



POLITECNICO DI MILANO

Piazza Leonardo da Vinci, 32 - 20133 Milano
Tel. +39.02.2399.1 - <http://www.polimi.it>



Advanced Course on

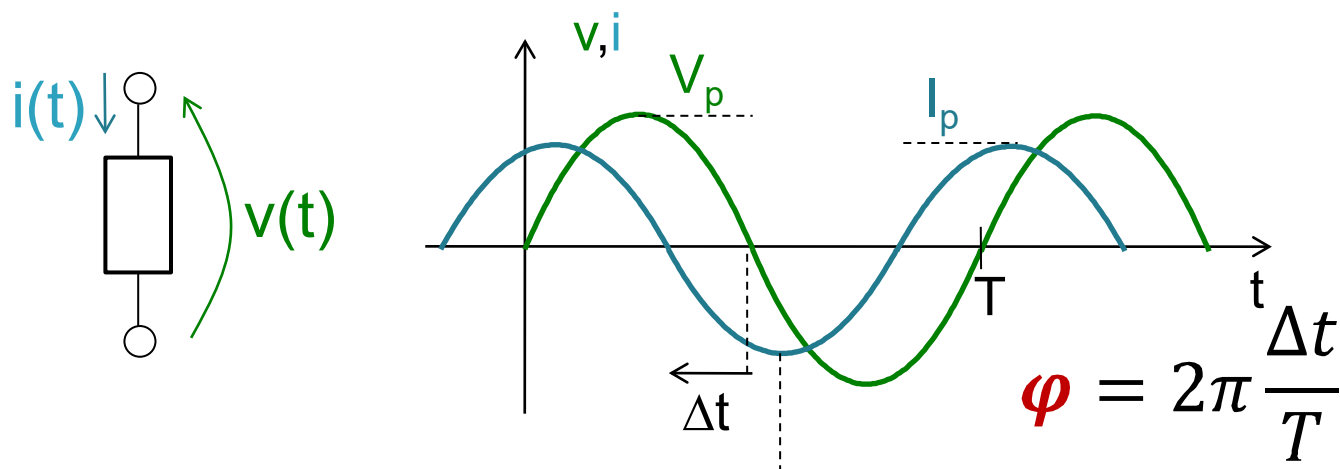
HIGH RESOLUTION ELECTRONIC MEASUREMENTS
IN NANO-BIO SCIENCE

Impedance Measurement *Architectures and performance*

Marco Sampietro



Definition



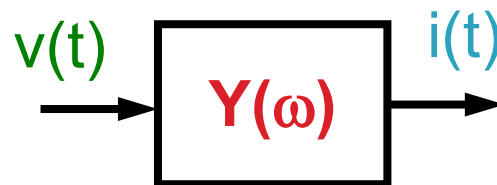
Amplitude
&
Phase
&
Frequency

$\mathbf{Z} = \frac{\mathbf{V}}{\mathbf{I}}$ is a complex quantity

Impedance [Ohm]

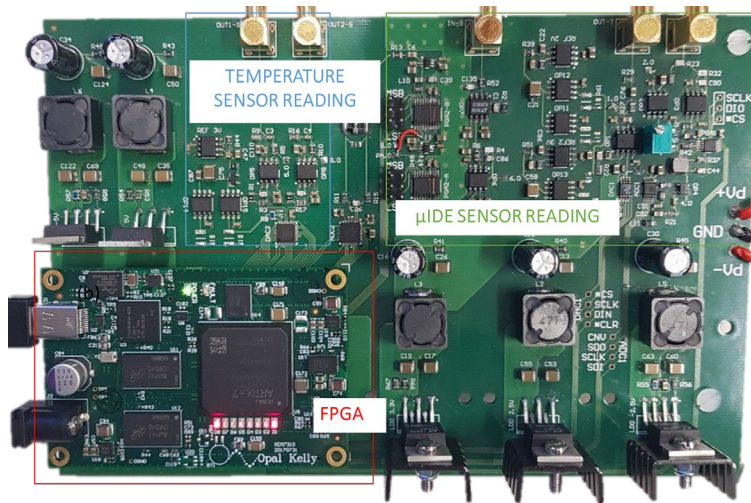


Admittance [Siemens]

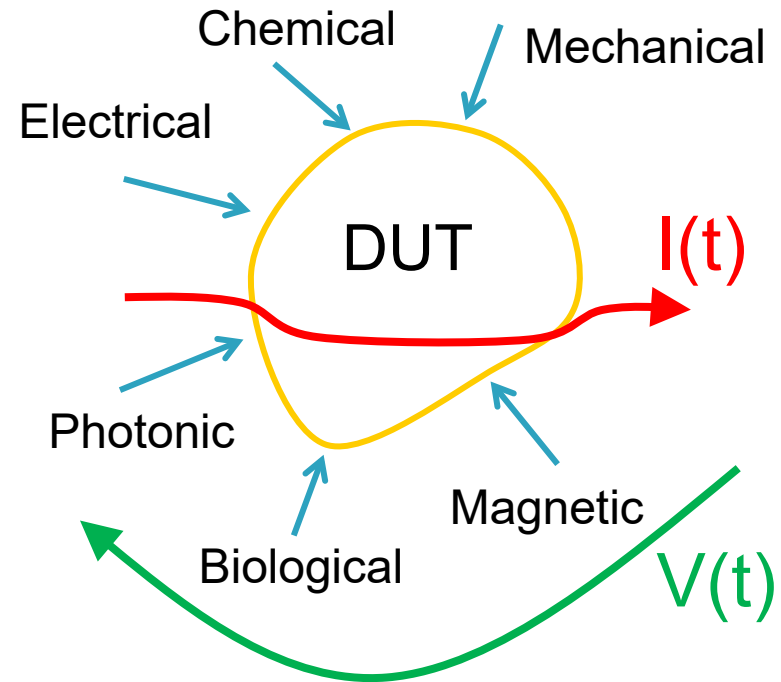




Why using/measuring/designing



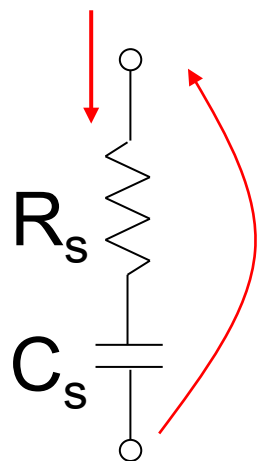
Impedance measurements extract R , L , C values in an electronic circuits ...



... but can also access the conduction properties and the dissipative properties of a new device/material/molecule/etc.

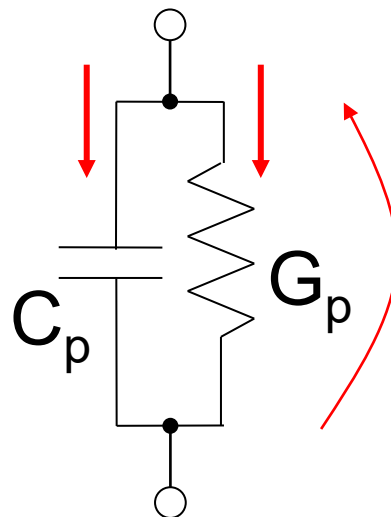


Impedance in terms of single R & C



$$Z(\omega) = R_s + \frac{1}{j\omega C_s}$$

Reactance



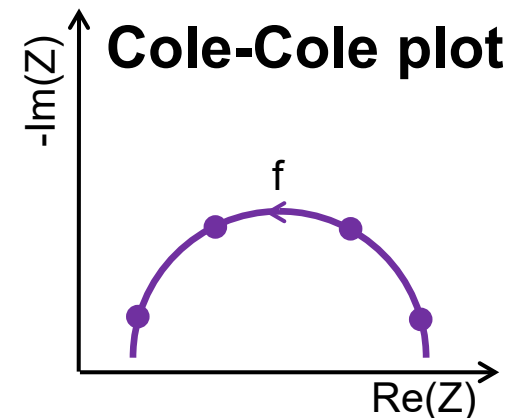
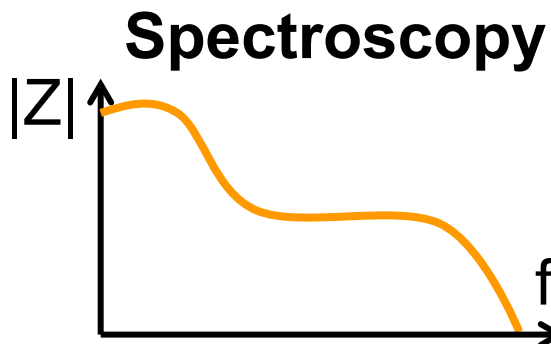
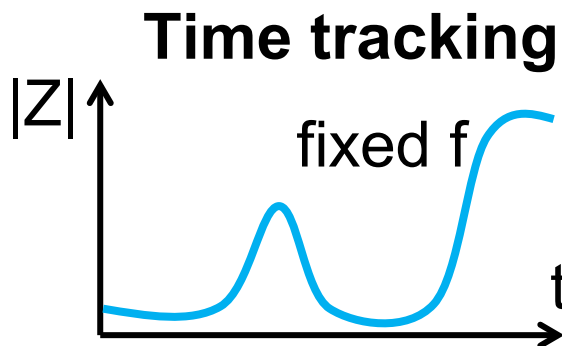
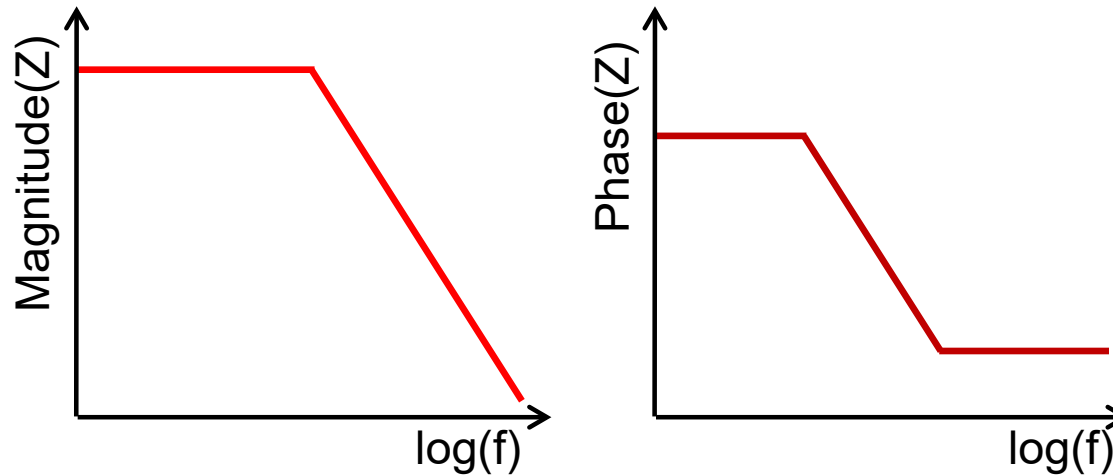
$$Y(\omega) = G_p + j\omega C_p$$

- $\text{Re}\{Z\}, \text{Re}\{Y\} \rightarrow$ energy dissipation ($4kT\text{Re}\{Z\}, 4kT\text{Re}\{Y\}$)
- $\text{Im}\{Z\}, \text{Im}\{Y\} \rightarrow$ energy storage

Plotting the Impedance

Alternative (**equivalent**) ways to plot impedance values

Bode Plots





If the DUT contains a resistive part and a capacitive part, how would be the impedance of the DUT as a function of frequency ?

What you say is true if the resistance and the capacitance are in series. What happens when the resistance and the capacitance are in parallel ?

To summarize, as the frequency increases:

- The magnitude of the reactance decreases.
- The impedance transitions from being mostly imaginary (capacitive) to being primarily real (resistive).
- The impedance magnitude approaches the resistance value.

becomes comparable to or smaller than the resistance ($X \leq R$), the impedance of the DUT starts to decrease.

3. At high frequencies: At very high frequencies, the reactance of the capacitor becomes negligible compared to the resistance. In this case, the impedance is primarily determined by the resistance value, similar to the behavior in the series configuration.

