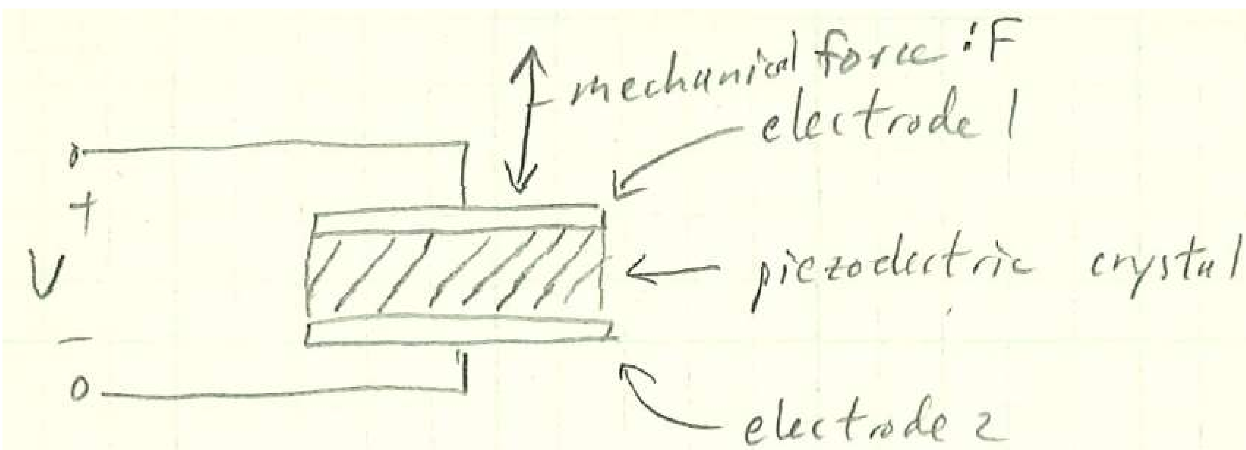
Sensing Methods: Voltage Sensing

Some sensors directly produce a voltage that is a function of the measurand.

1. Piezoelectric Crystals

Some crystals produce an electric charge when they are subjected to mechanical force (or rather the stress from that force). These crystals are called piezoelectric crystals. The crystal structure has many electrical dipoles, and they may be randomly oriented or aligned. Every dipole is a vector and all the dipole vectors in the crystal make up a vector field, **P**. Application of a mechanical stress changes **P**, which results in a change in the surface charge density, which results in the development of a voltage across the crystal. This effect is crystal plane orientation dependent. The opposite effect happens too: applying a sufficiently large voltage across the crystal results in a dimensional change.

Consider placing an "orientation appropriate" piezoelectric crystal between 2 electrodes:



A is the electrode surface area.

t is the separation distance between the two electrodes.

ε_r is the relative permittivity of the piezoelectric crystal.

Therefore, $C = \frac{\varepsilon_o \varepsilon_r A}{t}$

Also, $q = dF$

where d is an orientation dependent charge coefficient

Since also $q = CV$, then $V = \frac{q}{C} = \frac{dFt}{\varepsilon_o \varepsilon_r A}$

This equation can be rewritten to determine the force, F, resulting from applying a voltage, V. Therefore, piezoelectric crystals can be used as a sensor or as an actuator.

2. Seebeck Effect

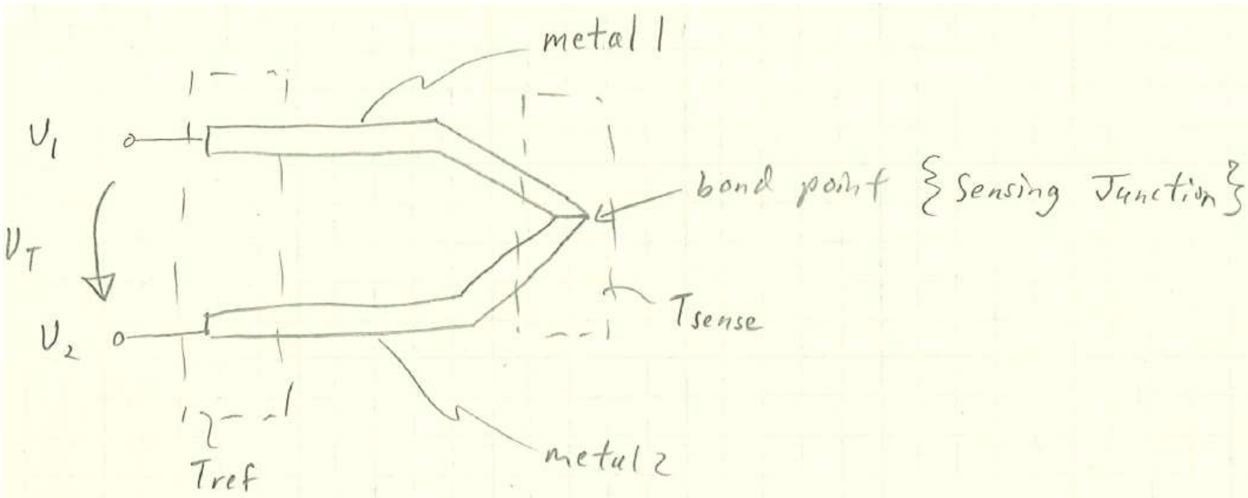
Dissimilar metals require different amounts of energy to liberate electrons from their surfaces.

