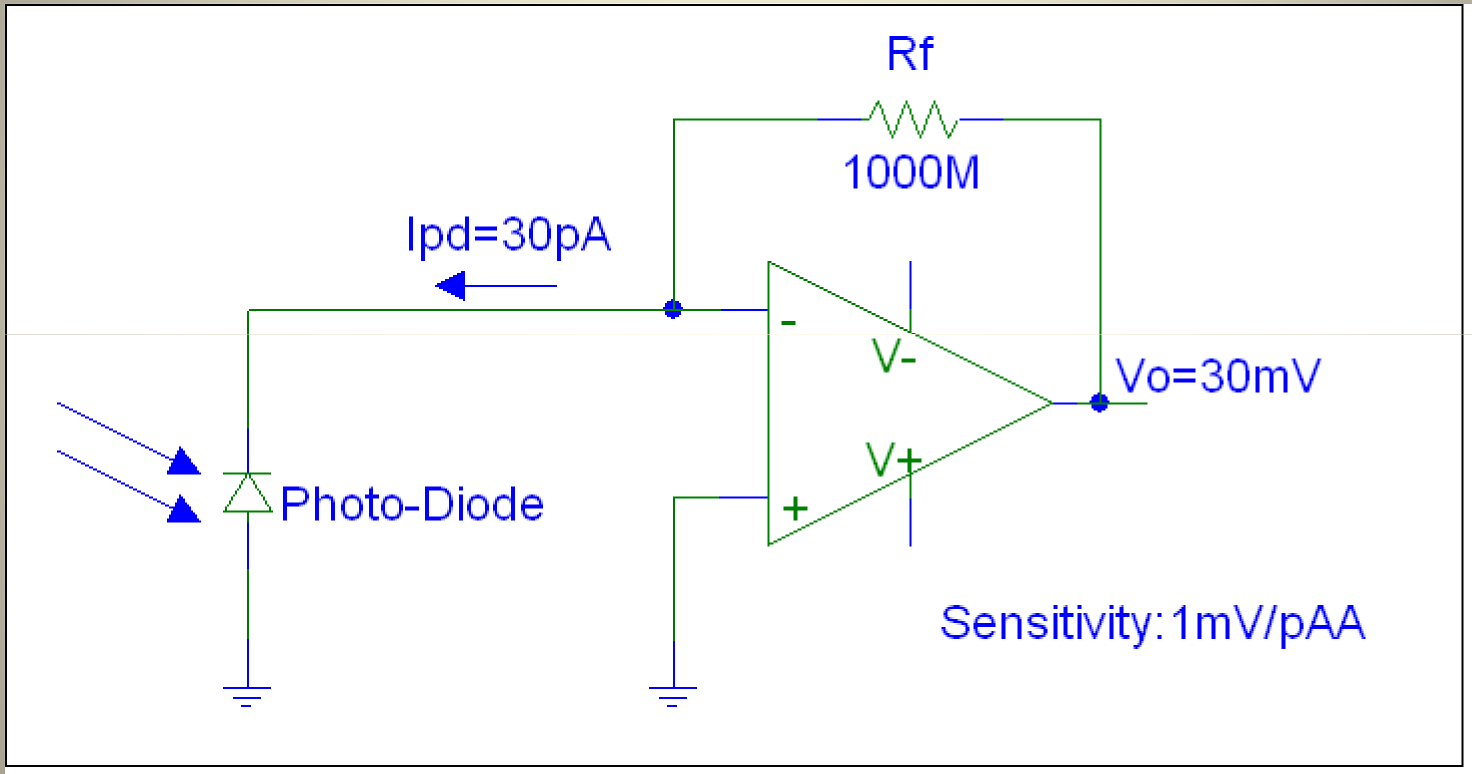
Photo-diode and APD



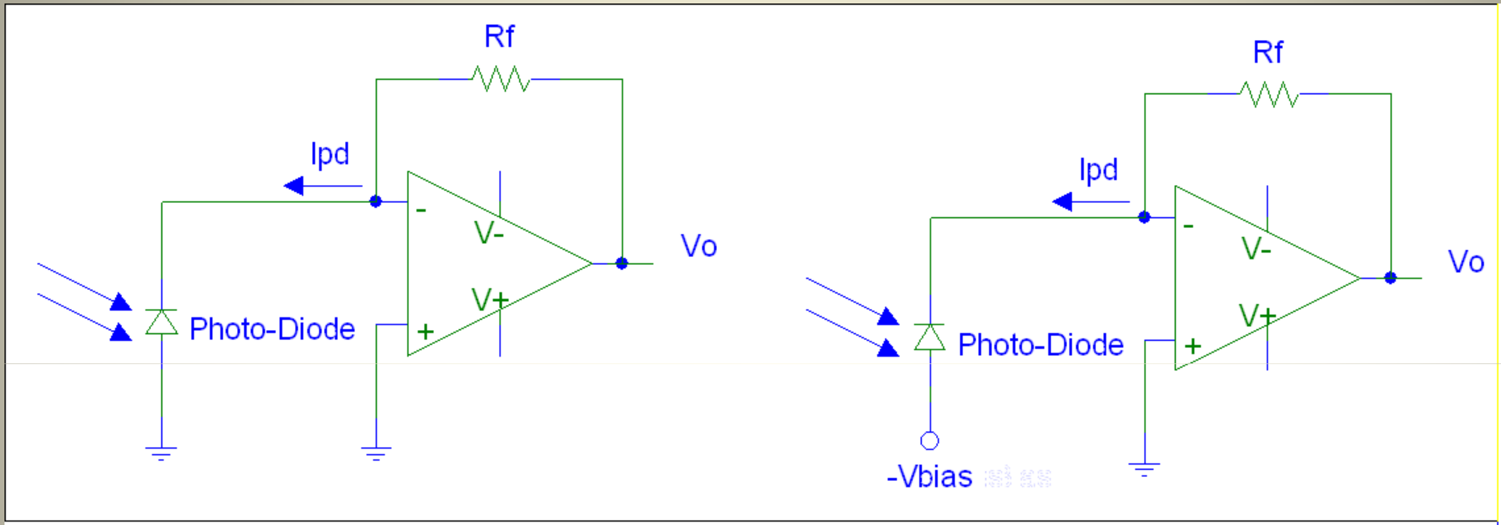
Photoconductor/Photo-resistor



Current to voltage circuit

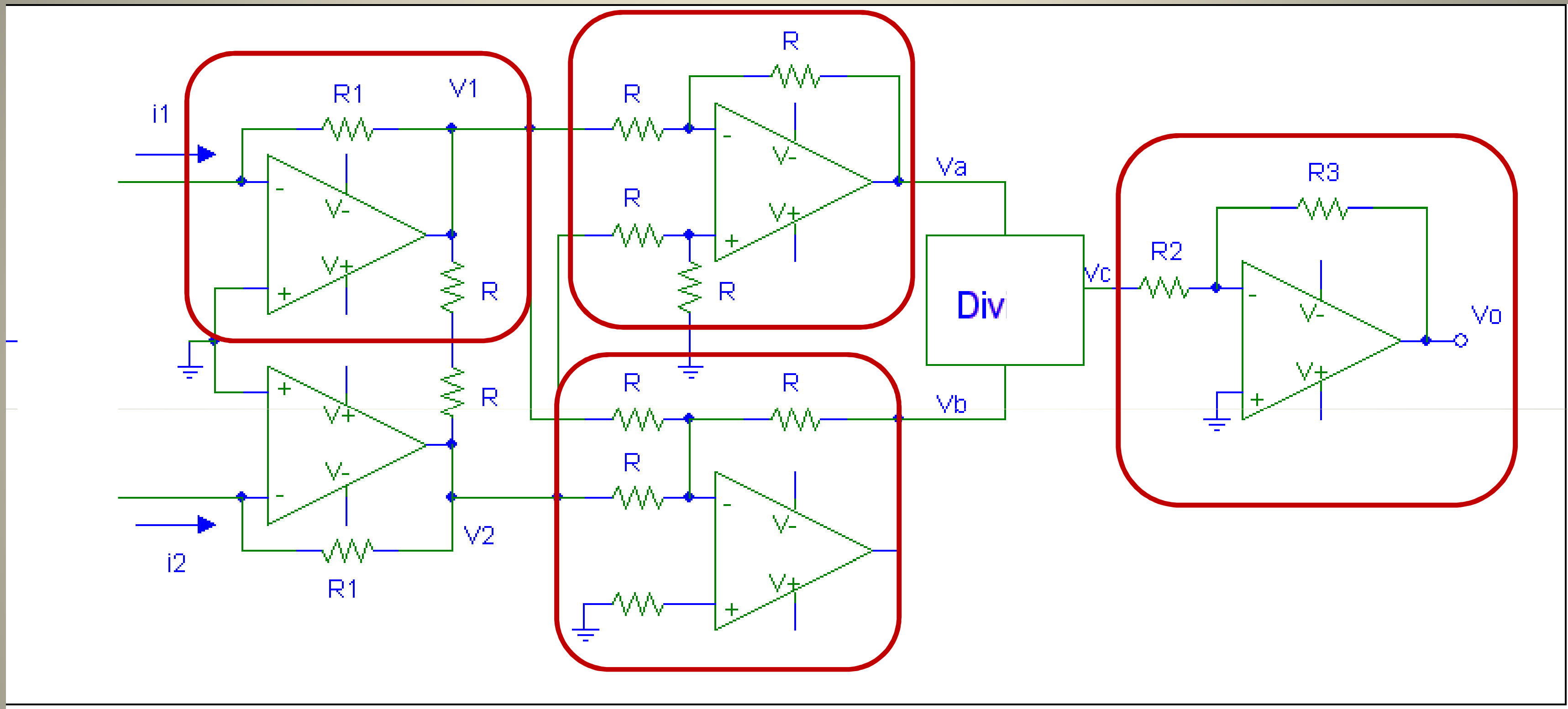


Biasing light detectors



PHOTOVOLTAIC	PHOTOCONDUCTIVE
Zero Bias	Reverse Bias
No “Dark” Current	Has “Dark” Current
Low Noise (Johnson)	Higher Noise (Johnson + Shot)
Precision Applications	High Speed Applications

Example of electronic signal conditioning



Current to voltage converter

Normalization to the intensity mean

Adjustment of sensitivity

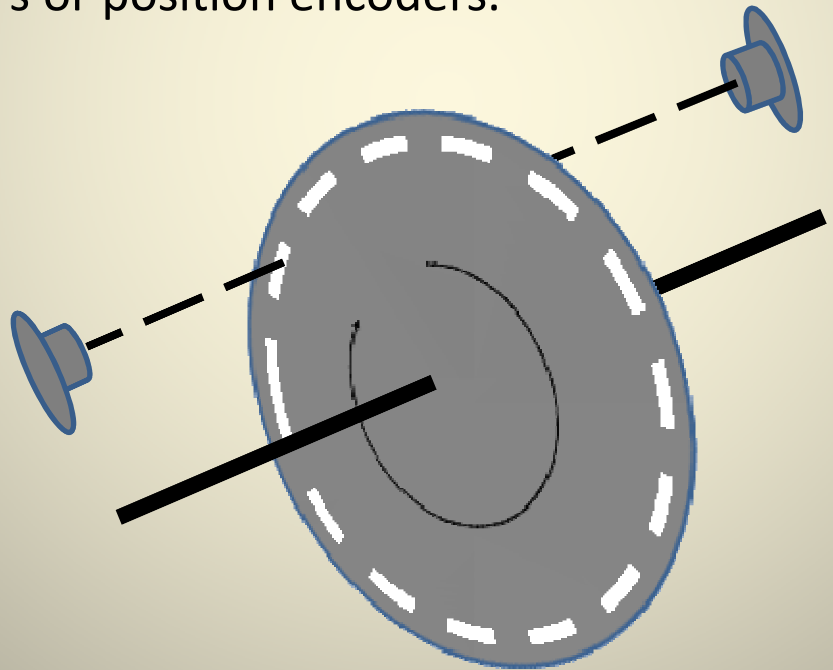
Basic Components for optical conditioning

- Emitters: LASER, LED and other light sources (lamps, SLED, etc.)
- Detectors: Photodiodes, APD, photo-conductors and others (Photo-transistors, LDR, etc.)
- Optical components:
  - Lenses, mirrors, beam-splitters, …
  - Polarizer, optical retarder, Wollaston prism, crystals, …
  - Diffraction gratings
- Optical fiber:
  - Transmission fibers
  - Intrinsic sensing
  - In fiber components (e.g. in fiber Bragg gratings)
- Optical modulators
  - Acousto-optic modulators and other actuators (e.g. PZT onto a fiber)

Position, Displacement and Rangefinders

- On/off intensity sensors, grating sensors and encoders:

