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DC bias circuit effects in CV measurements

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Outline

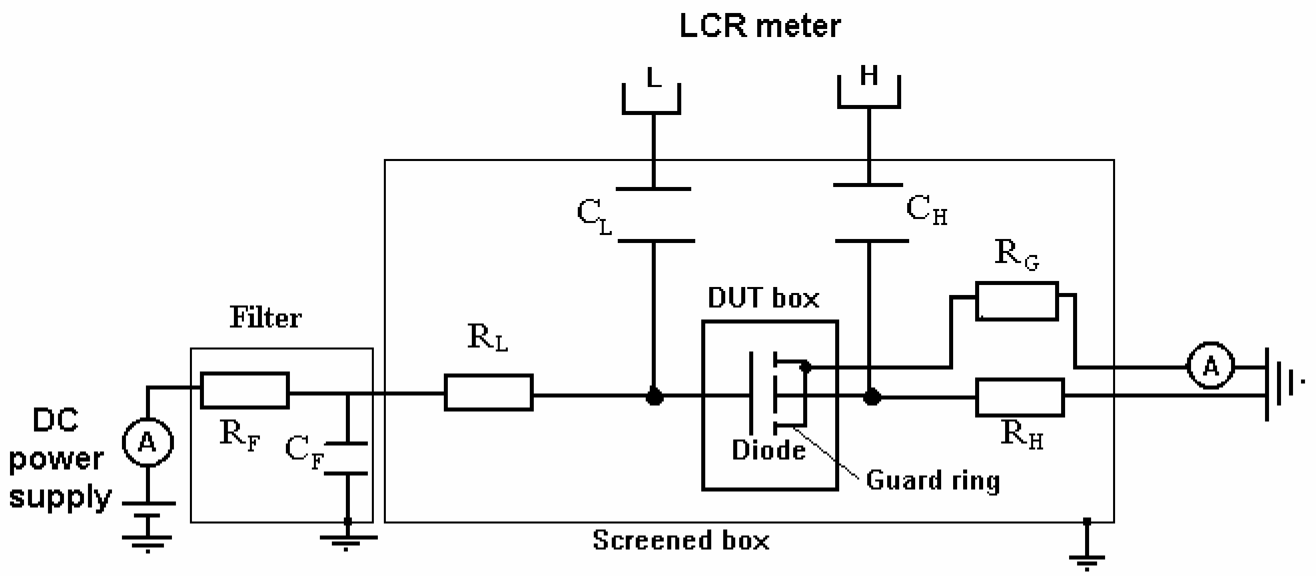
1. Introduction

A DC bias circuit is a necessary part of every CV measurement set-up. We will show that in some situations the effects of such a circuit cannot be taken into account by the usual “Open Correction” procedure.

The analysis presented here is applicable to the DC biasing *external* to the LCR meter and with capacitors decoupling the DC potential from the LCR meter inputs.

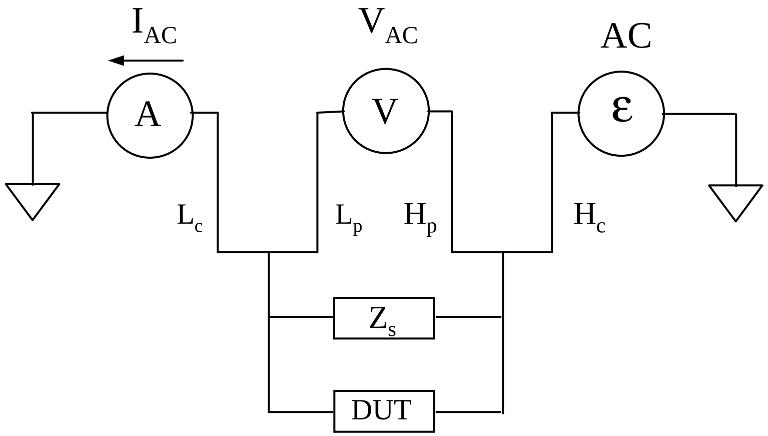
1. Introduction (continued)