This amount of energy, or "work", is quantified by the Work Function of the metal.

When two dissimilar metals are joined together to form a junction, electrons possess a tendency to move from the lower work function metal to the higher work function metal.

This results in the formation of a small voltage across the junction, and this junction potential is temperature dependent. This phenomenon is called the Seebeck effect.

Based on the Seebeck effect, a thermocouple consists of two dissimilar metals bonded at a point, the sensing junction, and brought to the temperature to be measured. The other end of the two metals is kept at a reference temperature:



T_{sense} is the temperature being sensed, and T_{ref} is a reference temperature.

V_T is the open circuit voltage appearing on the left end.

$$V_T = V_2 - V_1 = (P_2 - P_1)\left(T_{sense} - T_{ref}\right) = (P_2 - P_1)\Delta T$$

P_1 and P_2 are the Seebeck coefficients for the two metals. This temperature measurement sensor is called a thermocouple.

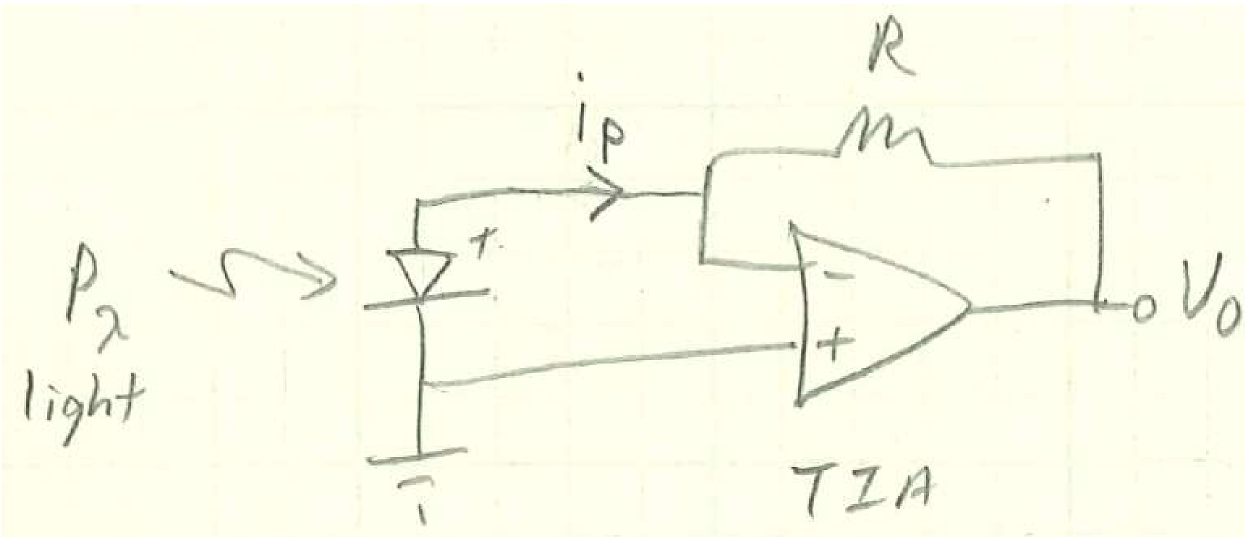
The theromocouple only produces a small current before the output voltage drops. So, a high impedance voltage meter is needed to accurately read it.

Thermocouples can be made in macroscale or in microscale (on chip) technologies.

Sensor Methods: Current Sensing

Some sensors directly produce a current that is a function of the measurand. One example is a photodiode.

This photodiode is interfaced with a TIA to produce an output voltage:



i_p is the diode photocurrent and i_p is proportional to light intensity, P_λ.

$$V_o = -Ri_p$$

A photodiode can be a pn junction diode structure or a Schottky diode structure (a p- or n-type semiconductor material in contact with a conductor) with exposure to light. Observe that positive current (the photocurrent) flows out of the anode.