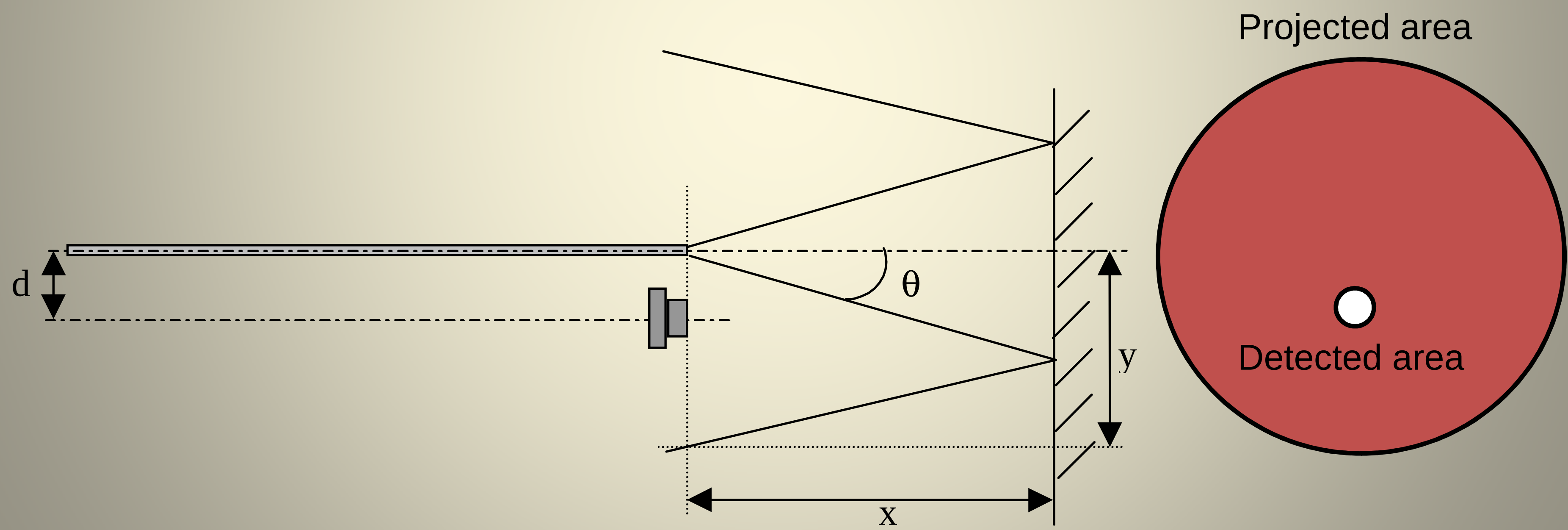
- An optical displacement transducer can be fabricated with two overlapping gratings which serve as light-intensity modulator. They can be used as proximity sensors or position encoders.



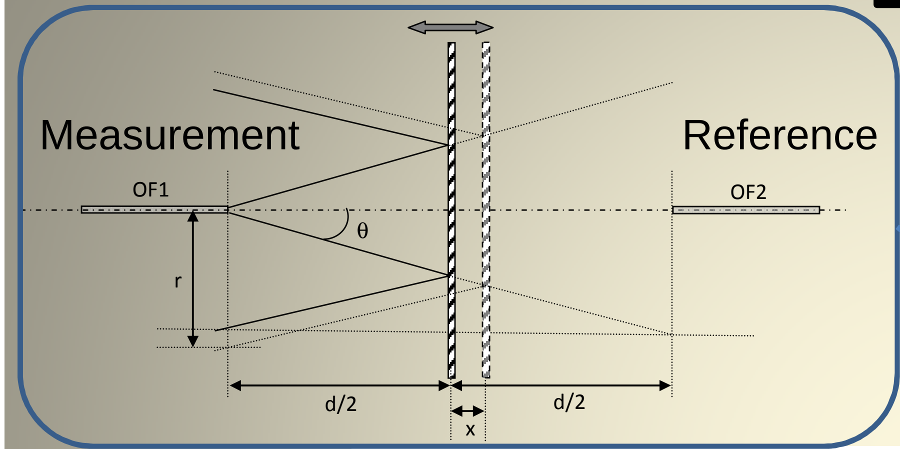
Position, Displacement and Rangefinders

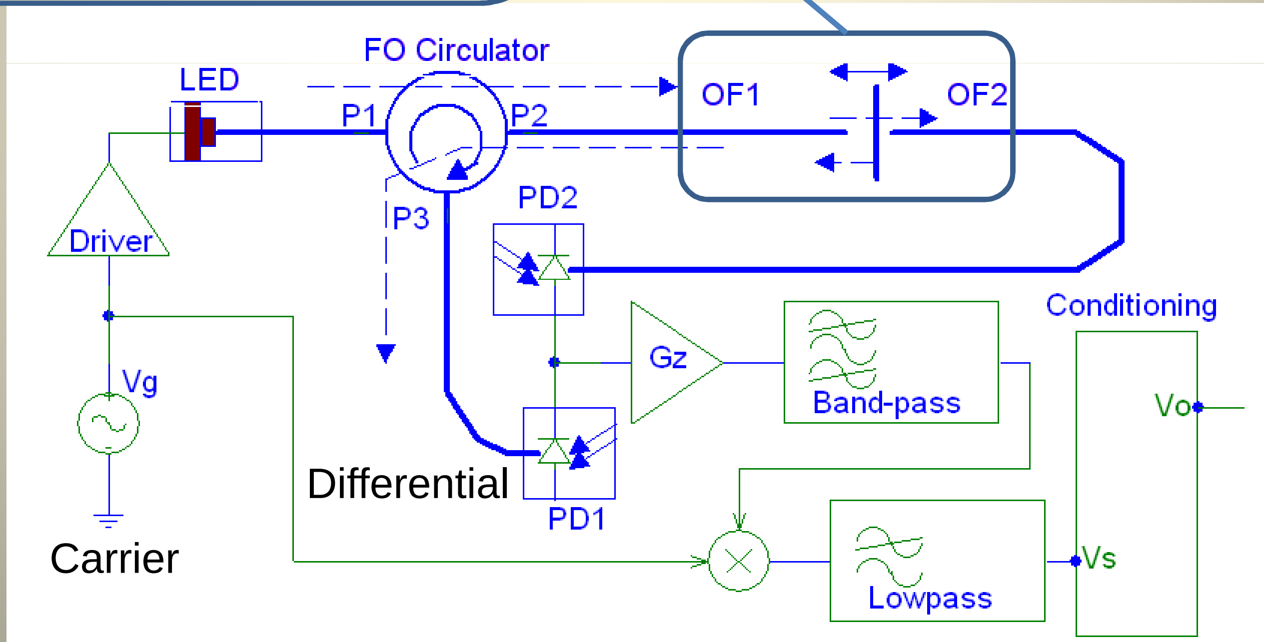
- Intensity sensor (attenuation):

- Intensity attenuates with distance. Sometimes mirrored reflection on the target is present, but in general diffused reflection must be considered.