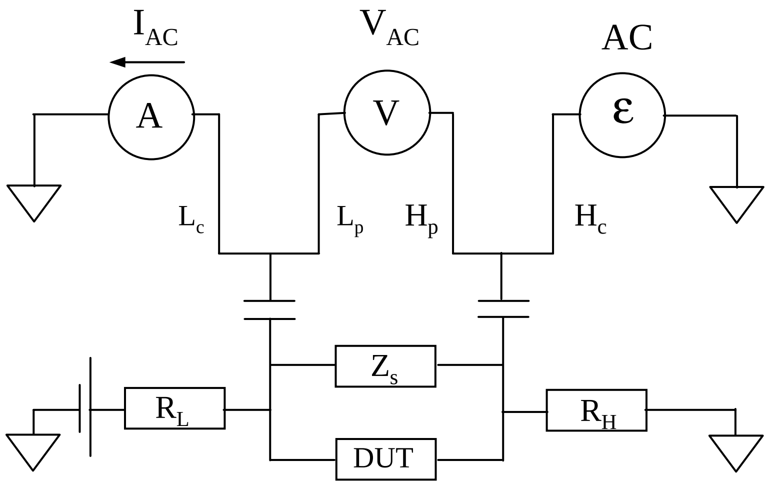
In the simulation and tests reported here we used our standard bias circuit described in NIM A492 (2002) 402.



The circuit elements have the following values: C_H=10μF, R_H=R_G=10kΩ, C_L=0.1μF, R_L=220kΩ, C_F=1μF, R_F=100kΩ. It is also possible to use R_L=10kΩ.

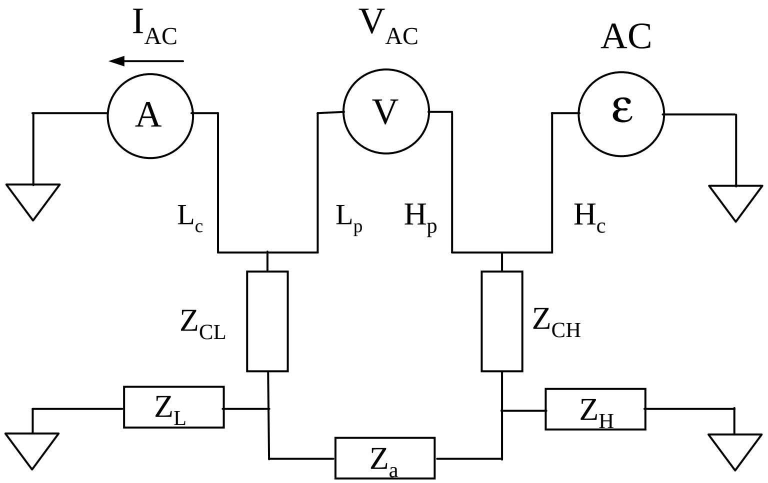
2. Theoretical considerations





The equivalent diagram for a measurement with a 4-terminal LCR meter without biasing is shown to the left. The measured impedance $Z_m = V_{AC}/I_{AC}$, where all parameters are complex numbers. Typically a stray impedance Z_s is measured without any DUT (Device Under Test) and subtracted from the measured results. This is called "Open Corrections".

Also shown is an example of a measurement with a simple external DC bias circuit.



General equivalent diagram for the 4-terminal LCR meter measuring a biased DUT. Z_a is the total actual impedance including Z_s.