To summarize, in the parallel configuration:

- At low frequencies, the impedance is mainly determined by the resistance.
- As the frequency increases, the capacitive reactance decreases, leading to a decrease in impedance.
- At high frequencies, the impedance is dominated by the resistance.



ChatGPT Q&A (2)

Be careful, you made a mistake.
When you say "*At very high frequencies, the reactance of the capacitor becomes negligible compared to the resistance. In this case, the impedance is primarily determined by the resistance value, similar to the behavior in the series configuration*", you are wrong.
At very high frequency the impedance become zero.
Do you agree ?



You are correct, and I apologize for the incorrect statement in my previous response. I apologize for any confusion caused.

In the parallel configuration of a resistance and a capacitor, at very high frequencies, the impedance does not become primarily determined by the resistance. Instead, it tends towards zero impedance. This occurs because the capacitive reactance decreases as the frequency increases, and at extremely high frequencies, it becomes very small compared to the resistance.

To clarify, at high frequencies:

- The capacitive reactance decreases with increasing frequency.
- As the frequency becomes very high, the capacitive reactance approaches zero.
- The impedance of the parallel combination tends towards zero because the reciprocal of a very large value (small reactance) tends towards zero.

Therefore, at very high frequencies, the impedance of a parallel combination of resistance and capacitance approaches zero rather than being primarily determined by the resistance. I apologize for the incorrect statement in my previous response, and I appreciate your correction.



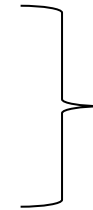
Myself : How can I measure the impedance of a device ?

chatGPT : Using an Impedance Analyzer

Using an LCR Meter

Bridge Circuit

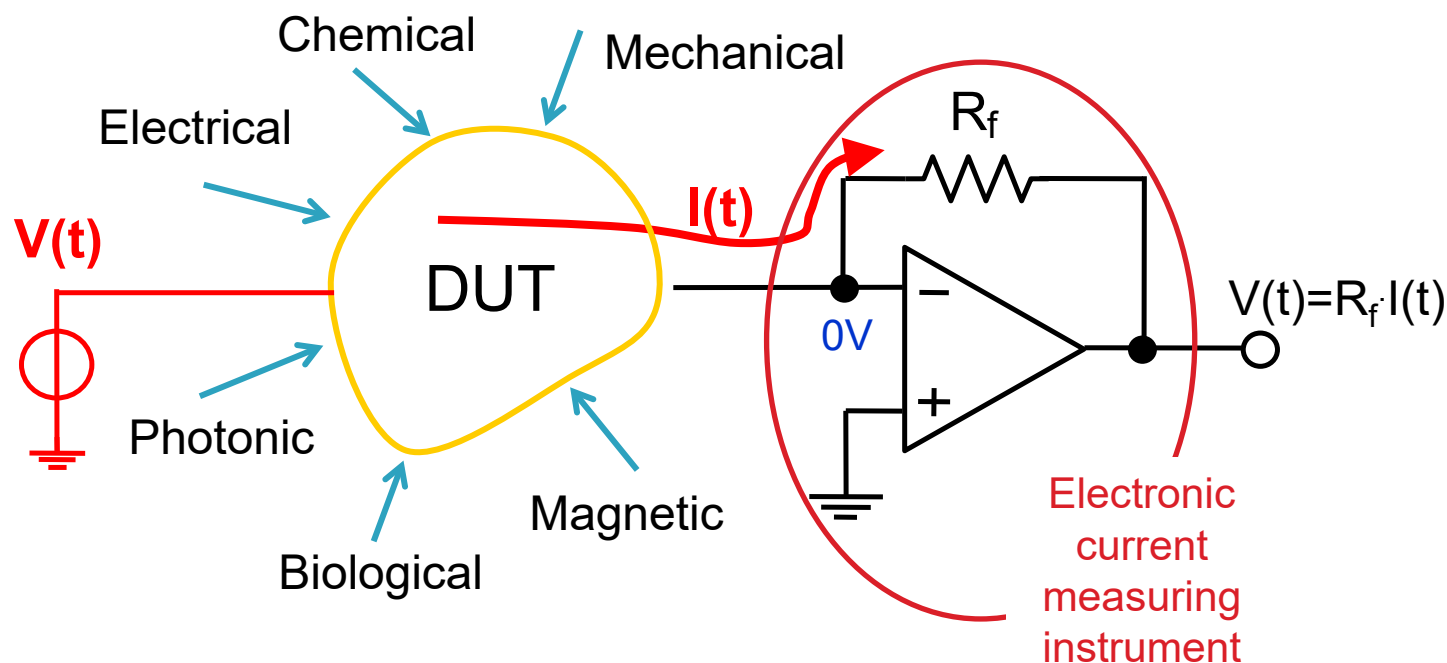
Oscilloscope and Function Generator using the voltage-divider principle



Lock-in
architecture



Lock-in configuration

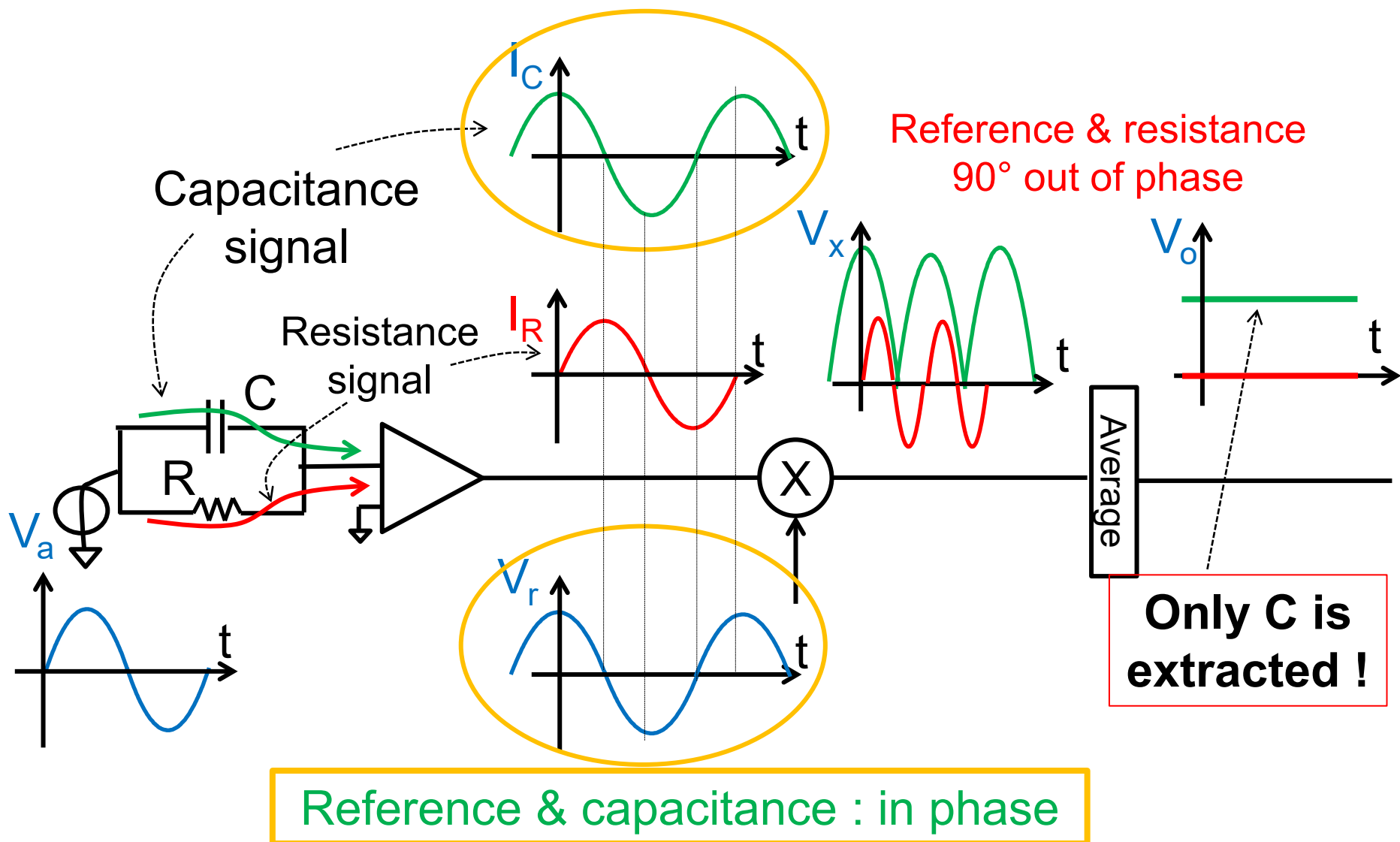


The Lock-in system is indeed ideal to perform IMPEDANCE measurements (and tracking it with time)