Example: Vibrations





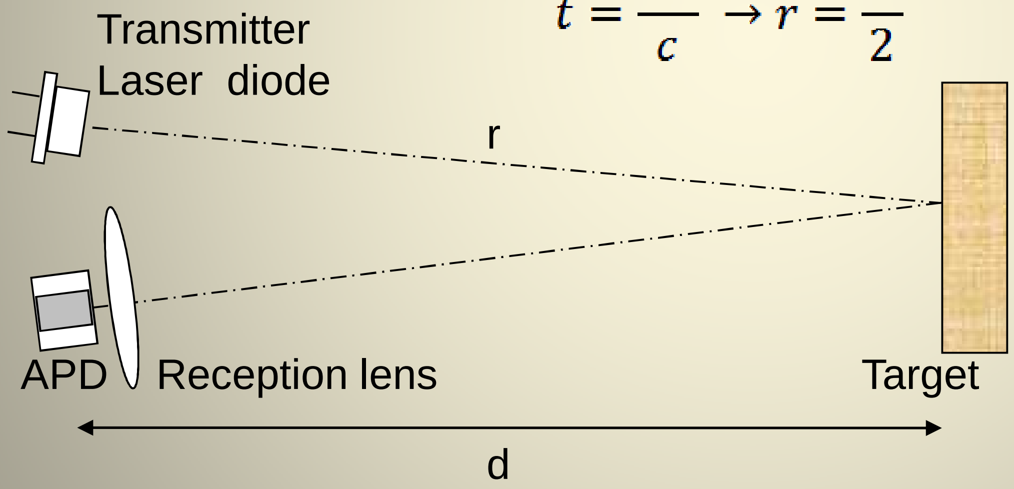
Synchronous detection

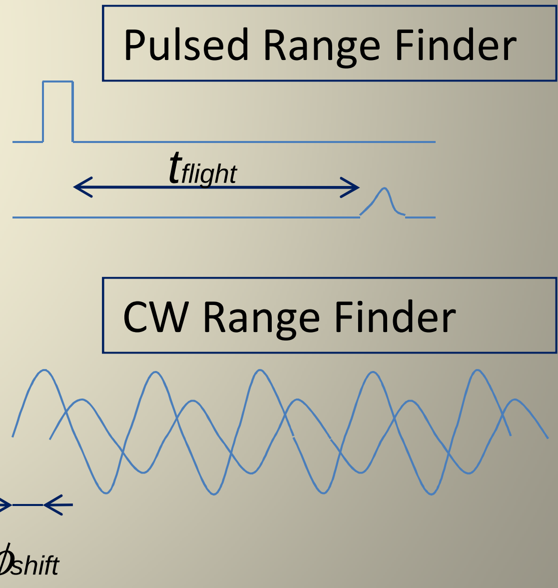
Position, Displacement and Rangefinders

- Optical Range Finders (time of flight):

- Range is obtained measuring the time difference between the sent pulse and the received signal. Pulsed and amplitude modulation systems are used.

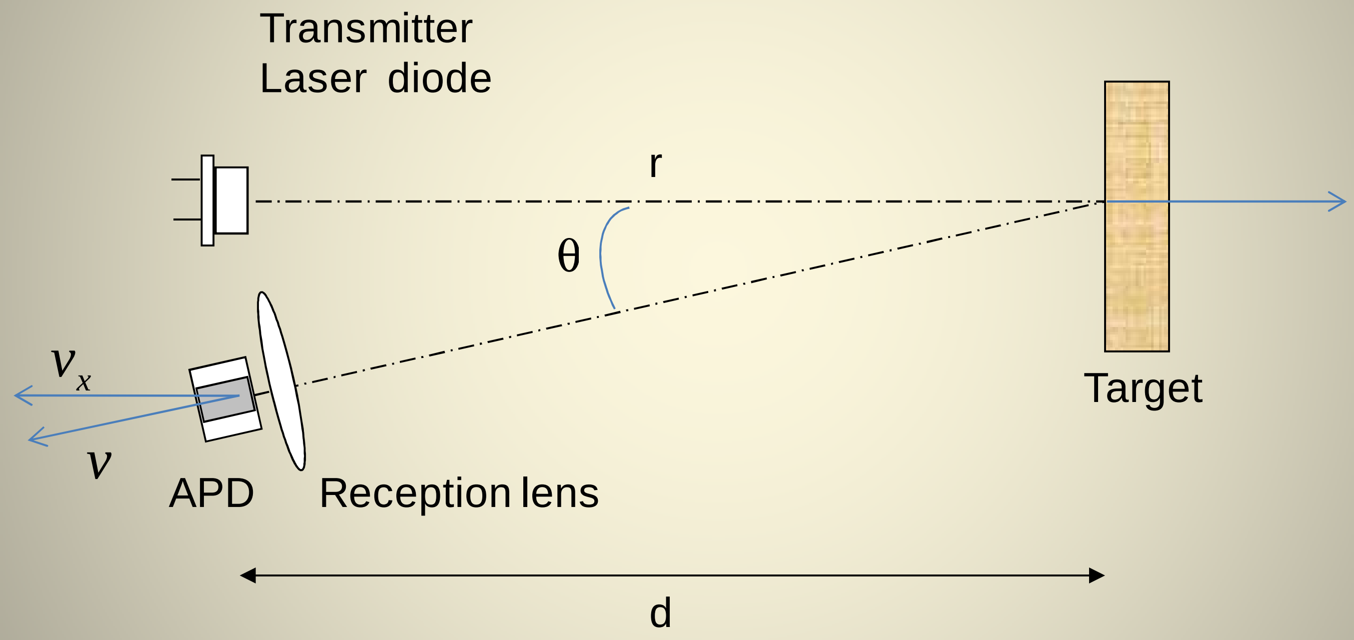
$$t = \frac{2\,r}{c} \rightarrow r = \frac{ct}{2}$$





Position, Displacement and Rangefinders

- Laser Doppler:

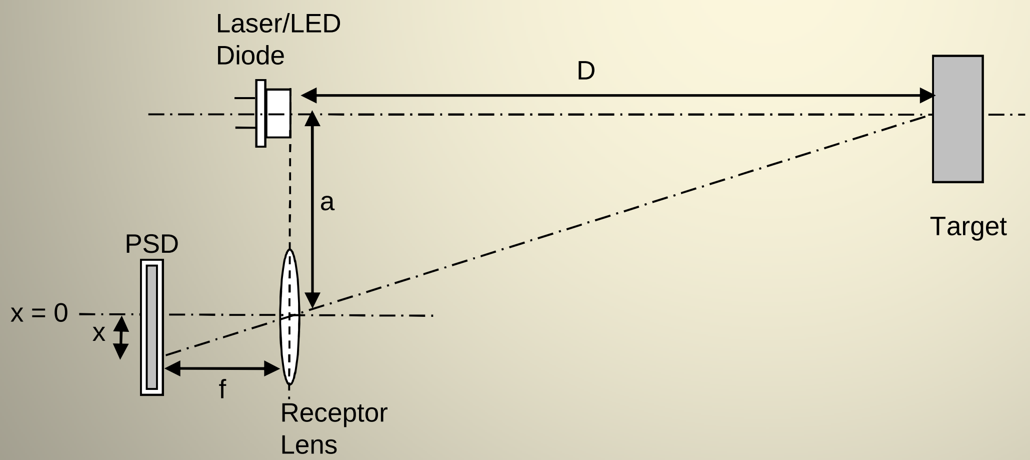


$$w_r = \frac{d[w_o \cdot t + w_o \cdot 2d(t)/c]}{dt} = w_o[1 + 2v_x / c]$$

Position, Displacement and Rangefinders

- Triangulation

- The position of light spot on a position sensitive photo-detector is related to the distance by triangulation. As an example, a PSD is a differential current device that gives an output related to the position of a collimated beam on the device surface. It provides one and two-dimensional position. Others are photo-detector arrays.