Solving Kirchhoff's equations one finds

$$Z_m = Z_a F_L F_H + Z_{CH} F_L + Z_{CL} F_H$$

where

$$F_L = 1 + \frac{Z_{CL}}{Z_L}; F_H = 1 + \frac{Z_{CH}}{Z_H}$$

Typically

$$|Z_a| >> |Z_{CH}|; |Z_a| >> |Z_{CL}|$$

Therefore

$$Z_m \approx Z_a F_L F_H$$

and similarly for admittance $Y=1/Z$

$$Y_m \approx \frac{Y_a}{F_L F_H} \qquad (1)$$

$Y_a = G_{pa} + j\omega C_{pa}$. If $G_{pa}/C_{pa} = \alpha$ = const $Y_a = C_{pa}(\alpha + j\omega)$ and as follows from eq.(1) Y_m is about scaled with C_{pa}. Also eq.(1) means that the conversion of Y_a into Y_m is approximately linear: $Y_m(Y_{a1}+Y_{a2}) \approx Y_m(Y_{a1}) + Y_m(Y_{a2})$.

Consider a simple case, when Z_{CL}, Z_{CH} are pure capacitors and Z_L, Z_H are pure resistors. Then

$$F_L = 1 - \frac{j}{\omega C_L R_L}; F_H = 1 - \frac{j}{\omega C_H R_H}; F_L F_H = 1 - \frac{1}{\omega^2 C_L R_L C_H R_H} - \frac{j}{\omega (RC)_{aver}}$$

where

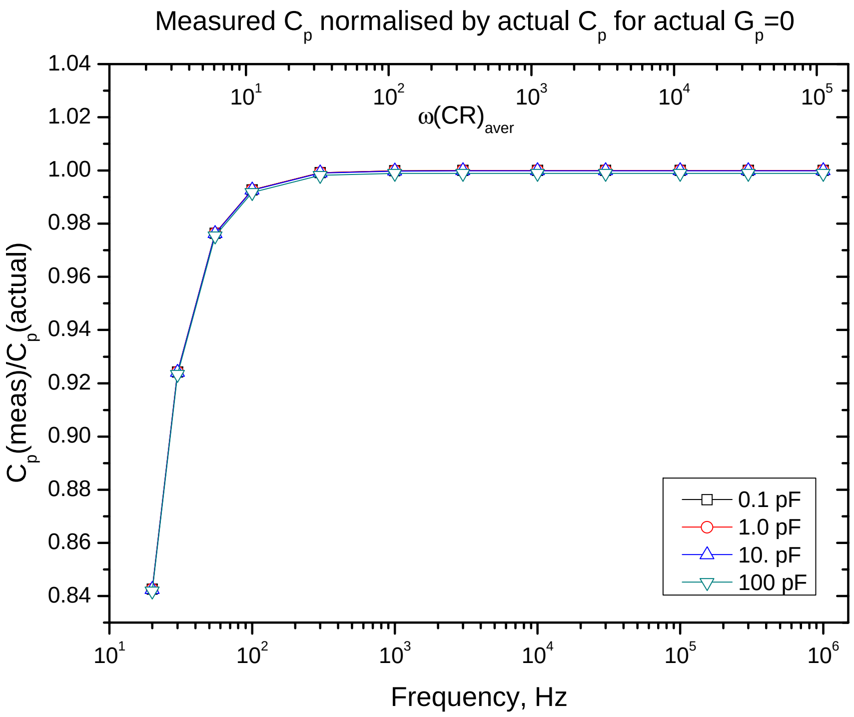
$$\frac{1}{(RC)_{aver}} = \frac{1}{C_L R_L} + \frac{1}{C_H R_H}$$

