SIGNAL RECOVERY:

Sensors, Signals, Noise

and

Information Recovery

http://home.deib.polimi.it/cova/

Signal Recovery

COURSE OUTLINE

- Scenery preview: typical examples and problems of Sensors and Signal Recovery
- Signals and Noise
- Filtering
- Sensors and associated electronics

Scenery preview

- Elementary view of sensor signal and noise for understanding challenges and problems for the recovery of information
- Preliminary overview of typical Resistive Sensors: Thermoresistances and Strain Gauges
- Preliminary overview of typical High-Impedance Sensors: Photodetectors for stationary and non-stationary optical signals

Recovery of information from sensors

- Sensors transduce physical variables (temperature, strain, light etc.) in electrical **signals**
- Electronic circuits process the electrical signals for recovering the information carried
- However, sensors and circuits carry also

NOISE

that is, additional random fluctuations of voltage and current

- If the signal is **NOT much higher** than noise, by collecting the sensor output as it is a degraded information is obtained, affected by significant errors
- By developing electronic processing tailored to the actual signal and noise such a degradation may be strongly reduced, if not eliminated

Preliminary overview of typical Resistive Sensors: Thermoresistances and Strain Gauges

Sensor case with small signal
Thermoresistance or RTD - Resistive Temperature Detector

Principle: resistance variation $(R_0 \Rightarrow R_0 + \Delta R)$
$\propto$ to temperature variation $(T_0 \Rightarrow T_0 + \Delta T)$

$$\boxed{\Delta R = \alpha\, \Delta T R_o}$$

$$\Delta T = T - T_o$$
$$R_o = R(T_o)$$

By supplying a **constant** current I_o , a voltage signal is obtained

$$\Delta V = \alpha \Delta T \cdot V_o$$

$$V_o = I_o R_o$$
$$\Delta V = V - V_o$$

Drawback: the temperature coefficient is **very small** $\boldsymbol{\alpha} \approx \mathbf{10^{-3}}$/°C
hence the signal generated by the sensor is small

Sensor case with small signal
Thermoresistance or RTD - Resistive Temperature Detector

The signal is further reduced by the requirement of employing a low voltage supply V_o for avoiding to heat the sensor

$P = V_o^{\,2}/R_o$ typically $R_o \approx 100\ \Omega$

For keeping P < 1μW it is necessary V_o < 10mV , which gives

$$\frac{\Delta V}{\Delta T} = \alpha V_o < 10\mu V/°C$$

A variation $\Delta T = 0{,}01°C$ thus gives a signal $\Delta V < 100nV$.
In real cases (e.g. in the control of biochemical reactions) the acceptable errors in the measured temperature are about 0,01 °C or even smaller, hence dedicated low-noise amplifier must be employed (ordinary wideband amplifiers have rms noise referred to input typically ≈10μV)

Sensor case with small signal
Resistive Sensor of Strain or SG - Strain Gauge

Strain $\varepsilon = \frac{\Delta L}{L_o}$ [measured in unit $\varepsilon = 10^{-6} = 1\ \mu strain$]

Principle : resistance variation ∝ to strain

ΔR = G εR_o with fairly small gauge factor G≈ 2

By supplying a **constant** current I_o , a voltage signal is obtained

ΔV =G$\varepsilon \cdot V_o$

$$V_o = I_o R_o$$
$$\Delta V = V - V_o$$

Drawback:

the strain to be measured is very small $\varepsilon \approx 1$ to $1000\ \mu strain$

(the elastic range of steel is $< 1\%$ i.e $\varepsilon < 10000\ \mu strain$)