Note: on a MEMS device where doped Si is in contact with a metal layer, exposure to light can generate a light-induced current into the device, which may or may not be problematic.

A photovoltaic cell (i.e. a solar cell) is a very large area pn junction diode.

Sensing Methods: Optical Sensing

Make use of some property of light that is = f(measurand).

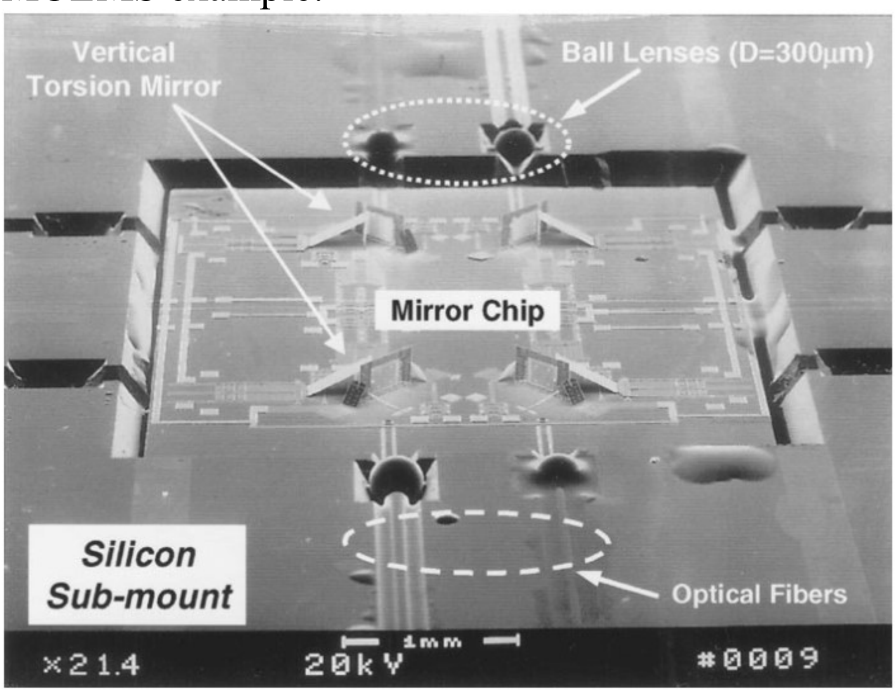
Properties of light that can *possibly* be manipulated for sensing purposes:

1) Intensity
2) Phase
3) Wavelength (Spectral Content)
4) Spatial Position
5) Frequency
6) Polarization

Optical components (detectors, sources, mirrors, lenses, gratings, waveguides, etc.) can be fabricated on or in a MEMS chip.

MOEMS: Micro-Opto-Electro-Mechanical Systems, which combine MEMS and micro-optics.

MOEMS example:



Curtesy: https://www.researchgate.net/figure/Scanning-electron-micrograph-SEM-of-the-2-2-2-fiber-optic-switch_fig9_3239903