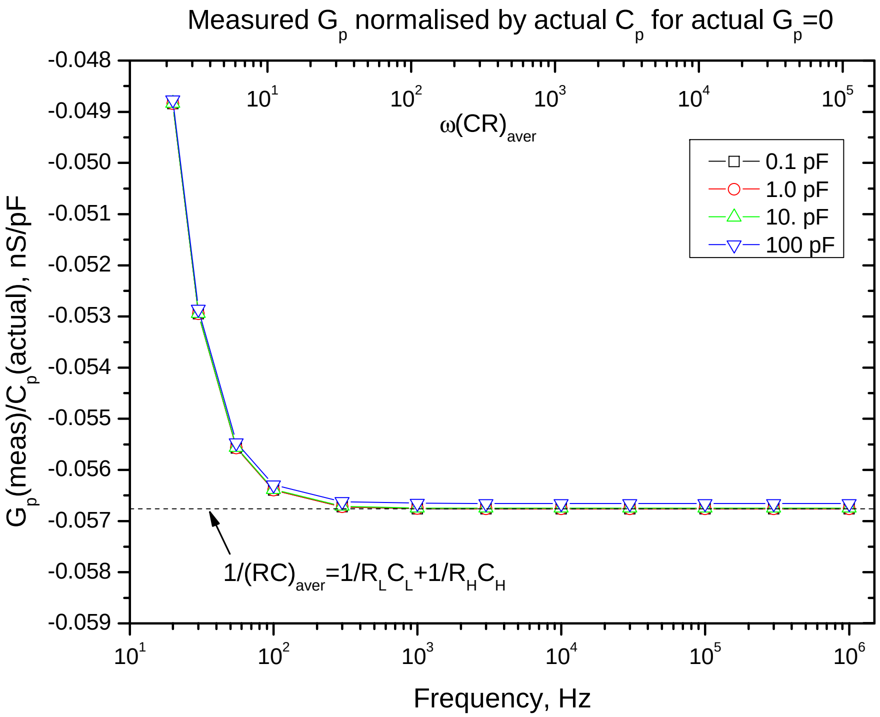
This parameter usually controls the major frequency dependence of the measured impedance (admittance). In practice it is often dominated by a minimum *RC*.

It is easy to show that for $\omega \to \infty$ the measured $C_{pm} \to C_{pa}$ (actual C_p *value*) while $G_{pm} \to G_{pa} - C_{pa}/(RC)_{aver}$, i.e. the asymptotic value of the measured conductivity is shifted down relative to its actual value and this shift is proportional to C_{pa}.

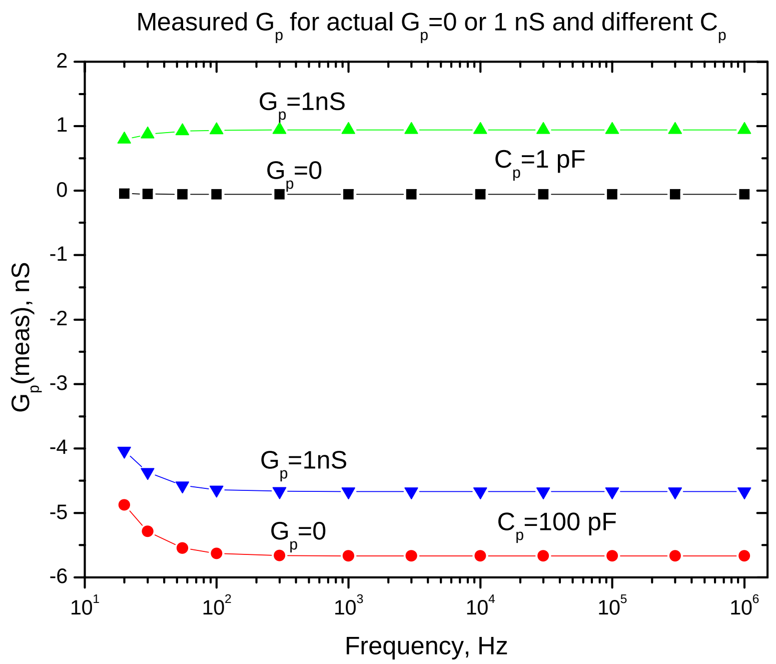
It is also clear that shorting of a decoupling capacitor makes the corresponding resistor irrelevant. Shorting of both capacitors nullify all DC circuit effects (for ideal generator, voltmeter, ammeter in the diagram!). Disconnecting the resistors can also practically eliminate the circuit effects when the decoupling capacitors are large enough.