By sweeping the frequency, you can easily perform IMPEDANCE SPECTRUM



Mixture of R & C in real sensors

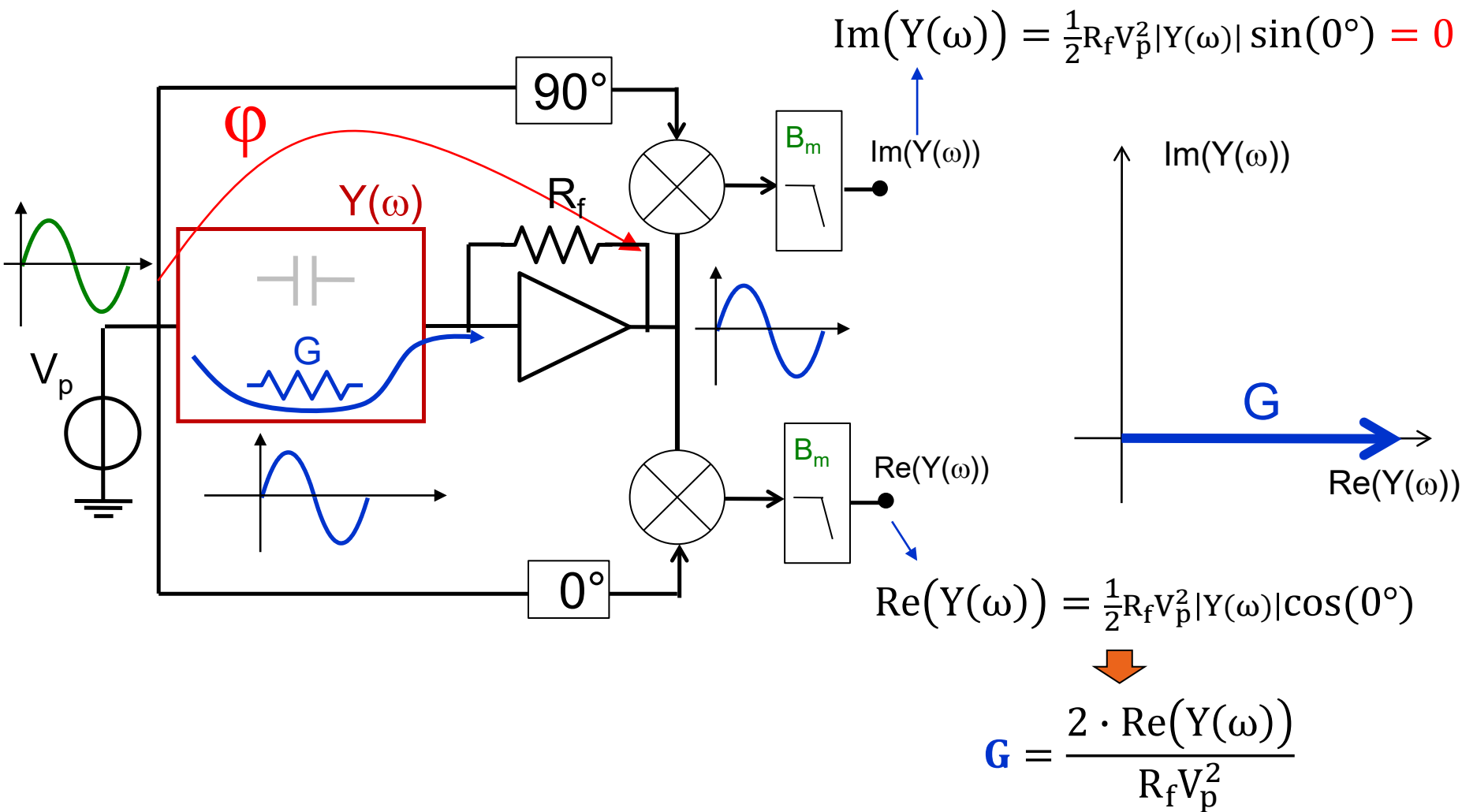






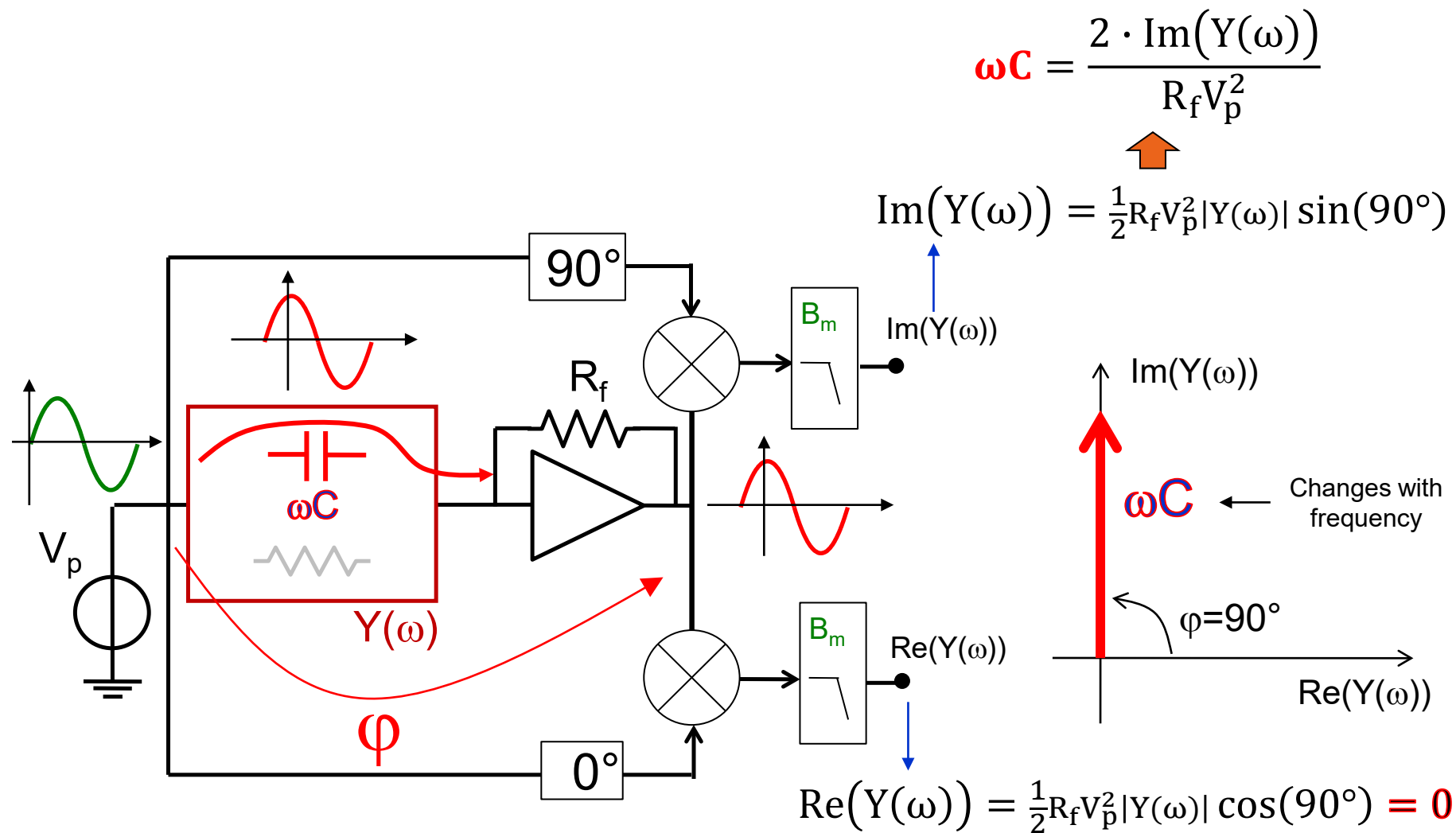
Lock-In: in-phase detection

Two multipliers are used to obtain both Re and Im of a DUT



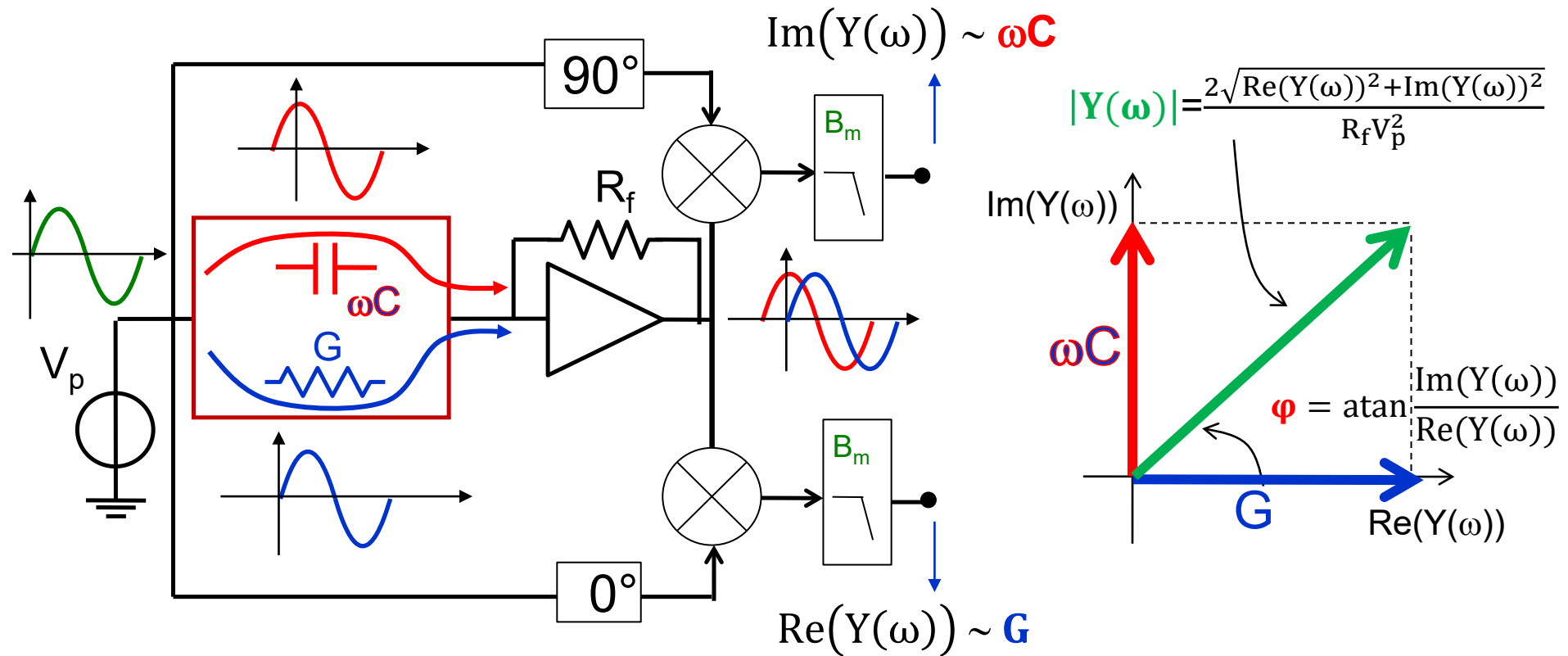


Lock-In: in-quadrature detection



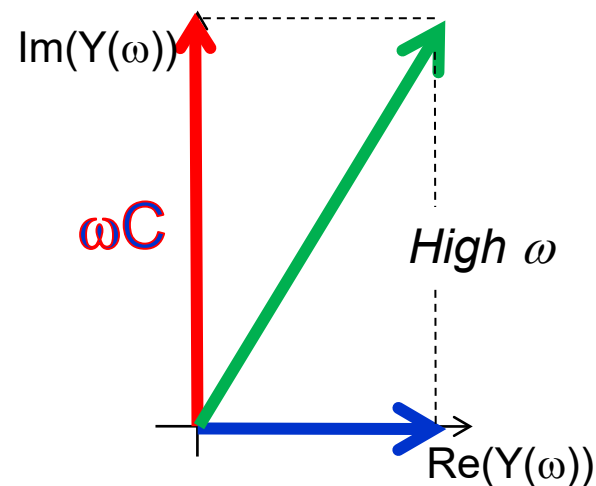
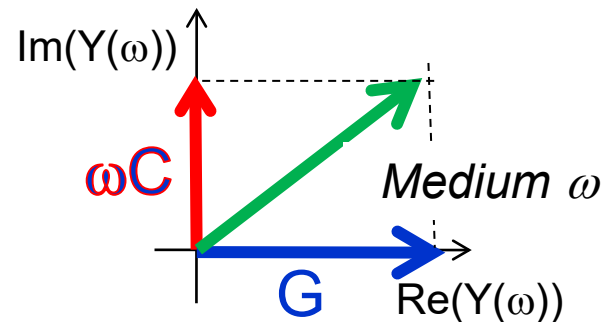
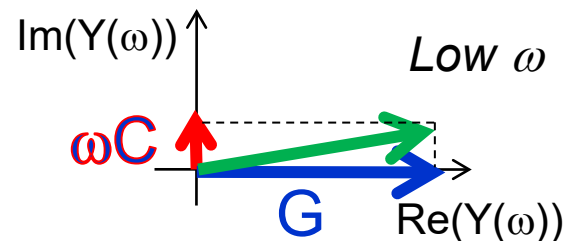
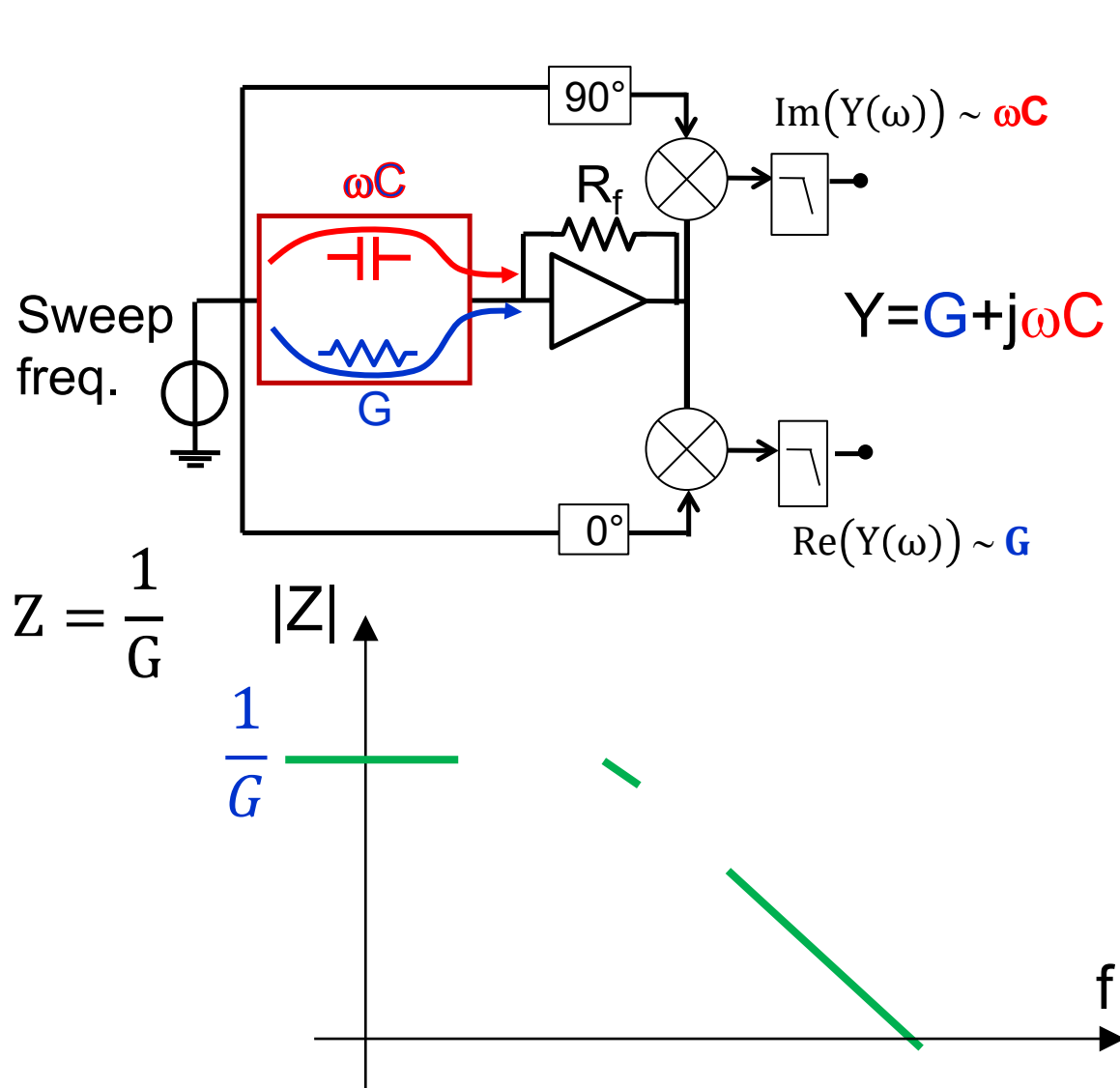