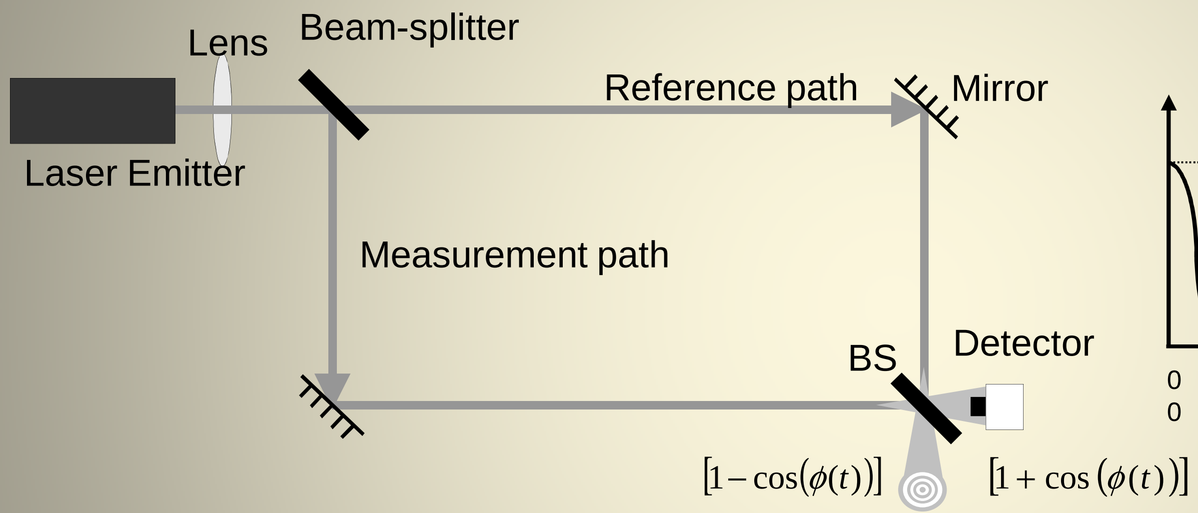


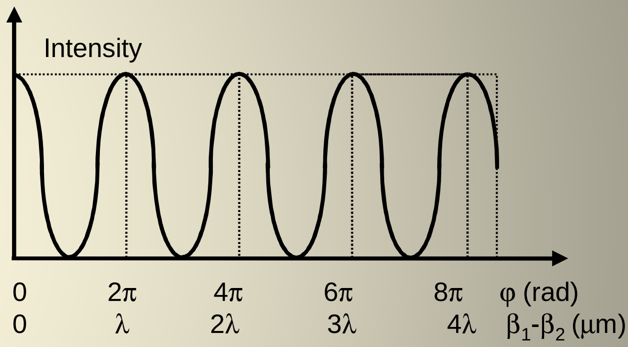
$$\frac{x}{f} = \frac{a}{D}$$

$$\frac{i_1 - i_2}{i_1 + i_2} = \frac{2x}{L}$$

Position, Displacement and Rangefinders

- Laser interferometry





$$I = \frac{\alpha I_0}{2}\left[1 + V\cos(\phi(t))\right]$$

$$V = \frac{I_{máx} - I_{mín}}{I_{máx} + I_{mín}}$$

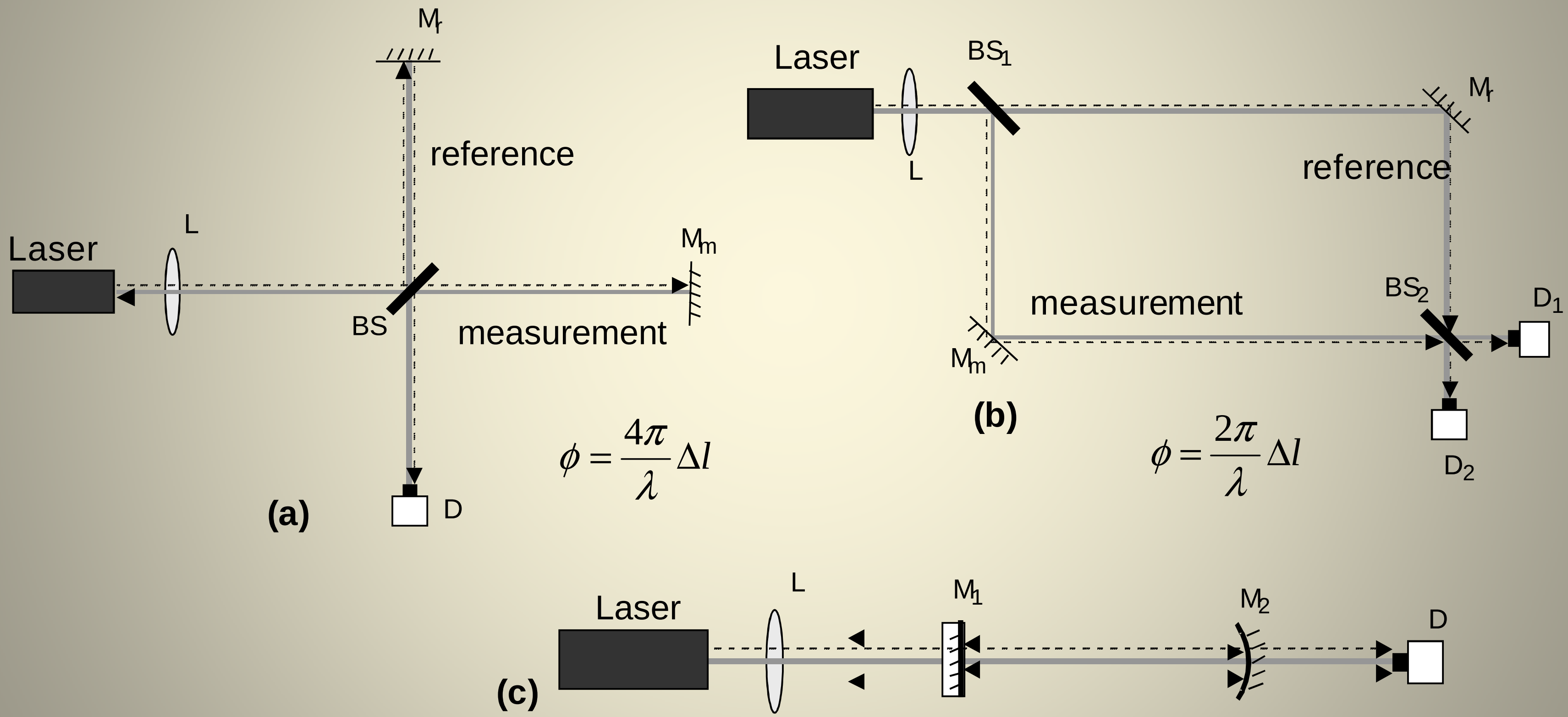
$$\phi(t) = \phi_m(t) - \phi_r = \frac{2\pi}{\lambda}\left|L_m(t) - L_r\right|$$