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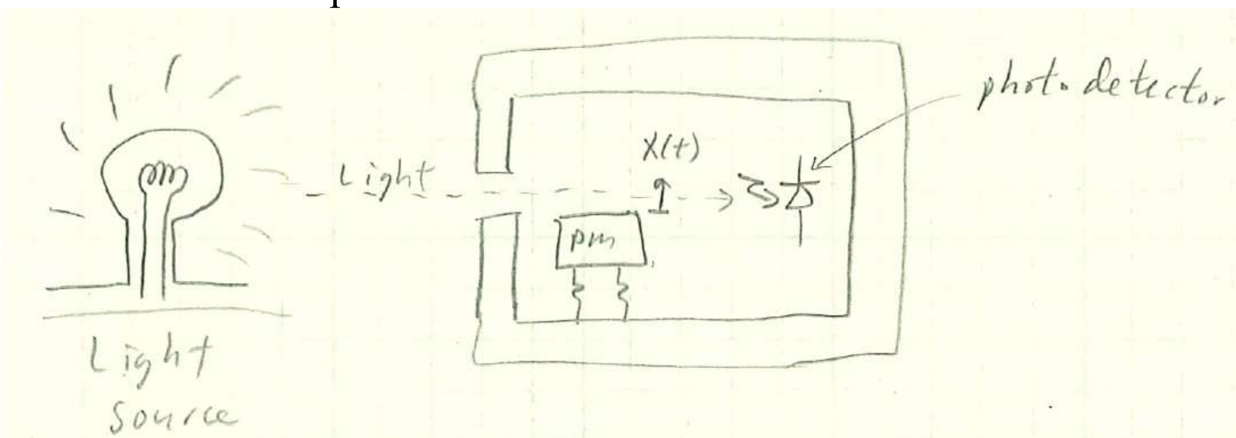
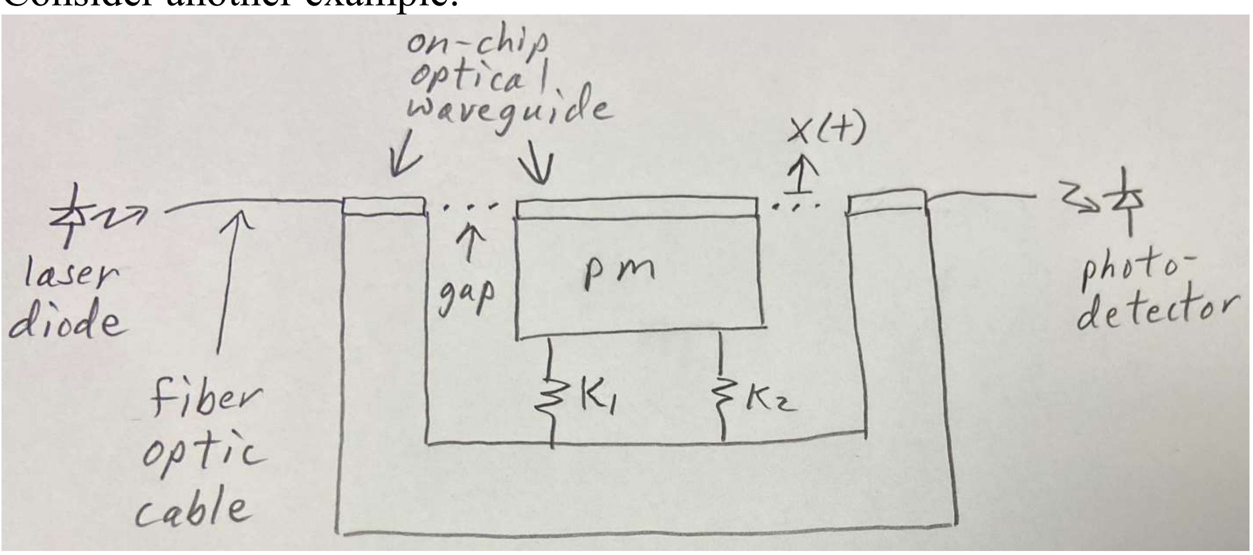
3. <u>Intensity</u> → optical power level

Consider this example:



Some measurand will move the proof mass (PM) by x(t) and partially or fully block the opening that light enters the box through. This modulates the light level (i.e. light intensity) of the light reaching the photodetector.

Consider another example:



At PM rest (i.e. x(t) = 0), the on-chip waveguides (could be fiber optic cable pieces) are aligned and maximum optical power reaches the photodetector. When the PM moves a small amount, the on-chip waveguides misalign and optical power to the photodetector drops.

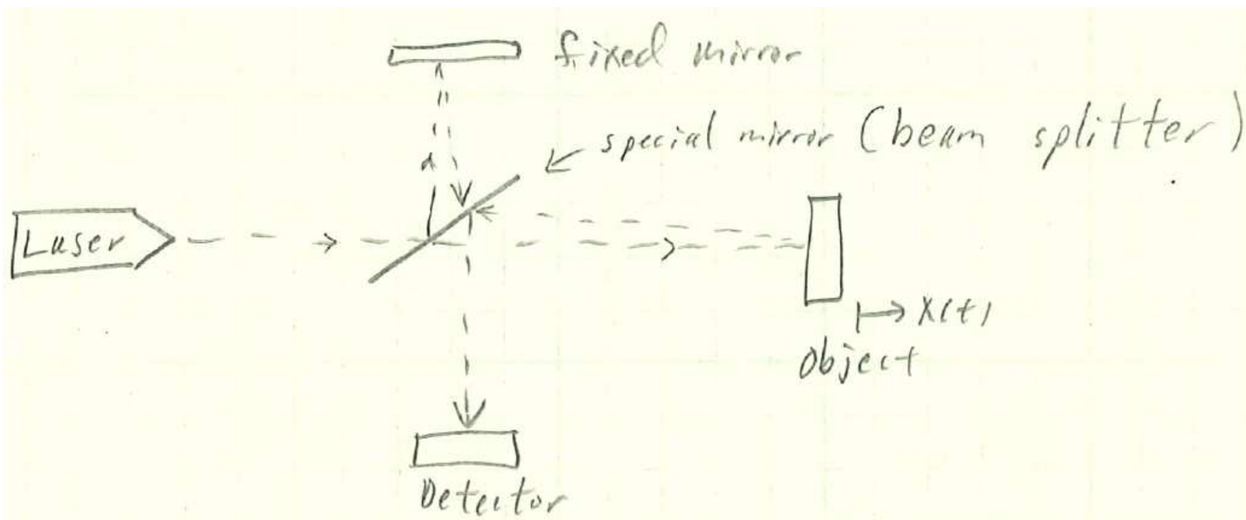
Note, there are two performance issues with this approach:

1) The diameter (or width) of the optical waveguide determines the possible range of x(t) measurement.

2) This technique actually measures |x(t)|.

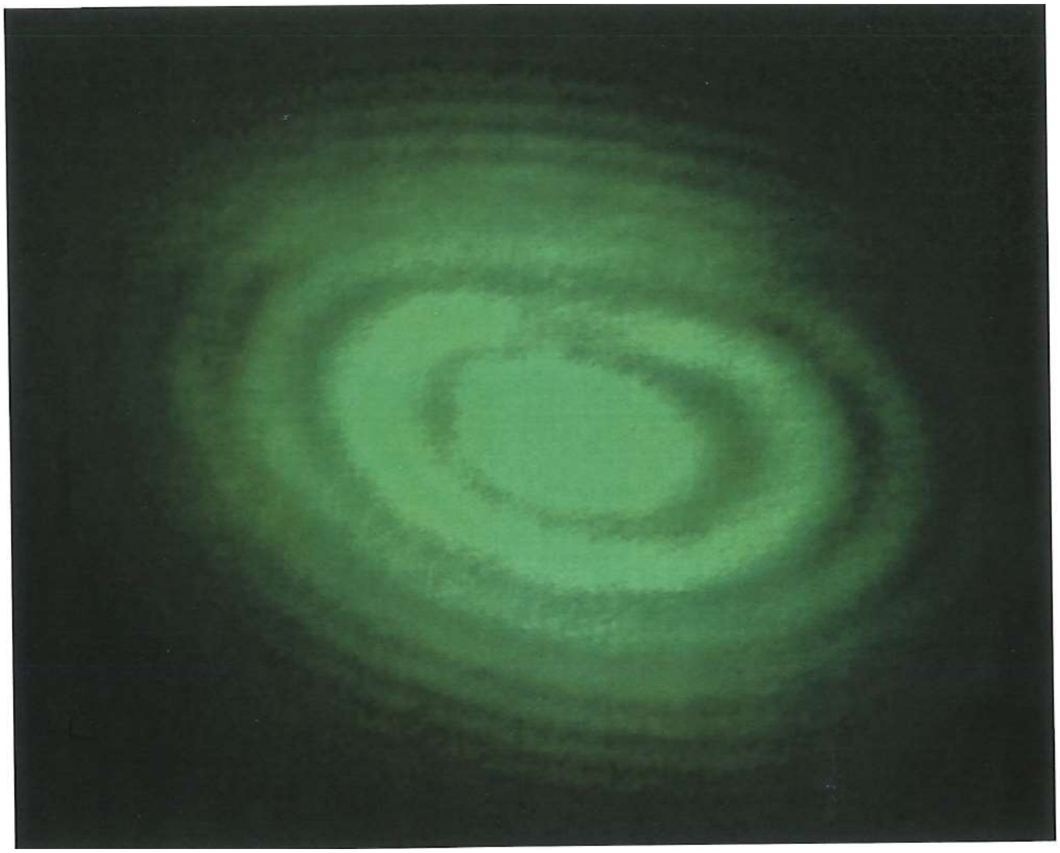
4. <u>Phase</u>

With a coherent light source (i.e. a laser), all the photons possess a definite phase relationship to each other. Therefore, consider an <u>interferometer</u>:



The light from the fixed mirror and the object (x(t) motion) add constructively (optical power maxima) and destructively (optical power minima), producing an "interference pattern" of the optical wavelength.