Lock-In: Impedance of R||C





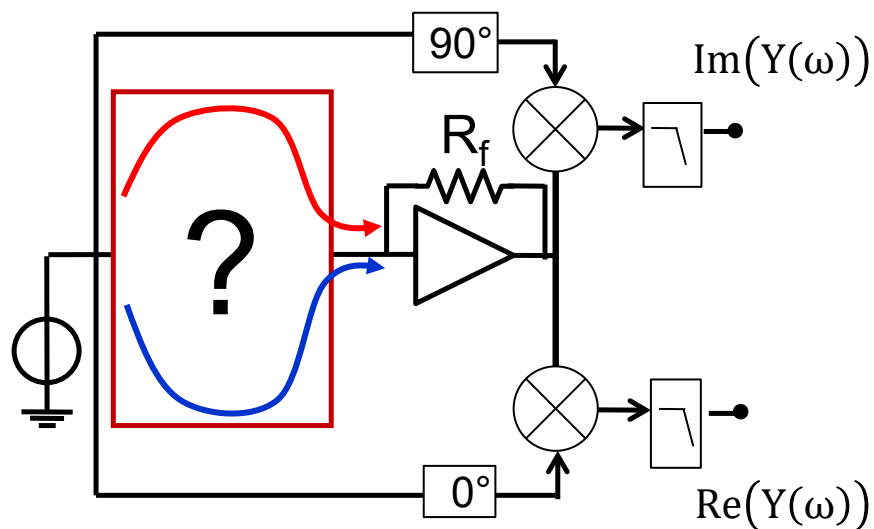
From single frequency to spectrum



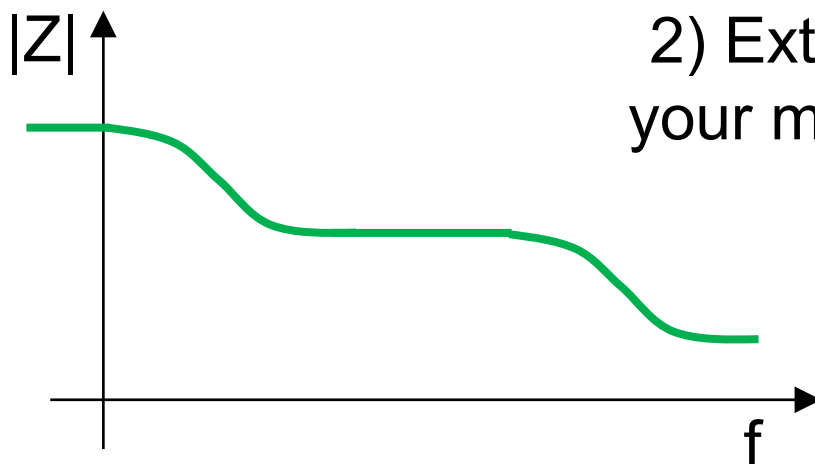


Extracting elements from a spectrum

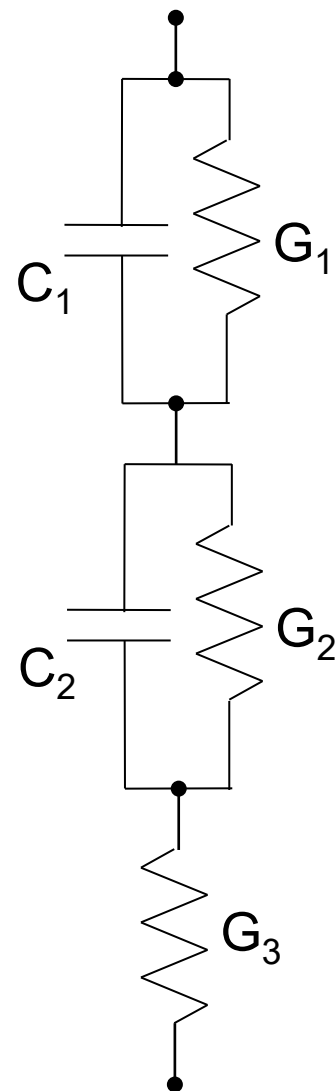
What is inside my device ?



1) Measure at different frequencies

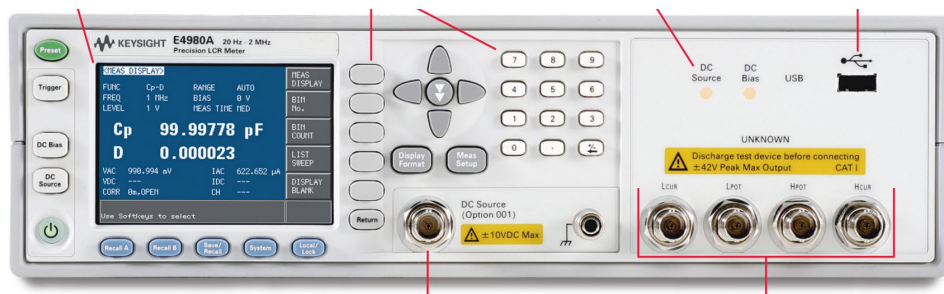


2) Extract your model

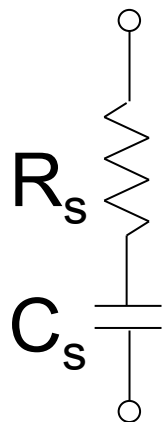




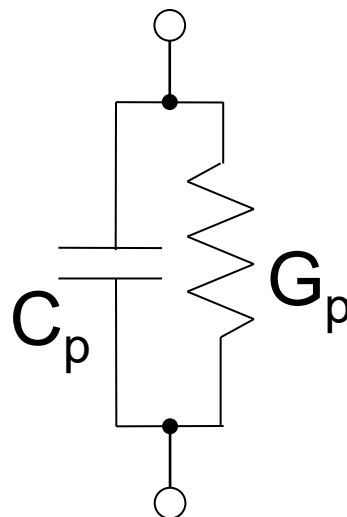
Pre-defined models in LCR meters



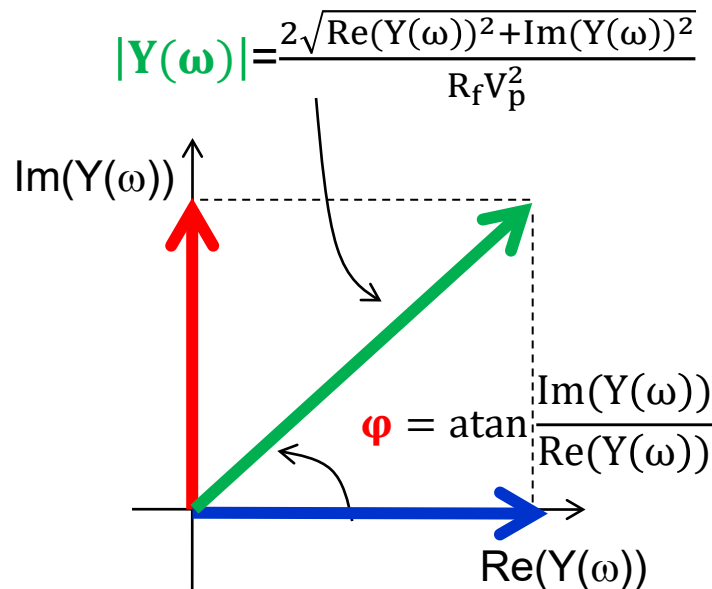
You select the model.
The instrument gives you the R & C values



$$Z(\omega) = R_s + \frac{1}{j\omega C_s}$$



$$Y(\omega) = G_p + j\omega C_p$$





Calibration

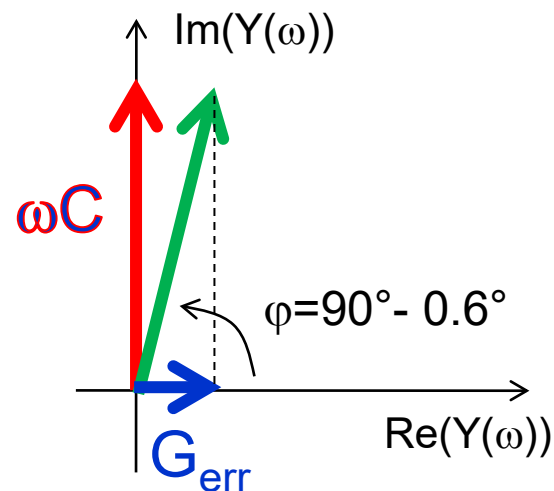
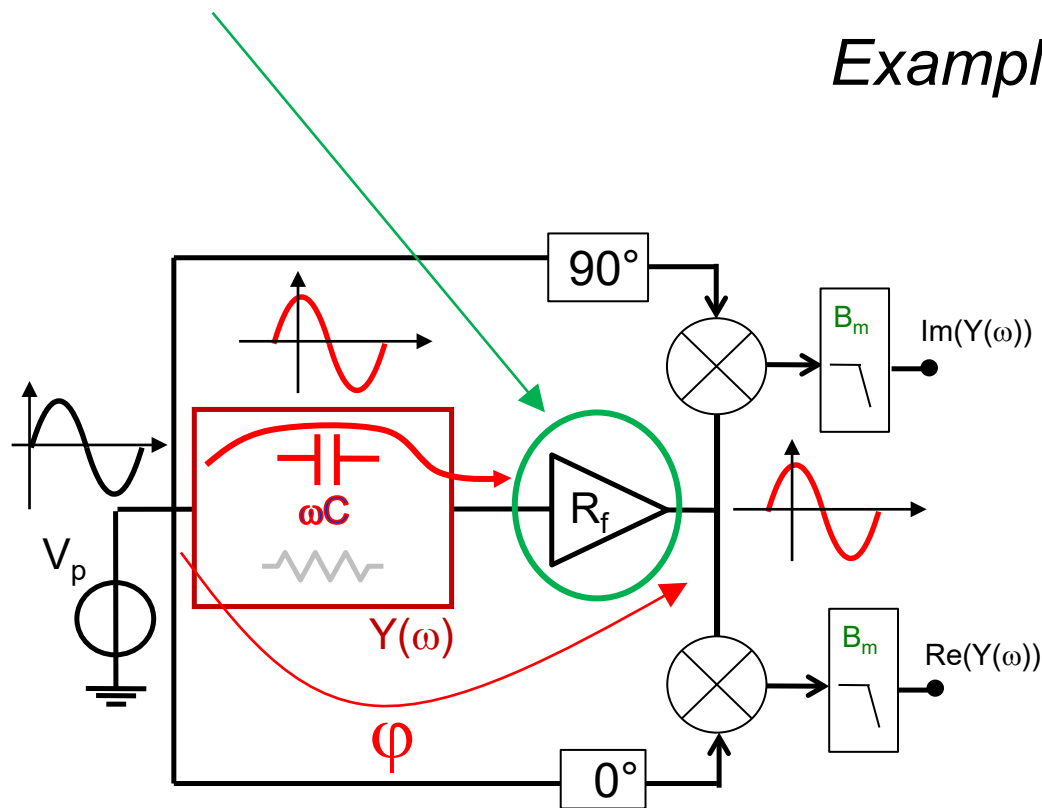
Amplifiers and connections introduce errors in amplitude and phase