Sensor case with small signal
Resistive Sensor of Strain or SG – Strain Gauge

Further drawback:
V_o must be small for avoiding to heat the sensor

$$P = {V_o}^2/R_o \qquad \text{typically } R_o \approx 100\Omega$$

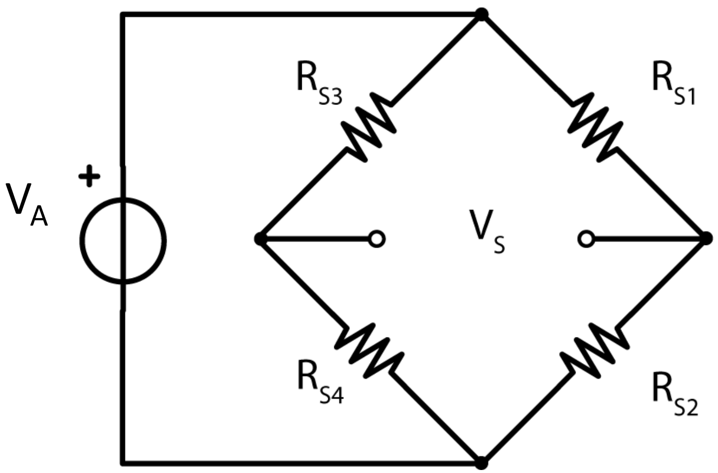
For keeping P< 1µW it is necessary V_o < 10mV, hence

$$\frac{\Delta V}{\varepsilon} = GV_o < 20nV/\mu strain$$

For instance: with $\varepsilon = 10\ \mu strain$ voltage signal $\Delta V < 200nV$

ordinary amplifiers have much higher rms noise referred to input (typically ≈10µV for 1 MHz amplifier bandwidth)

Resistive Sensors with small signal



*invented by Samuel Hunter Christie and popularized by Charles Wheatstone

Wheatstone* Bridge

- sensor arm: R_{s1} & R_{s2}
- reference arm: R_{s3} & R_{s4}
- differential output signal V_s (differential preamplifier is employed)

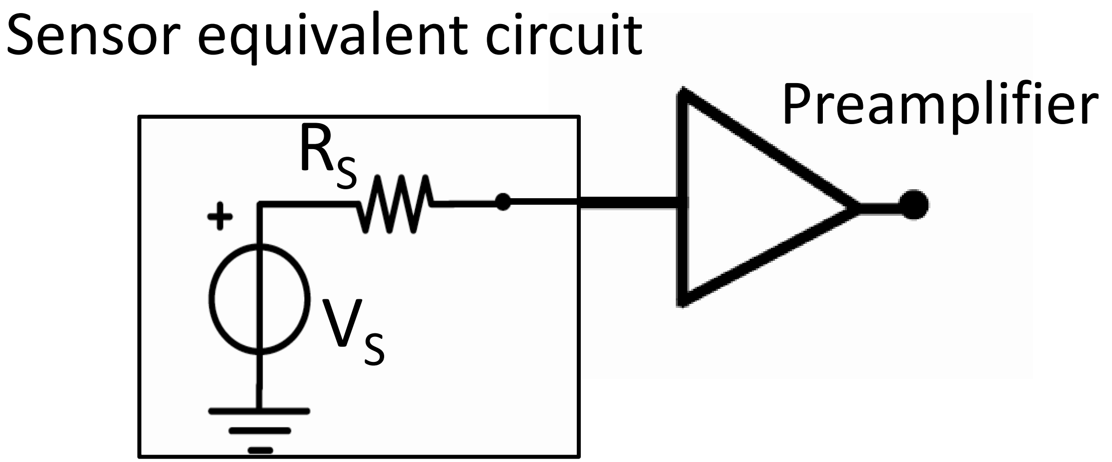
Basic configuration:

- 1 sensor R_{s2}
- 3 balancing resistors R_{s1} , R_{s3} , R_{s4}
  $R_{s1} = R_{s3}$ and $R_{s4} = R_{s2o}$
  (R_{s2o} sensor reference value)

- ❑ other configurations of sensors and balancing resistors are also employed
- ❑ V_A voltage supply, can be DC or AC

Resistive Sensor with small signal

- A Resistive Sensor is seen by the following circuit as a voltage source of signal with a low resistance in series



- In various cases the voltage signal is very small
- A suitably designed **preamplifier** (high input impedance, low-noise, wide- or narrow-band, etc.) has to be coupled to the sensor for picking up the small signal