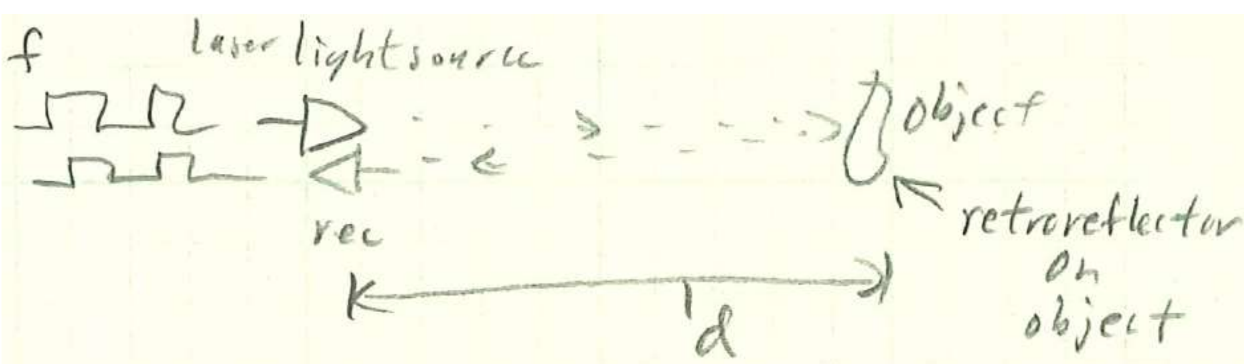
Example interference pattern:



Since x(t) changes the interference pattern, an interferometer can be used to measure very small displacements (fractions of a wavelength):

Green laser: $\lambda = 532$ nm
HeNe (red) laser: $\lambda = 632.8$ nm

Interferometers are useful for measuring the transmissibility, as we already discussed. They are also useful for range finding:



Let τ_d be the time delay for the pulses to reach the target and return, where:

$\tau_d = \frac{2d}{c}$. The speed of light is c: $3x10^8$ m/s.

Example: if d = 100 m and f = 1 MHz, then:

$$\tau_d = \frac{2(100)}{3\times10^8} = 6.67 \times 10^{-7} s.$$

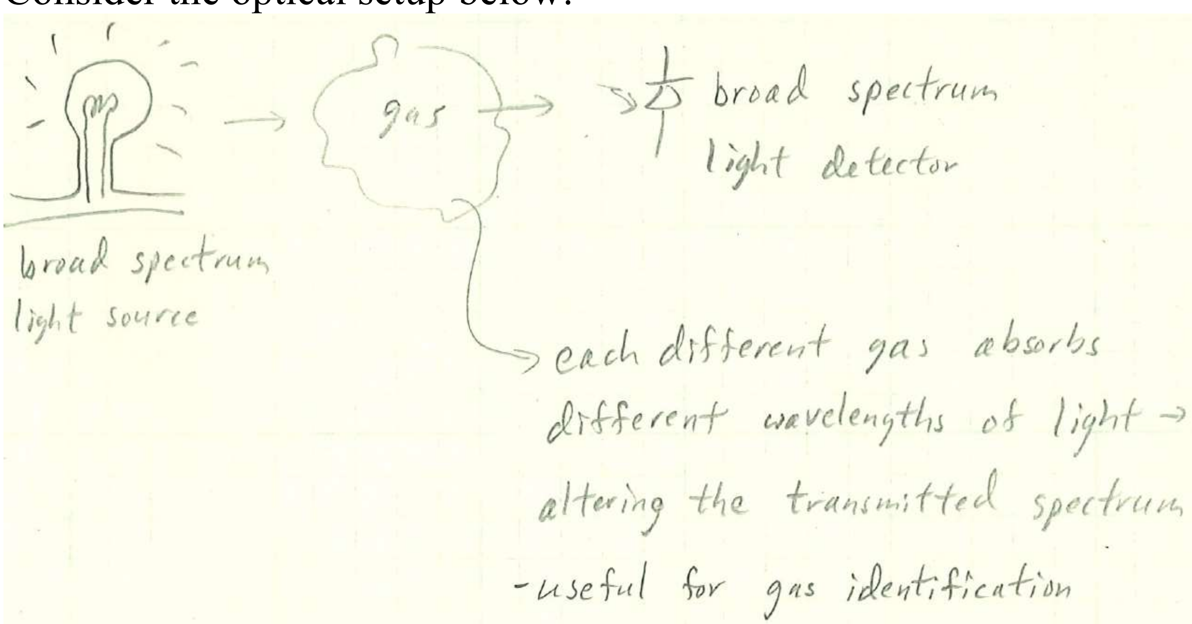
The resulting pulse train phase delay is PD, where:

$$PD = 360^o \left(\frac{\tau_d}{T}\right) = 360^o \left(\frac{6.67\times10^{-7}}{1\times10^{-6}}\right) = 240^o.$$

Note: a 240^o phase shift of a 1 MHz pulse train is very detectable! Note, if PD > 360^o, a range ambiguity exists.