Example:

$C=1\text{pF}$ at 1MHz

Phase error 0.6°

(a pole distant two decades)



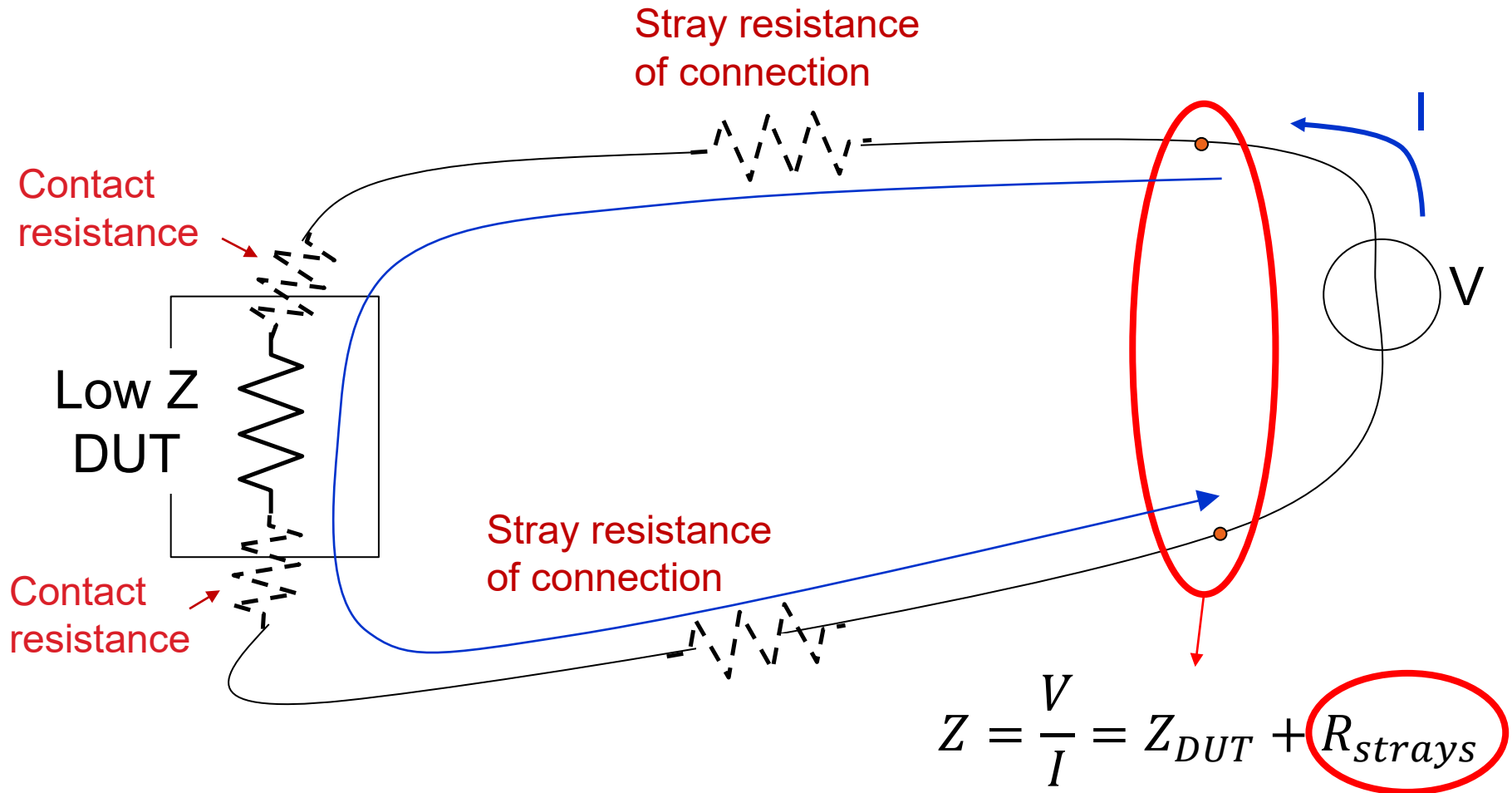
Ideal calibration: with a known sample (amplitude and phase)

$$G_{\text{err}} = \omega C_x \sin(0.6^\circ) = 6 \cdot 10^{-8} \text{ S} \\ (16\text{M}\Omega, \text{ to be compared with } \infty)$$

If $\varphi_{\text{err}}=10^\circ$ than $1/G_{\text{err}}=1\text{M}\Omega$!

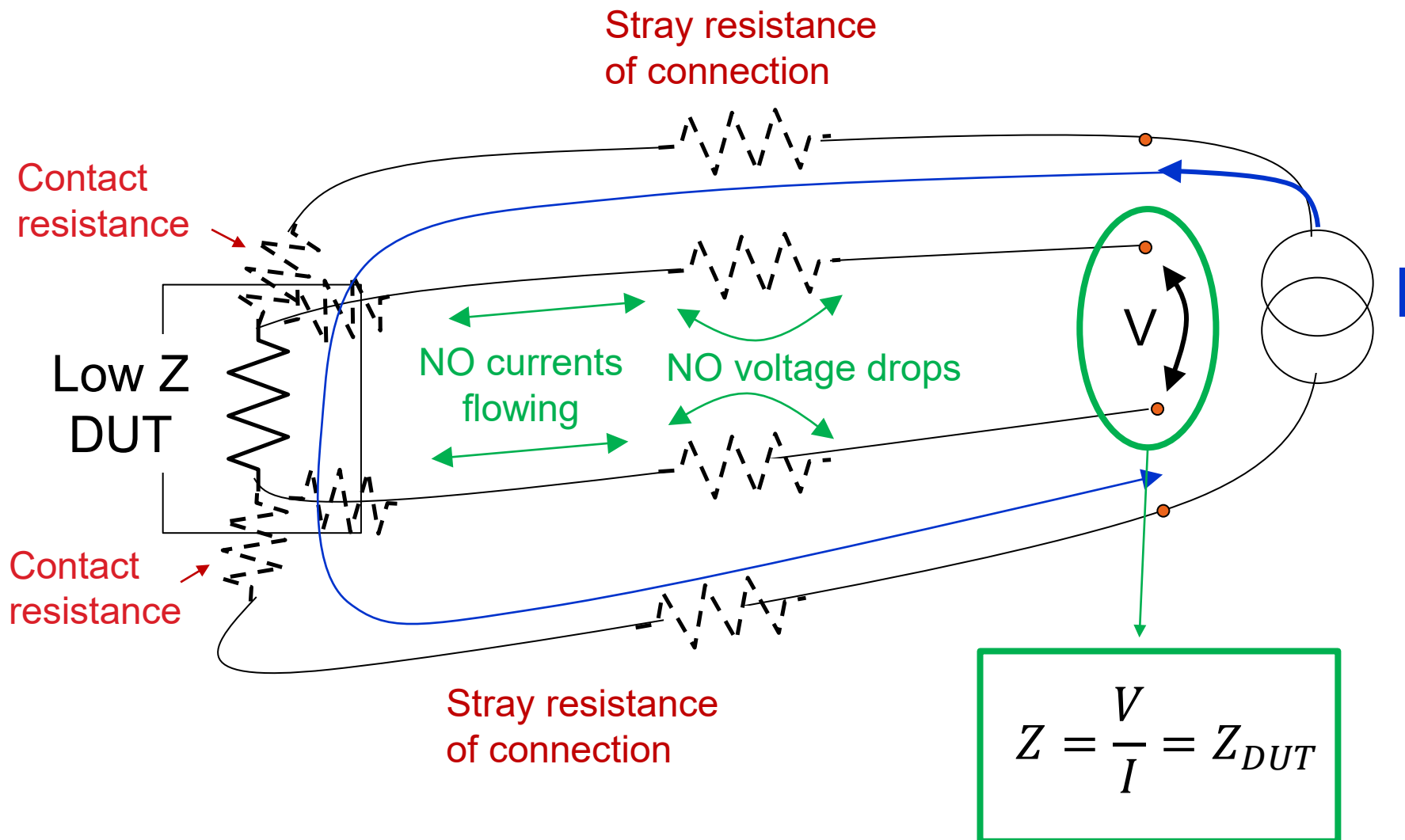


Contribution of strays (resistances)