Resistive Sensor Signal types to be processed

Various types of sensor signals have to be processed, depending

a) on the behavior of the physical quantity (temperature, etc.)

b) on the DC or AC bias supply of the sensor

- For constant physical quantity to be measured we get

  with DC bias → DC signal: V_m

  with AC bias → AC signal: $V_m \cos\omega t$

- For slowly varying physical quantity we get

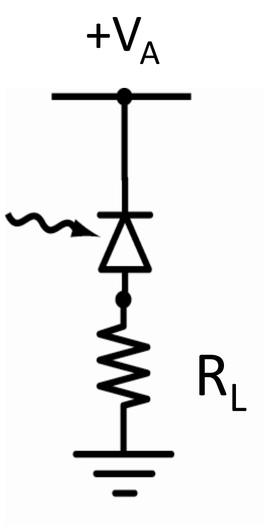
  with DC bias → slowly varying signal: $V_m(t)$

  with AC bias → modulated AC signal: $V_m(t)\cos(\omega t)$

The signal must picked up by a specifically designed preamplifier (low-noise, high input impedance, wide- or narrow-band, etc.)

Preliminary overview of typical High-Impedance Sensors: Photodetectors

Sensor case with small signal: Photodiode (PD)

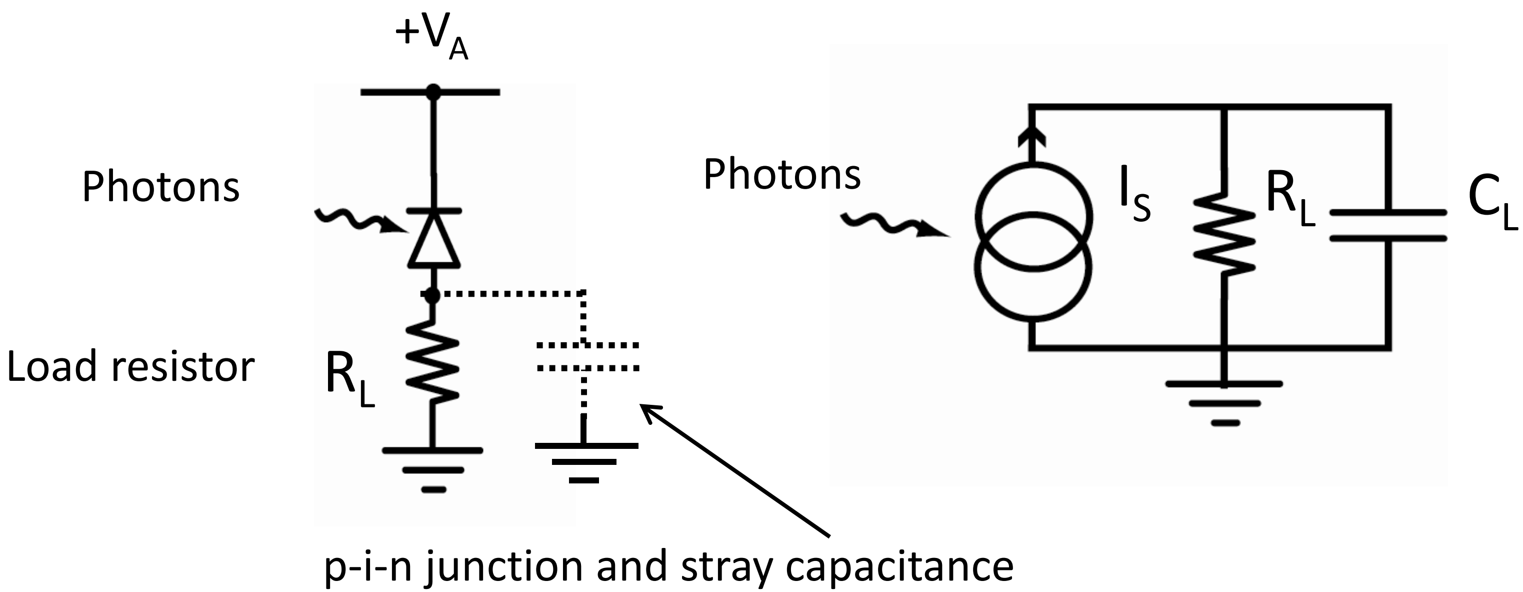


Principle:

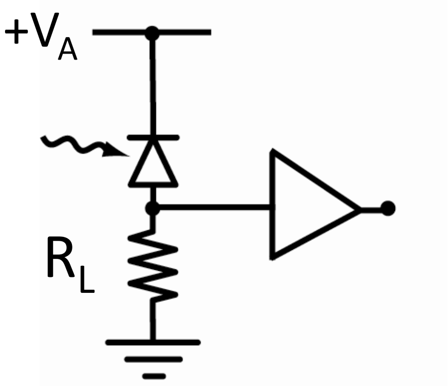
- Light directed onto a reverse-biased p-i-n junction
- 1 absorbed photon → 1 free charge carrier (hole-electron pair)
- Free carriers driven by electric field travel in the junction
- Signal current flows at PD terminals

Sensor case with small signal: Photodiode (PD)

- A photodiode is seen by the following circuit as
  a current-source with a very high-resistance in parallel
- The current signal from the source is VERY SMALL



Sensor case with small signal: Photodiode (PD)



Let's consider first a versatile **wide-band** circuit configuration

- **Low resistance** load, e.g. R_L = 1kΩ
- Low capacitance load, e.g. C_L = 1pF
- Preamplifier with wide-band (e.g. 100MHz) and low-noise

➢ In this case the resistor R_L is the dominant noise source and causes

$\sqrt{\overline{i_n^{\,2}}} \cong 40nA$ current noise referred to the preamp input

➢ The signal current I_s has to be compared with such noise

➢ The optical signal is small; moreover not all incident photons are absorbed and contribute to I_s (Photon Detection Efficiency PDE < 1)

➢ A suitably designed preamplifier has to be coupled to the sensor for picking up the small signal

➢ **Various types of optical signals** are met in the applications: stationary or modulated, single pulse, repetitive pulses

Sensor case with small signal: Photodiode (PD) with **Stationary** light signal

cases with **stationary** optical power $\mathbf{P_L}$ **= constant**
Continuous Wave (CW) light sources: LEDs, Lasers, etc.

- Measurements are required down to very low P_L << 100nW *(for comparison: a red laser pointer has $P_L \approx$ 1mW)*
- P_L = 100nW of red light (λ = 612nm) corresponds to: $n_p \approx 3 \cdot 10^{11}$ photons/s = 300 photons/ns
- The signal current I_s thus generated is small, comparable to noise also in case of PDE= 100% :
  $I_s \approx$ 50nA

Sensor case with small signal: Photodiode (PD)

light signal with **modulated** optical power

modulated power → $P_L = P_{Lm} \cos \omega_m t + P_{Lo}$ ← *mean power*

- The information is entrusted to a modulated light signal for distinguishing the signal from background light and other unwanted sources and for better extracting the signal from noise
  (note that $P_{Lm} < P_{Lo}$: the modulated power P_{Lm} is lower than the mean power P_{Lo} , the total optical power P_L can't be negative)

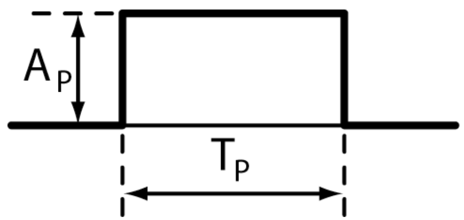
- The signal generated by the sensor thus includes a modulated current

$$I_S = I_{Sm} \cos \omega_m t + I_{So}$$

- very small modulated current I_{Sm} can be measured, even much lower than the total current noise referred to the preamp input

- measurement of P_{Lm} can thus be carried out down to power level quite lower than in cases with steady power P_L (CW cases)

Sensor case with small signal: Photodiode (PD)
Single-pulse light signal



The INFORMATION is carried by the AMPLITUDE A_P of a light pulse.
Such a case is met in various applications, e.g. in biomedical and genetic analysis.