5. Wavelength (Spectral Content)

Consider the optical setup below:



This instrument is called a <u>spectrometer</u>. Example spectrometer results:

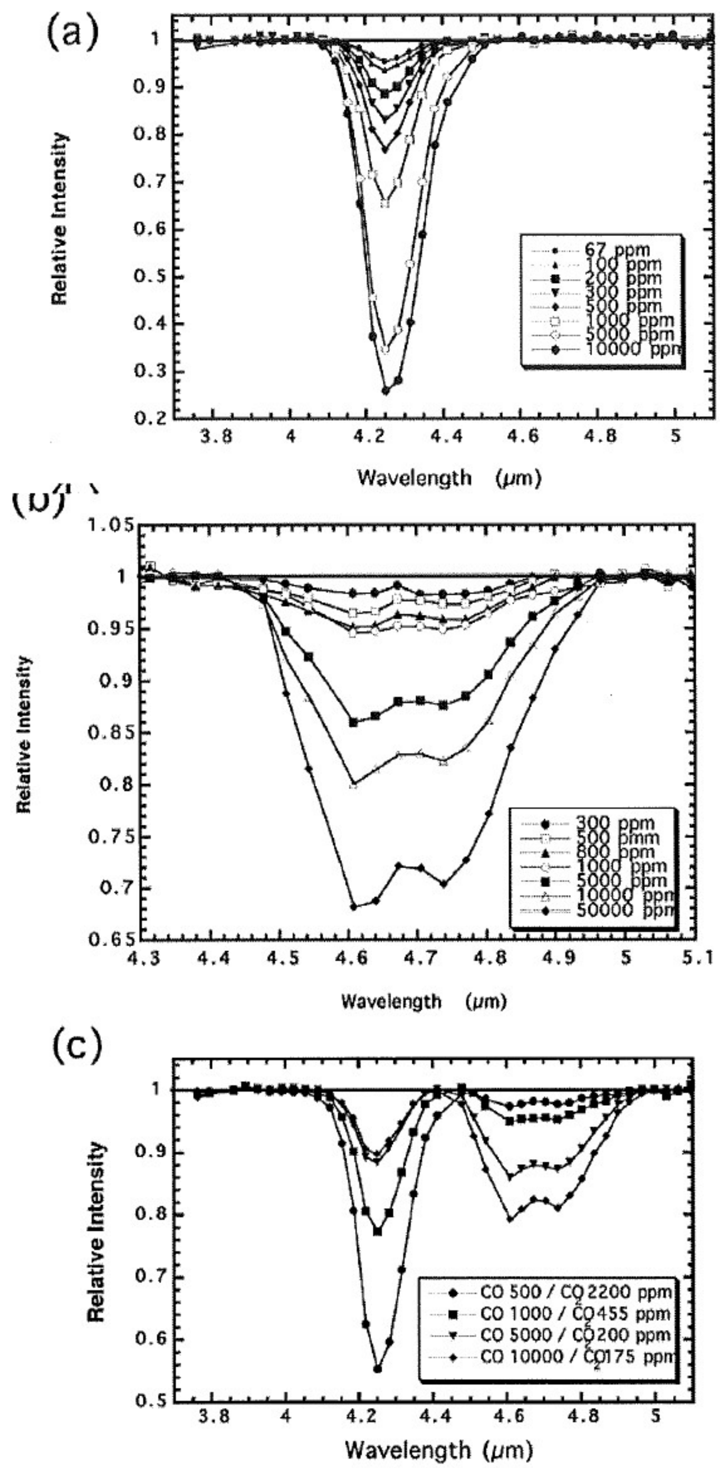


Fig. 5. Absorption spectra for CO_2 (a), CO (b) and a mixture of CO_2 and CO (c) for various gas concentrations.