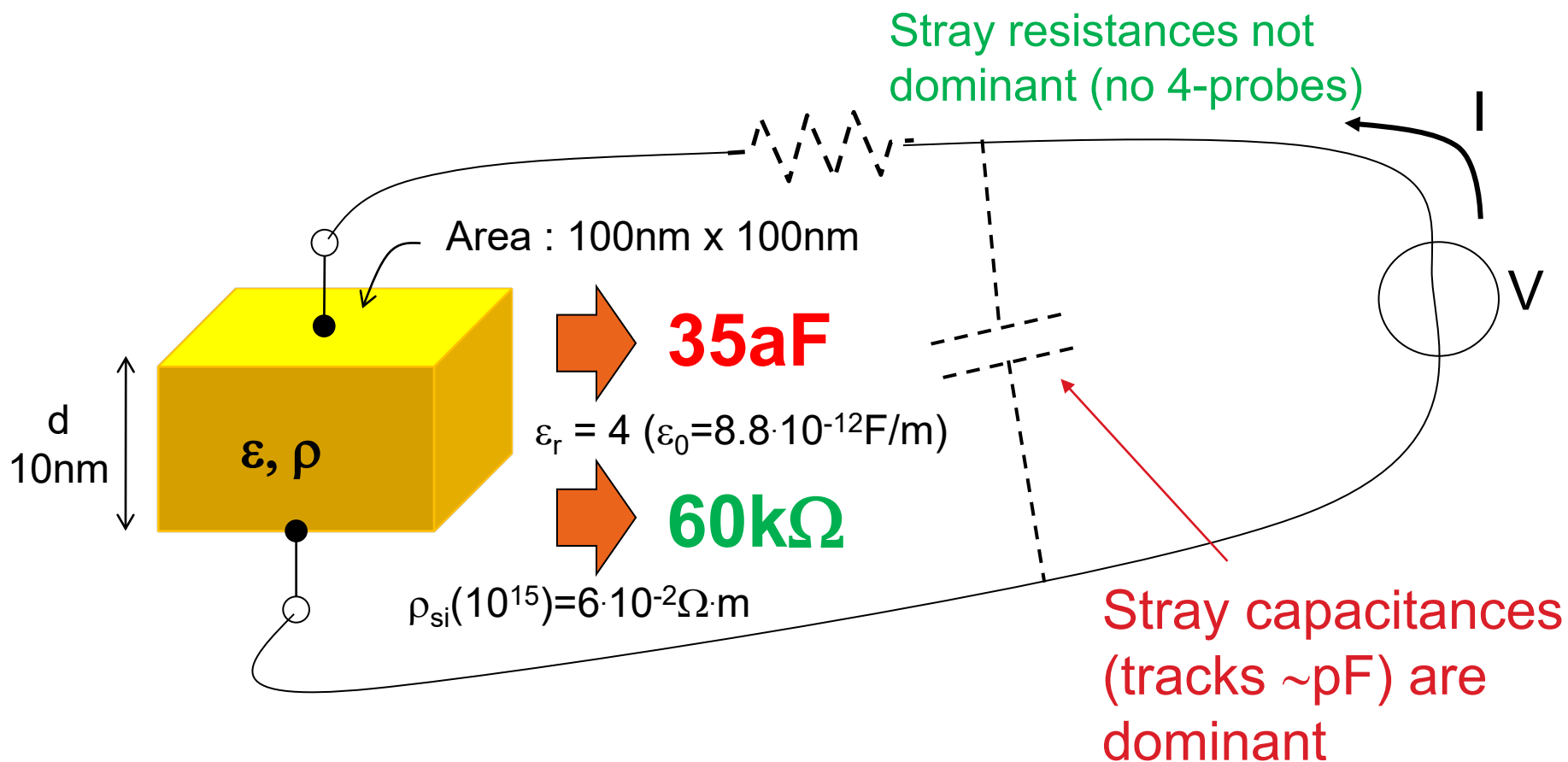


4 probes Impedance measurement





Impedance at the Nanoscale

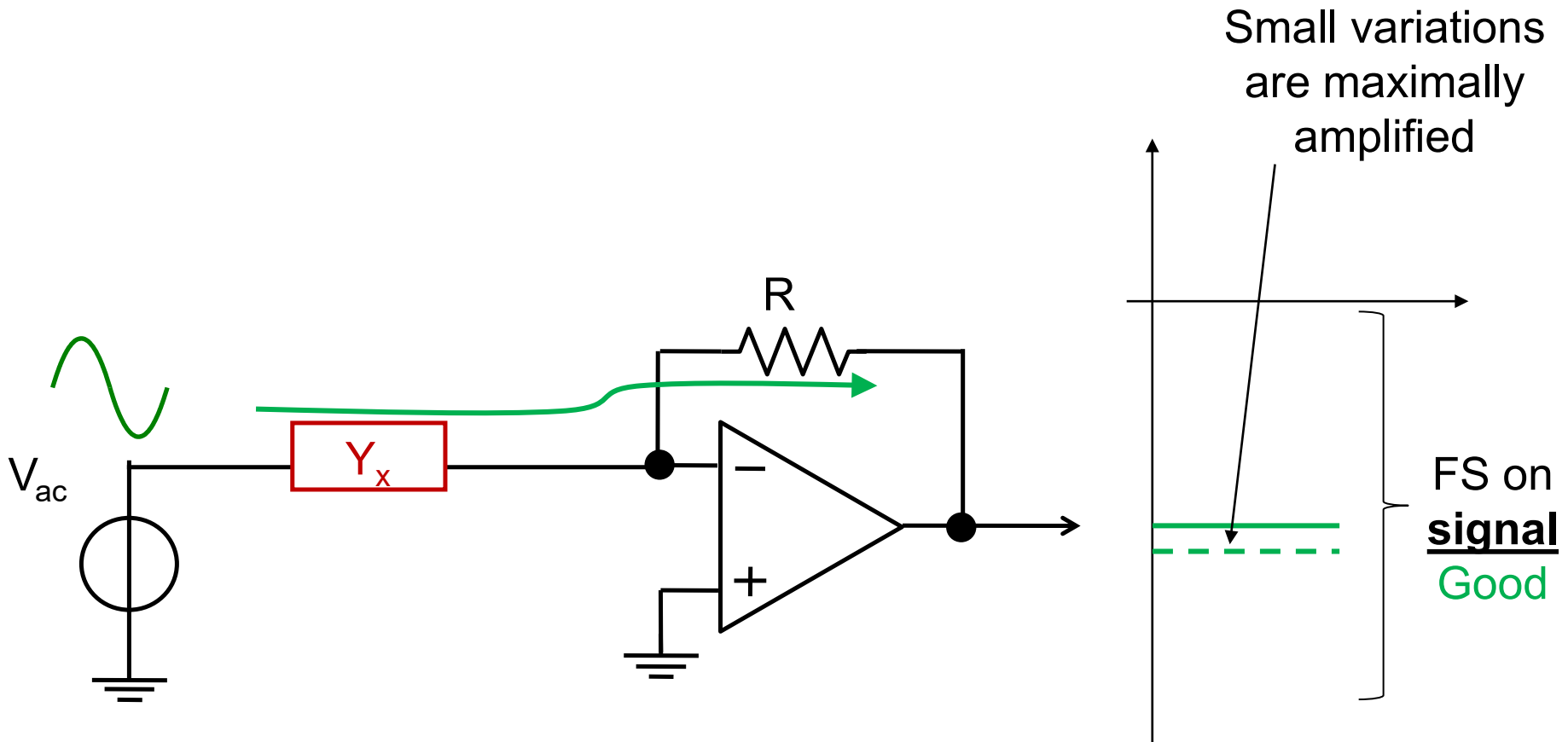


$$\tau = RC = \rho \frac{d}{\text{Area}} \cdot \epsilon \frac{\text{Area}}{d}$$

$$\tau = \rho \cdot \epsilon = 2\text{ps} \text{ *independent* of size}$$



Problems given by strays (capacitance)



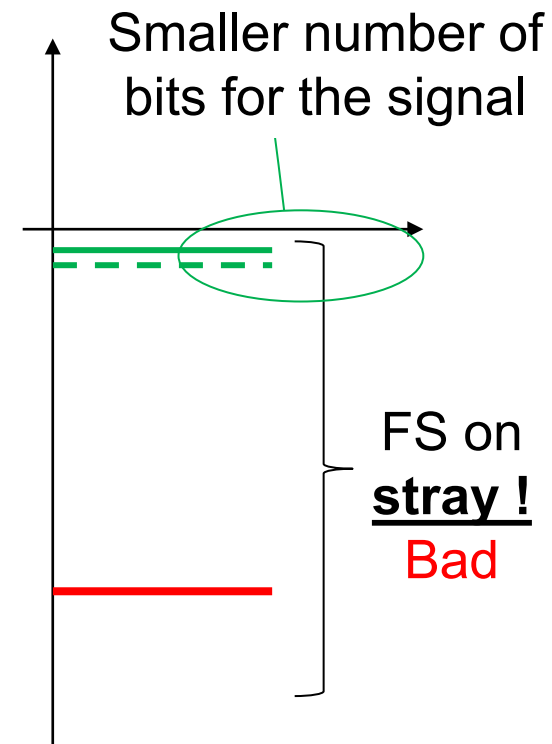
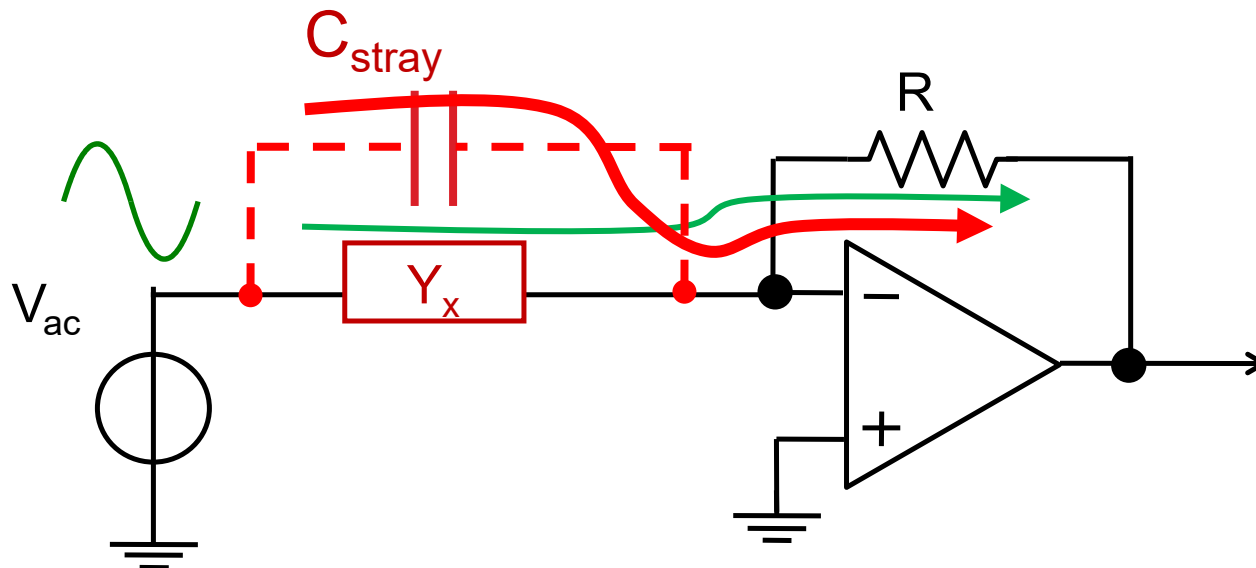
Reduction of sensitivity

A stray parallel capacitance C_{stray} may:

- saturate the front-end or gain stages

➔ Reduce gain \Rightarrow reduce resolution

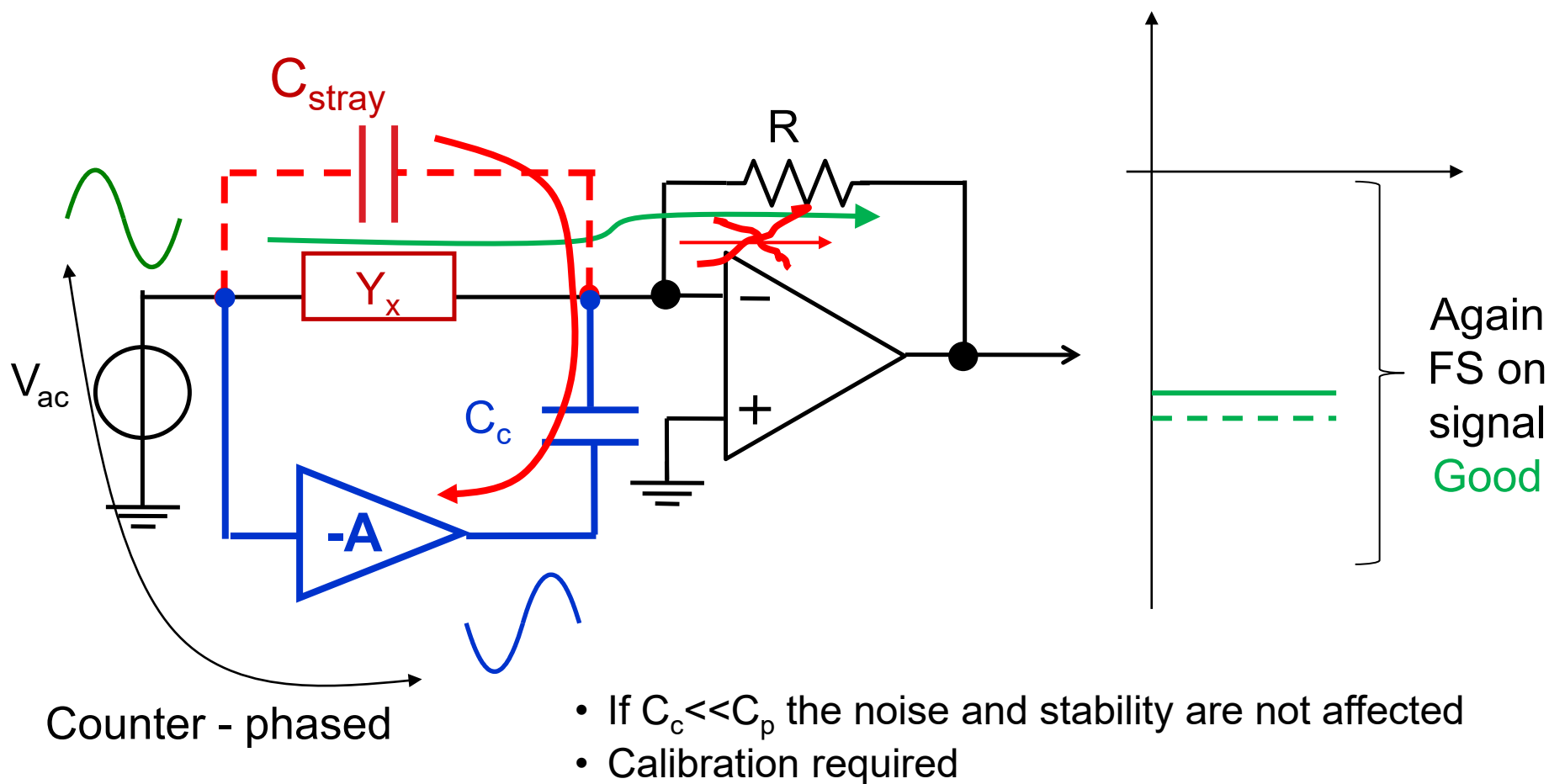
- require ADC with large bit number





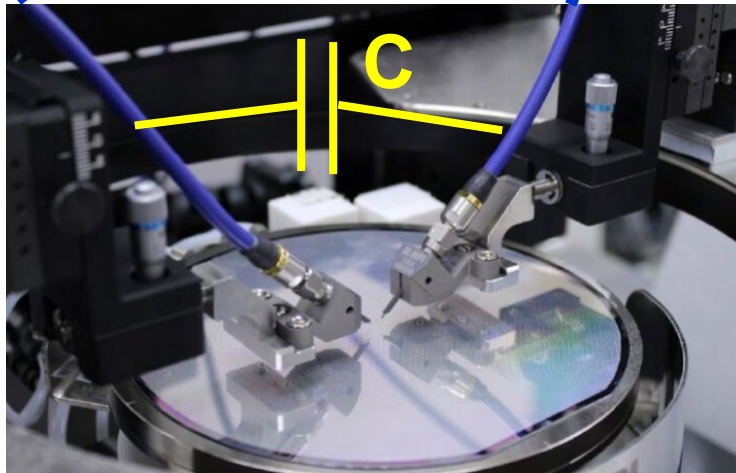
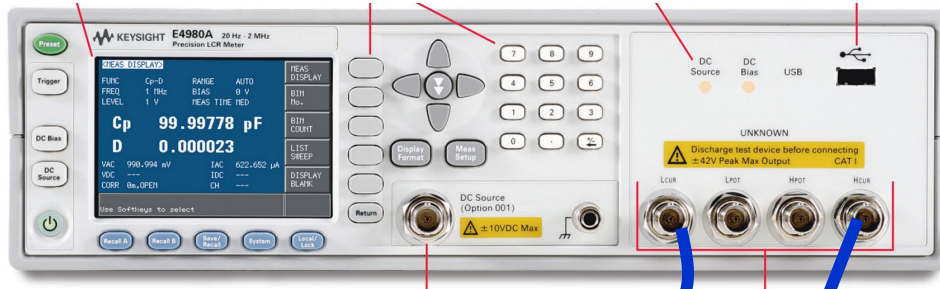
Compensation in current sensing

An **active capacitance compensation** can be useful:





Strays compensation in LCR meter (1)

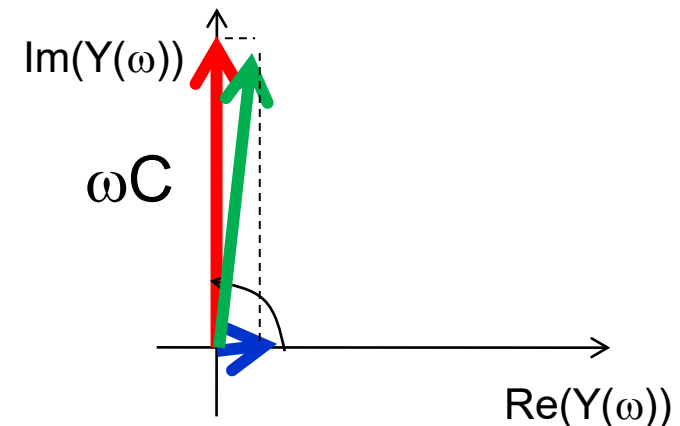


OPEN

You Lift the probes (a little)

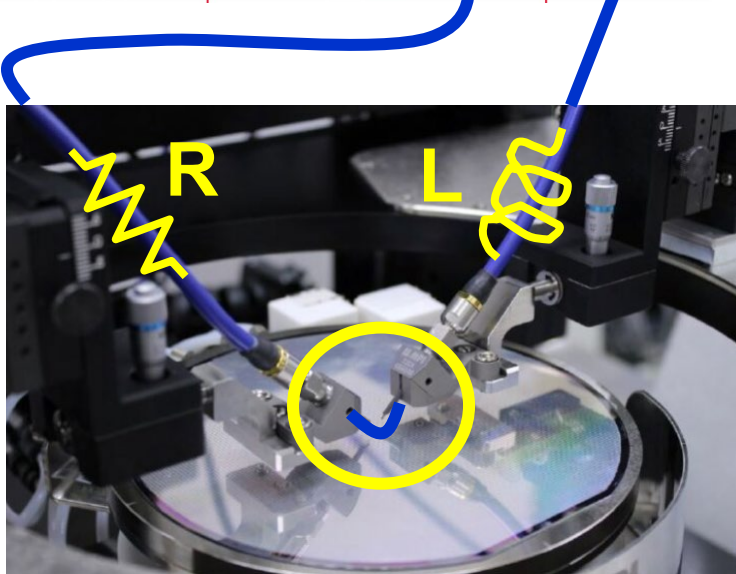
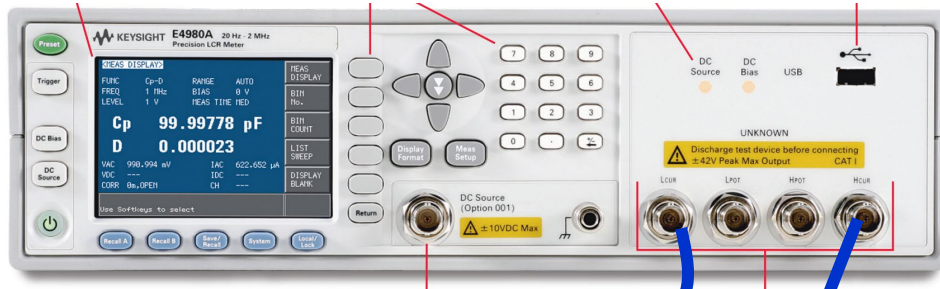
The instrument :

- Measures (the strays, mainly capacitance)
- Memorizes the values Re and Im at different f
- Correct the following meas. with these values





Strays compensation in LCR meter (2)

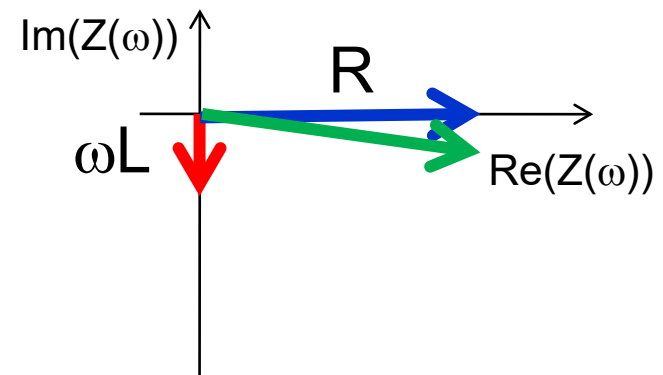


SHORT

You Put probes in contacts

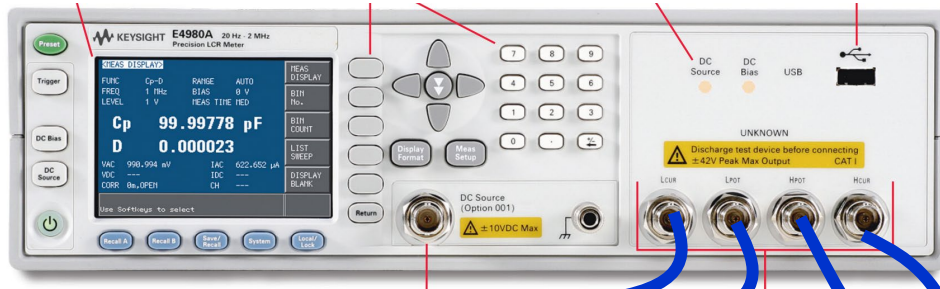
The instrument

- Measures (the strays, mainly resistance-inductance)
- Memorizes the values R_e and Im at different f
- Correct the following meas. with these values

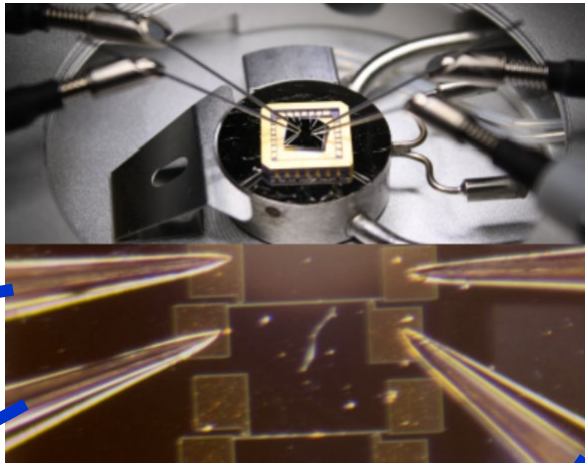




Strays compensation in LCR meter (3)



In addition USE 4 PROBES

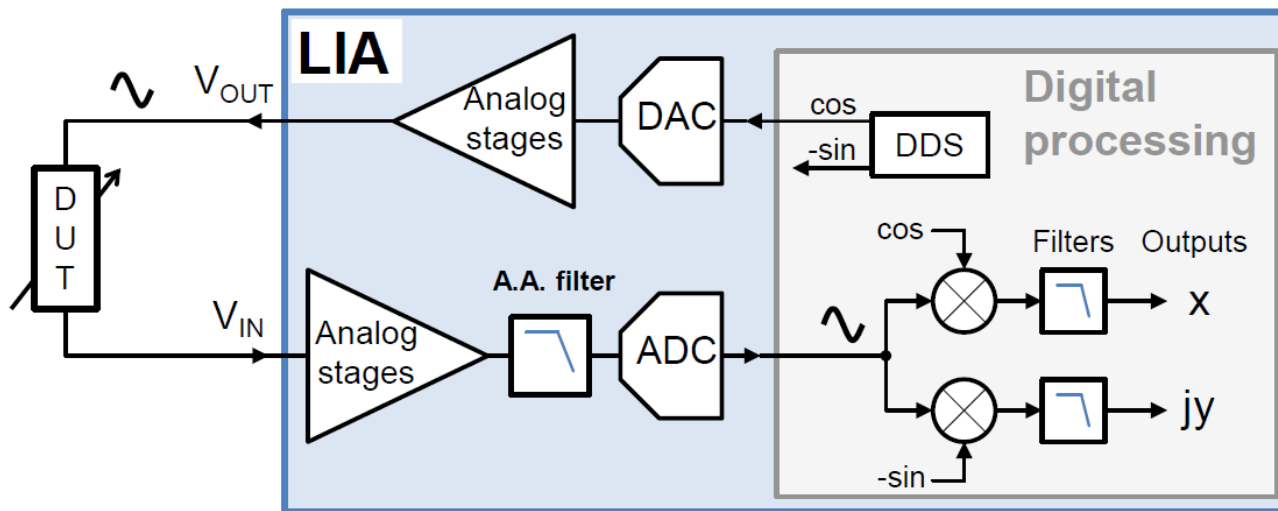




Digital LOCK-IN amplifiers

Impedance spectroscopy with lock-in requires a separate measurement for each frequency → **long time**

Alternatives : Apply many-frequencies as stimulus and process in parallel;
Apply white noise at input and calculate the DFT of signals.