Measurement of displacement

$$\phi(t) = \frac{2\pi}{\lambda(t)}\left|L_m - L_r\right|$$

Measurement of wavelength

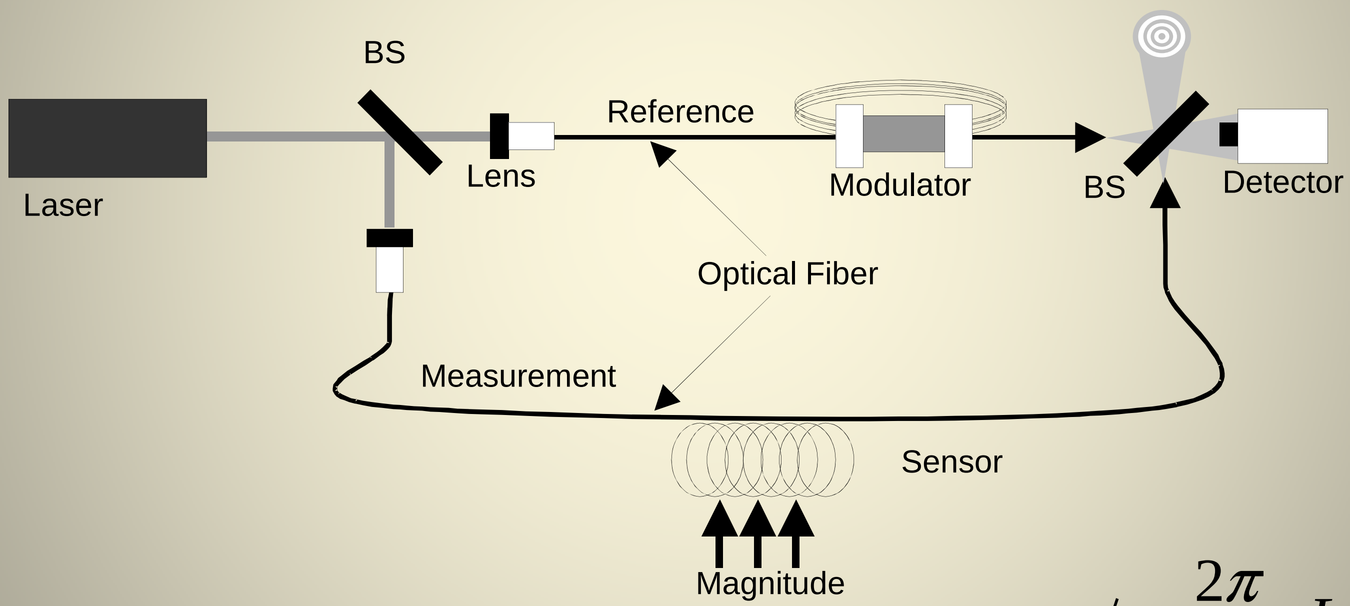
Laser interferometers



$$\phi = \frac{4\pi}{\lambda}\Delta l$$

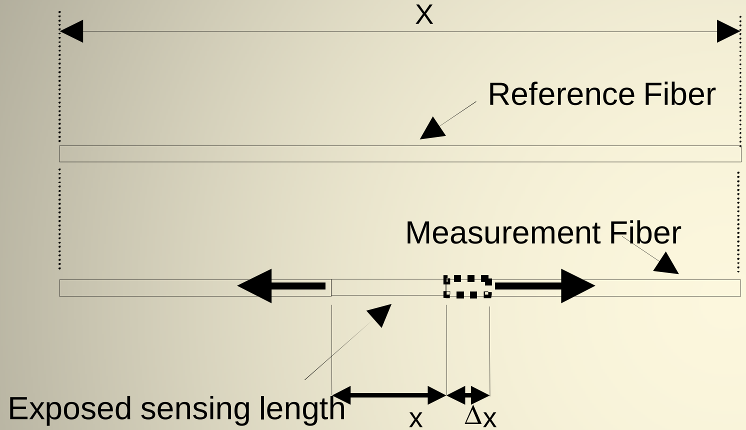
$$\phi = \frac{2\pi}{\lambda}\Delta l$$

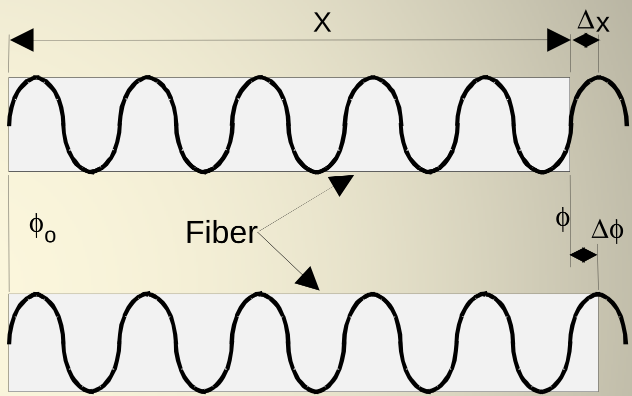
Optical Fiber Interferometers



$$\phi = \frac{2\pi}{\lambda} nL$$

Optical fiber intrinsic sensing





Optical path

$$\phi = \frac{2\pi}{\lambda} nL = k \cdot \beta$$

$$\partial\phi = k \cdot \partial\beta = k\left(n \cdot \partial L + L \cdot \partial n\right)$$

Gage factor (includes strain-optic)