Thin film pyroelectric array as a detector for an infrared gas spectrometer

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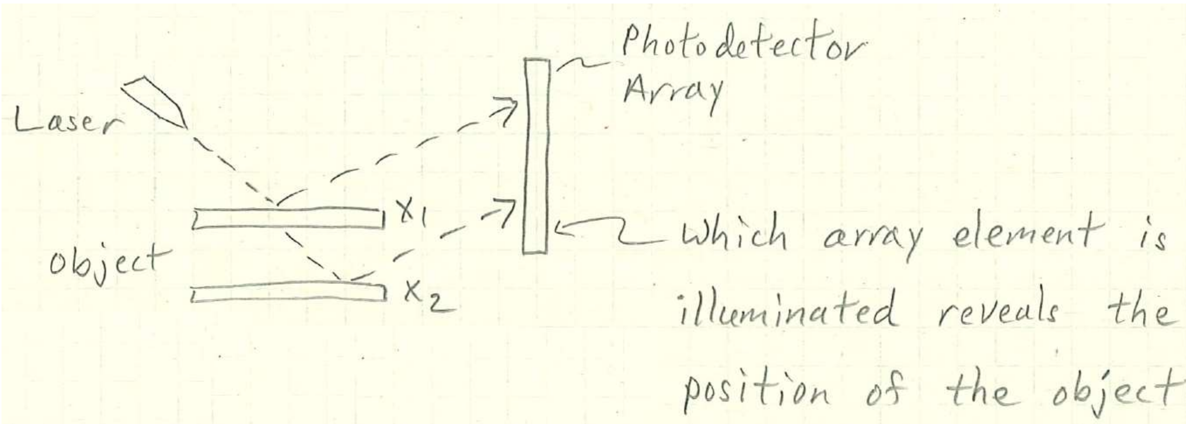
6. Spatial Position

Consider:



This system can be used to measure translational or angular movement. The photodetector array could also be a 2-D array, such as a CMOS or CCD camera chip, which could be used to measure 2-D motion.

7. Frequency

Change-of-frequency based detection makes use of the Doppler shift. The general equation for the Doppler shift is:

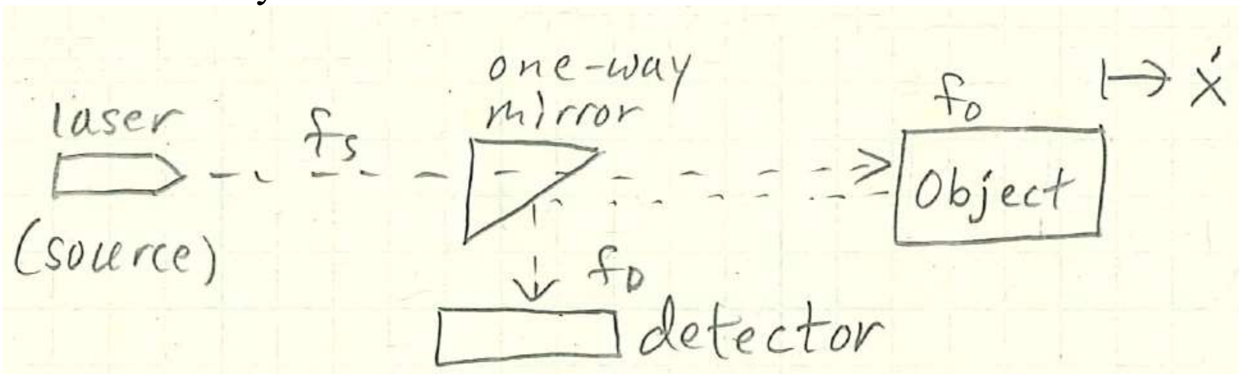
$$f = \left(\frac{c \pm \dot{x}_r}{c \mp \dot{x}_s}\right) f_s$$

Where f_s is the emitted frequency and f is the observed frequency. Also, c is the wave speed (could be the speed of light, but also could be the speed of sound).

Also, $\dot{x}_r$ is the receiver velocity: $+\dot{x}_r$ if the receiver is moving toward the source, and $-\dot{x}_r$ otherwise.

Similarly, $\dot{x}_s$ is the source velocity: $+\dot{x}_s$ if the source is moving away from the receiver, and $-\dot{x}_s$ otherwise.

Consider this system:



So what is f_D?

$$f_O = f_s\left(\frac{c-\dot{x}}{c}\right) = f_s\left(1-\frac{\dot{x}}{c}\right)$$

$$f_D = f_O\left(\frac{c}{c+\dot{x}}\right) = f_O\left(\frac{1}{1+\dot{x}/c}\right) = f_s\left(\frac{c-\dot{x}}{c+\dot{x}}\right)$$

With light: c = 3x10^8 m/s → $\Delta f = |f_s - f_d|$ is very small.

However, with sound: c = 331 m/s (20°C, dry air, 1 atm)*

*some texts list other values for the speed of sound…

With sound as the wave, Δf is much larger and therefore easier to work with for "slow" moving objects.

8. Polarization

Light is an EM wave, and surface properties of an object reflecting light can alter the EM vector representation. Some optical systems make use of this for applications such as machine vision.