Next lesson
by Giorgio
Ferrari

This afternoon
by Francesco
Zanetto



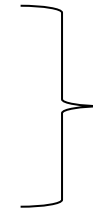
Myself : How can I measure the impedance of a device ?

chatGPT : Using an Impedance Analyzer

Using an LCR Meter

Bridge Circuit

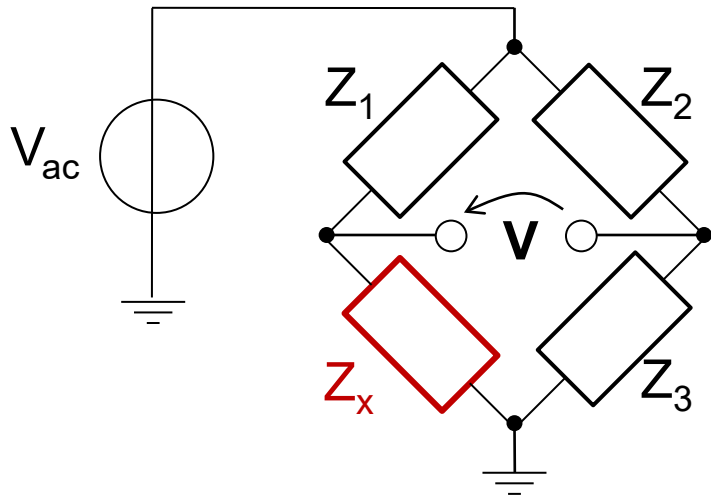
Oscilloscope and Function Generator using the voltage-divider principle



Lock-in
architecture



Balancing Bridge: Working Principle

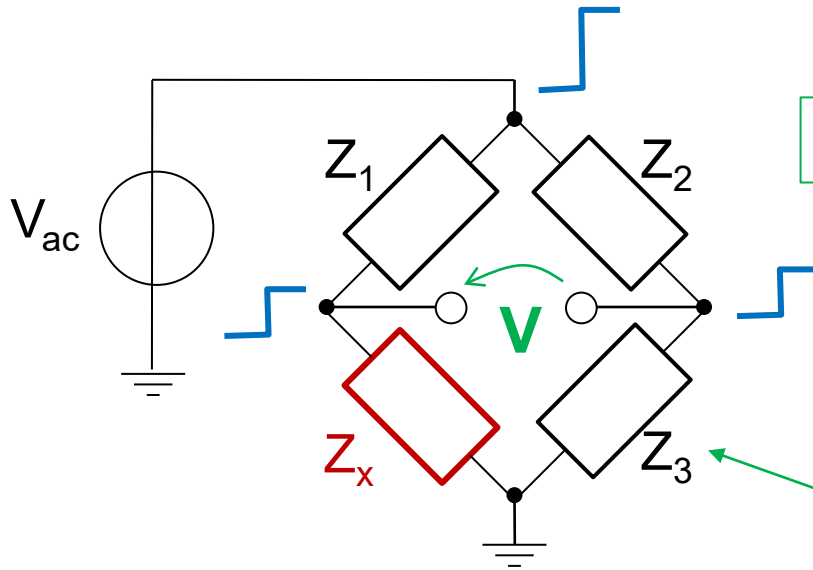


- Z_1, Z_2, Z_3 known and variable (switches)
- V_{ac} sinusoidal

$$V = V_{ac} \left(\frac{\mathbf{Z}_x}{Z_1 + \mathbf{Z}_x} - \frac{Z_3}{Z_2 + Z_3} \right)$$

Balanced for $V = 0 \Rightarrow \mathbf{Z}_x = Z_3 \frac{Z_1}{Z_2}$

Bridge Pros and Cons



Pros:

Voltage reader operates always with $V \approx 0V$

Common mode rejection

Good accuracy (no active stages, depends on the accuracy of the reference impedances)

Cons:

- Requires several switches
- Slow balancing routine
- Not very convenient for spectroscopy

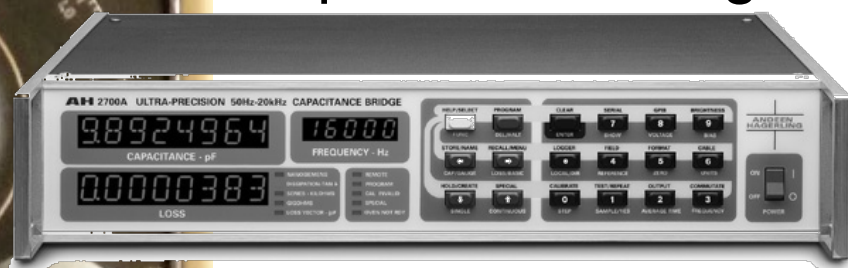


Examples of Commercial Instruments

GR 1650-A (1957) ...fully manual



**Andeen-Hagerling
AH 2700A
50Hz-20kHz
Capacitance Bridge**

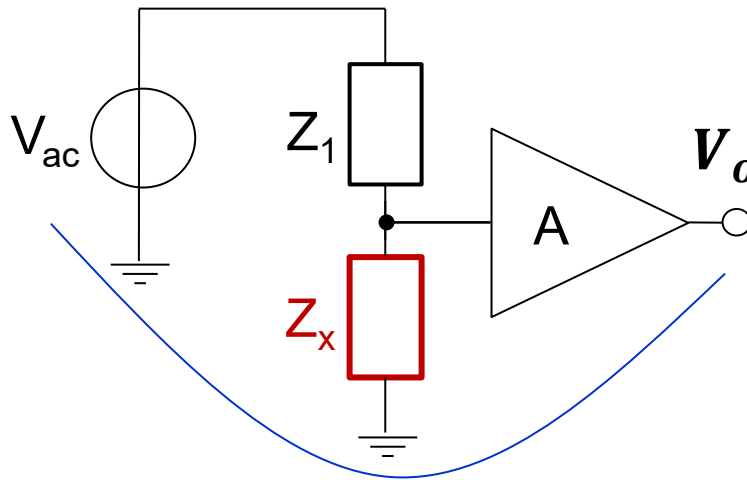


0.5aF, 1PΩ resolution

Ratiometric: Half Bridge

Ratiometric i.e. V_{out} depends on the impedance ratio

↓
Independent of the absolute value



$$V_{out} = V_{ac} \frac{Z_x}{Z_1 + Z_x} A$$

↪

$$Z_x = Z_1 \frac{V_{out}}{AV_{ac} - V_{out}}$$

A phase sensitive detector is needed

Z_1 has to be accurate (wide dynamic) :

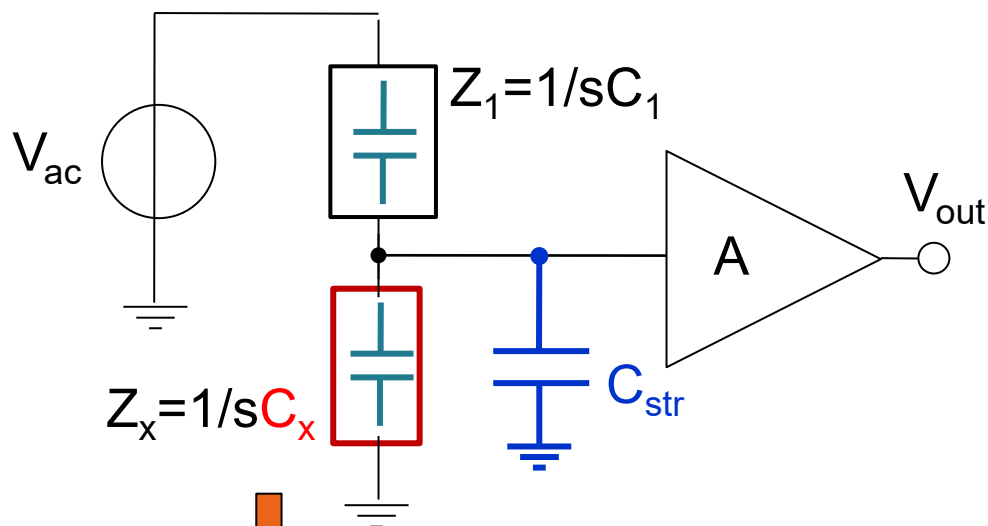
- $Z_x \gg Z_1$: $V_{out} \approx AV_{ac}$
- $Z_x \ll Z_1$: $V_{out} \approx 0$

↪ $Z_1 \sim Z_x$

Difficult at the
nanoscale



Capacitance detection: Effect of C_{stray}



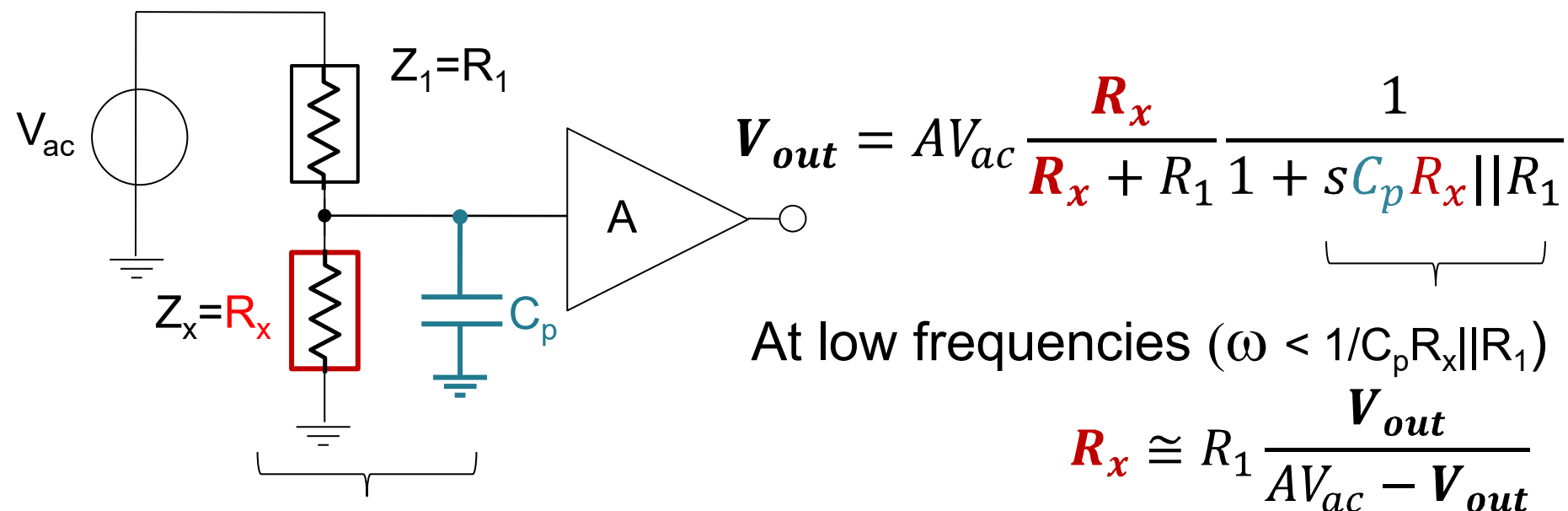
$$C_x = C_1 \frac{AV_{ac} - V_{out}}{V_{out}} - C_{str}$$

Reduces the accuracy !

DC bias of Z_x not defined



Resistance detection: Effect of C_{stray}



At high frequencies ($\omega > 1/C_p R_x || R_1$)

→ R_x shunted by C_p !

Example: a cube of intrinsic Si ($\sim 1\text{k}\Omega\text{ cm}$), side = 50nm

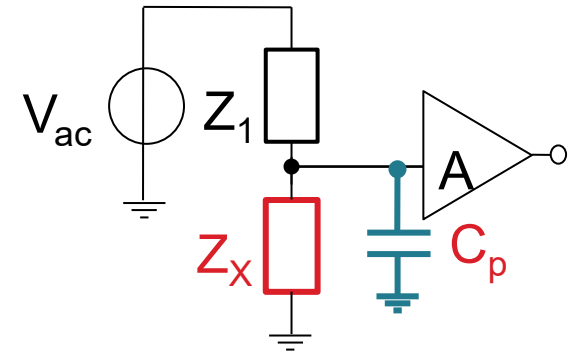
→ $R_x = 200\text{M}\Omega$, cut-off frequency = 160Hz ($C_p = 5\text{pF}$)



Comparison

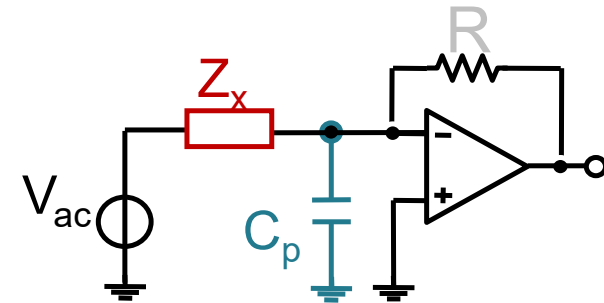
Ratiometric:

- C_p limits bandwidth and accuracy
- No control of the voltage applied to Z_x
- Z_1 must match Z_x



Current sensing:

- Independent of C_p (wide-band opamp)
- Precise control of the voltage applied
- Need to access both terminals of Z_x
- Loop stability depends on Z_x (but at the nanoscale dominated by stray capacitance \approx known)



In terms of resolution they are **equivalent**



Go to chatGPT and ask questions on this lesson :

How can I measure the impedance of a device ?

How to use an Impedance Analyzer.

How do I choose the frequency of the AC signal ?

How would change the impedance as a function of frequency ?

...

Do you find this lesson as an added value to chatGPT ?