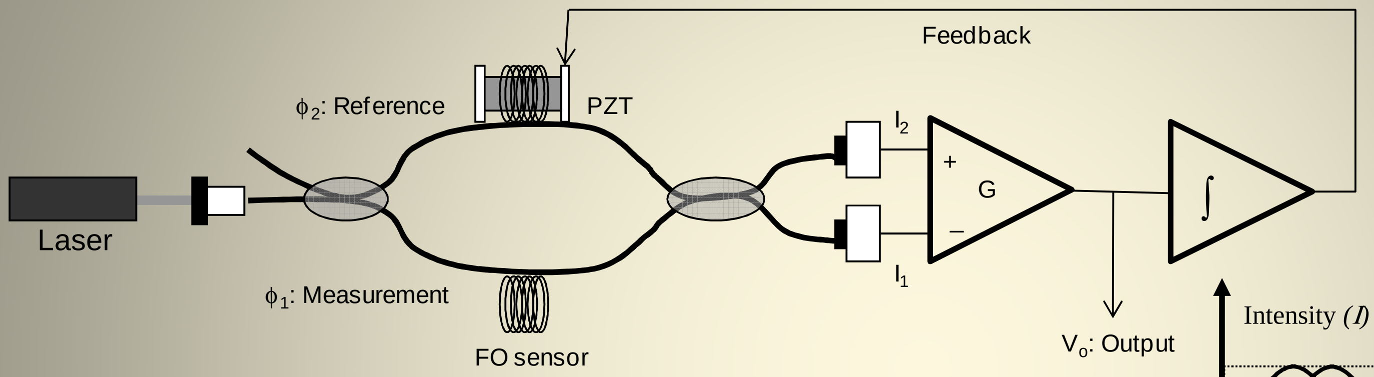
$$\frac{\partial\phi}{L} = kn\,\xi \cdot \varepsilon$$ Strain

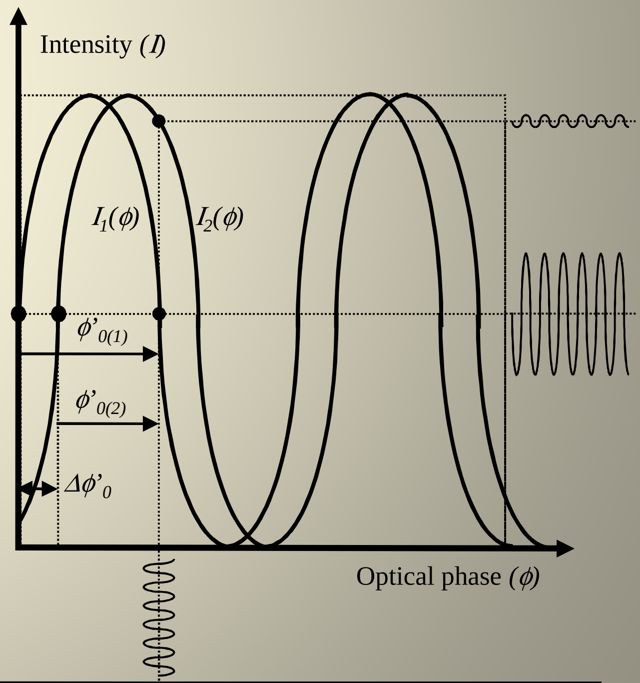
$$\frac{1}{L}\frac{\partial\phi}{\partial T} = kn\left[\frac{1}{L}\frac{\partial L}{\partial T} + \frac{1}{n}\frac{\partial n}{\partial T}\right]$$ Temperature