Example: Flow Cytometry

- single cells travel in fluid flow system and cross a laser beam;
- the laser excites fluorescence in the cell;
- the fluorescence intensity carries information about the cell. The scattered laser light background is blocked by optical filters, the fluorescence is detected by a PD

NB1: just the MAGNITUDE of the pulse matters, NOT THE WAVEFORM

- Therefore, high-fidelity amplification is NOT required
- filtering that modifies the pulse shape can be employed

NB2: if pulses occur in sequence EACH pulse must be INDIVIDUALLY measured

Sensor case with small signal: Photodiode (PD)
Repetitive-pulse light signal

The pulse carrying INFORMATION is repeated in sequence and ALL the pulses in the sequence carry THE SAME information.

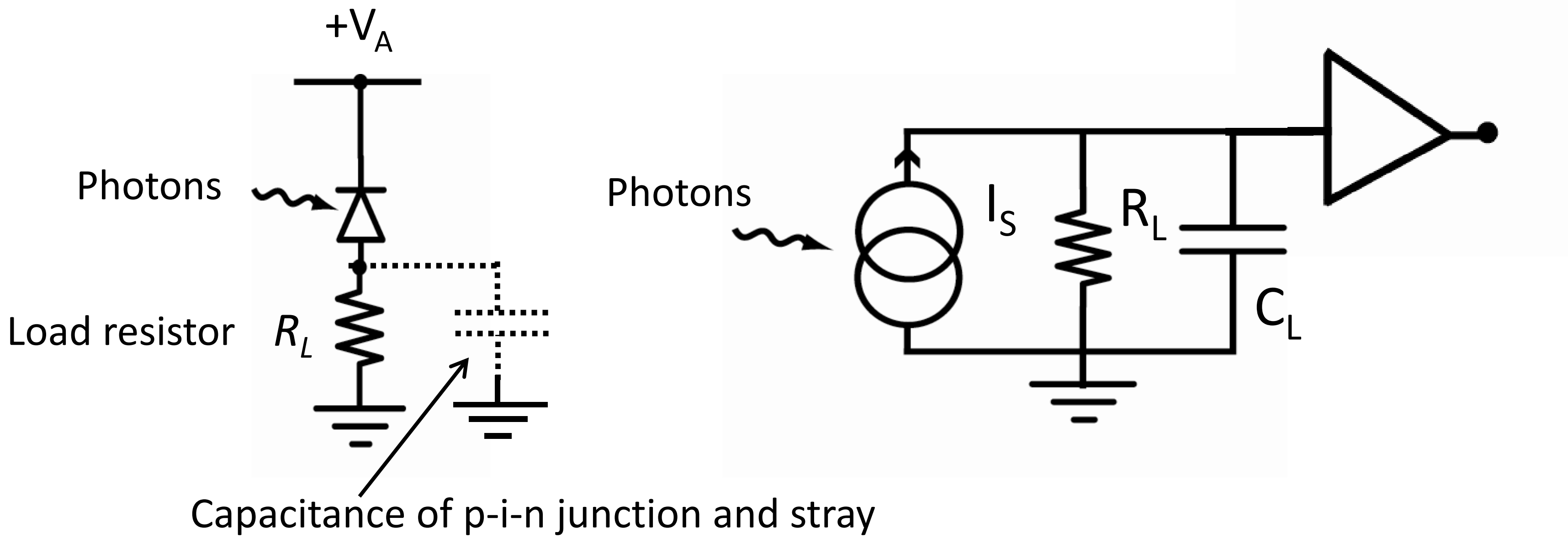
Example: reflectometry

- Laser pulses are directed to a target
- Reflected pulses are detected and their size carries info about the target

The redundant information available can be exploited by means of measurements that SUM (or average) the amplitude of ALL THE PULSES

Sensor case with small signal: Photodiode (PD)

Photodiode: it is almost a current-source (very high-resistance source) of small current signals



A suitable high load R_L and a specifically designed low-noise preamplifier must be employed, depending on the measurement required

Set-Up for Sensor Measurement