Thermo-elastic coefficient

Thermo-optic coefficient

Example: Closed-loop

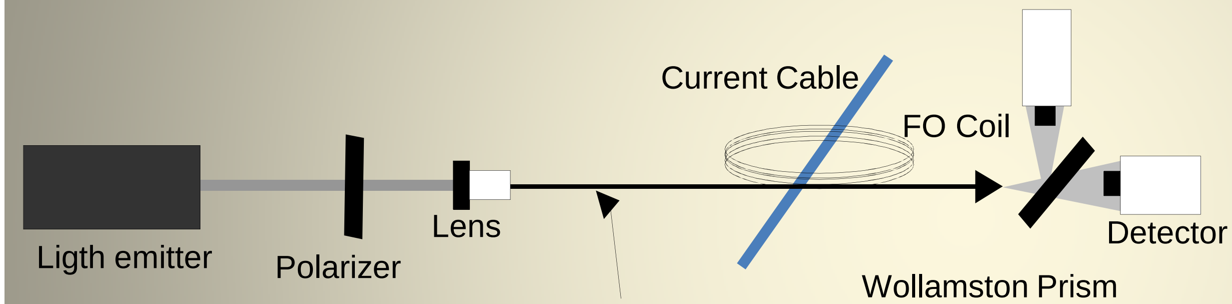


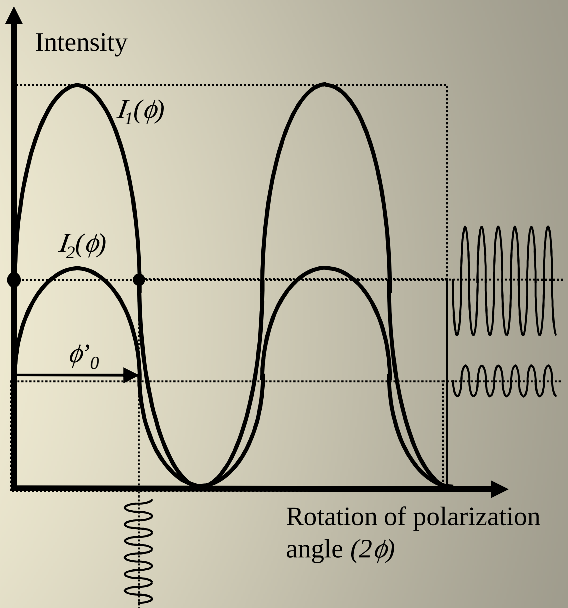


$$I_1 = \frac{I_0}{2}\left[1+\cos(\phi_1-\phi_2)\right]$$

$$I_2 = \frac{I_0}{2}\left[1-\cos(\phi_1-\phi_2)\right]$$

Polarimetry



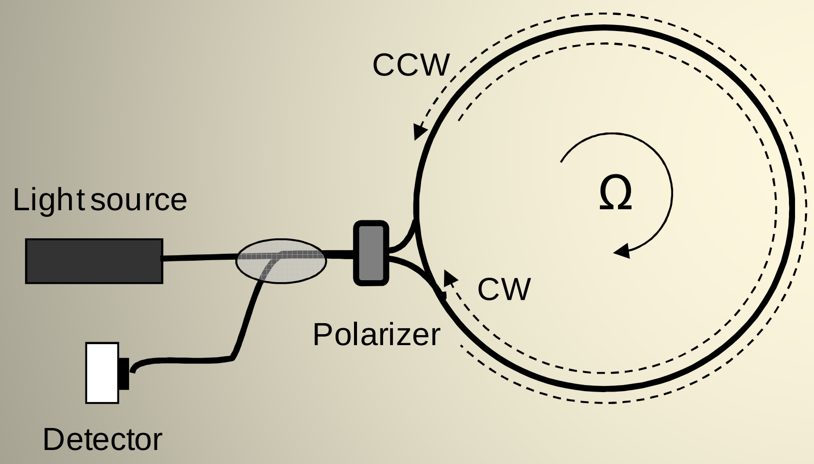


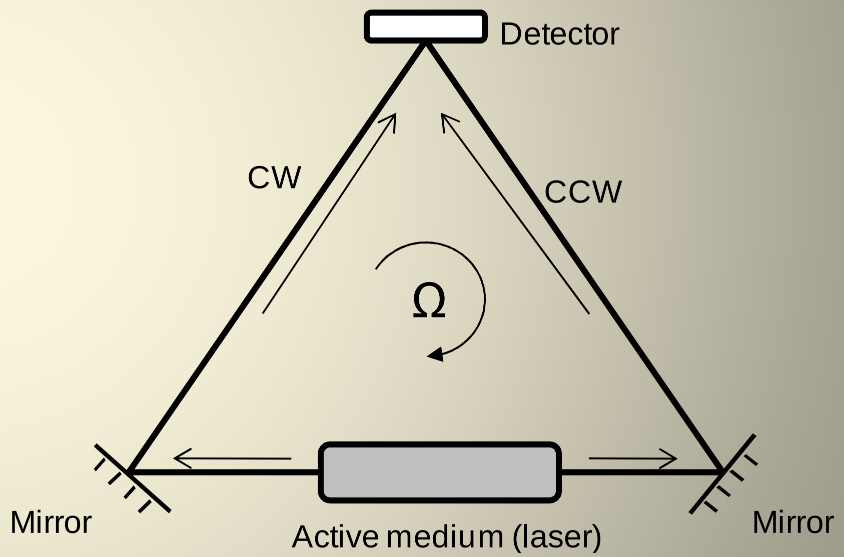
$$I = \frac{I_0}{2}\left[1 - \cos(2\phi)\right]$$

$$\frac{i_1 - i_2}{i_1 + i_2}$$

Gyroscopes

- Optical gyroscope is based on the Sagnac effect and are implemented both using fiber optics and free-space optics.

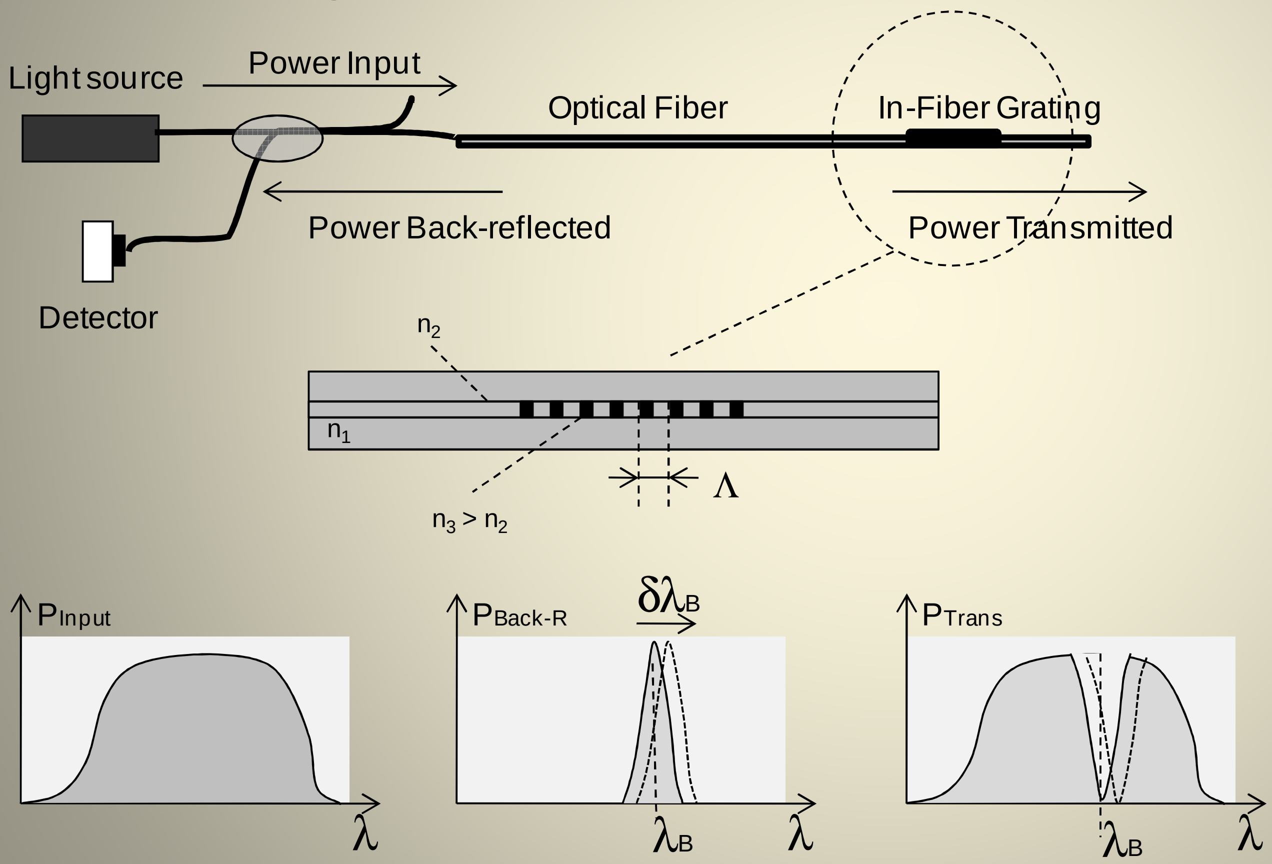




$$\Delta L = \frac{4A}{c_o}\Omega \qquad \Delta\phi = \frac{2\pi}{\lambda_o}\frac{4A}{c_o}\Omega \qquad f = q\frac{c_o}{P} \qquad \Delta f = -\frac{4A}{\lambda_q nP}\Omega$$

Optical fiber Bragg gratings

- Wavelength based sensor.



$$\frac{\partial \lambda_B}{\lambda_B} = K \cdot \varepsilon$$

Strain

$$\frac{\partial \lambda_B}{\lambda_B} = (a_{Tl} + a_{Tn})\partial T$$

Temperature

Summary

- In this chapter we have focused on the principles of measurement used in optical and optoelectronic sensors and their optical and electronic basic signal conditioning. Examples of sensors based on intensity, polarization, optical phase and wavelength have been presented.
- A survey of input sensor mechanisms have been addressed through the case of position, displacement and rangefinders: grating sensors and encoders, attenuation, time of flight, laser Doppler, triangulation and laser interferometers.
- Some applications have been described in more detail through representative examples of fiber-optic sensing: optical fiber interferometry, polarimetry, gyroscopes and in-fiber Bragg gratings.