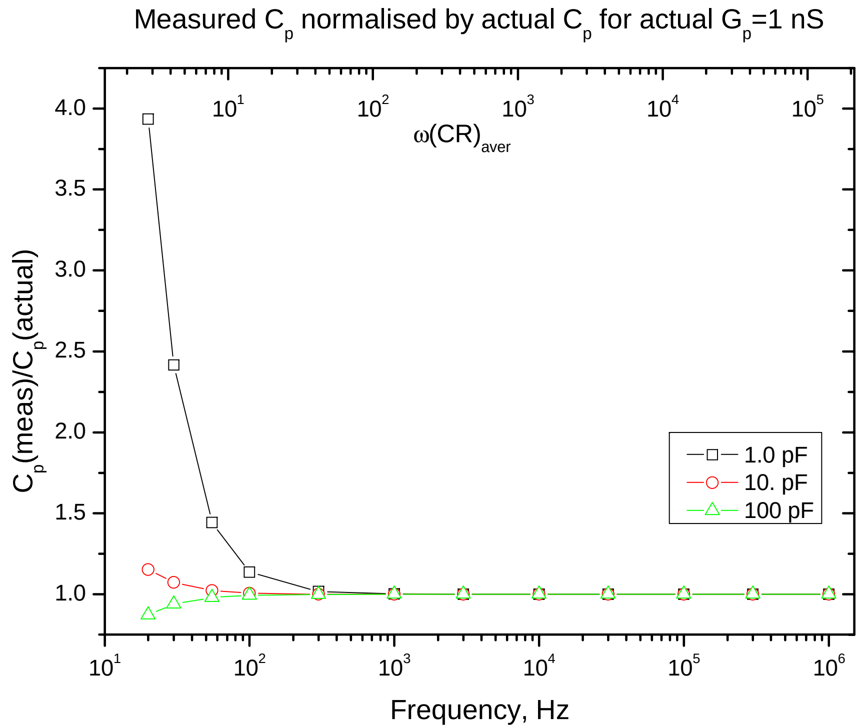
3. Simulation

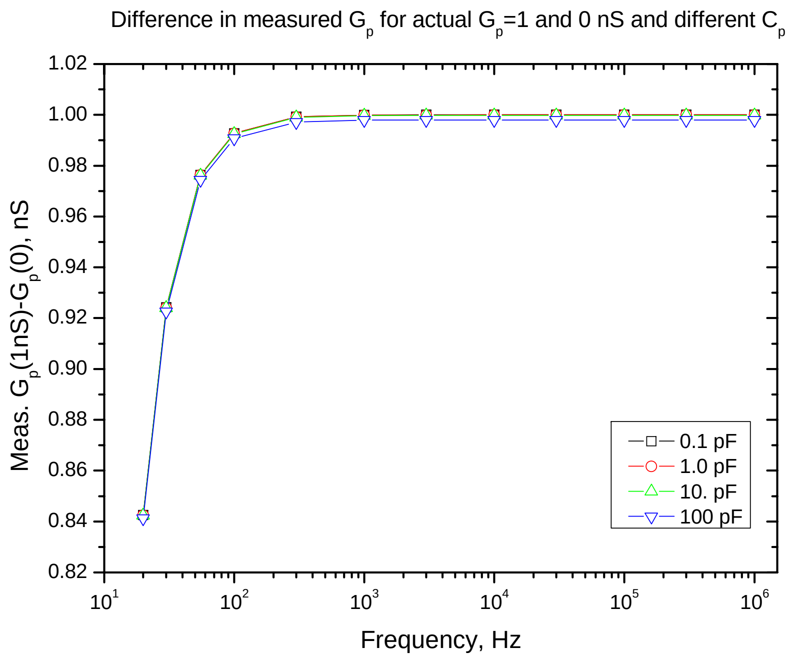




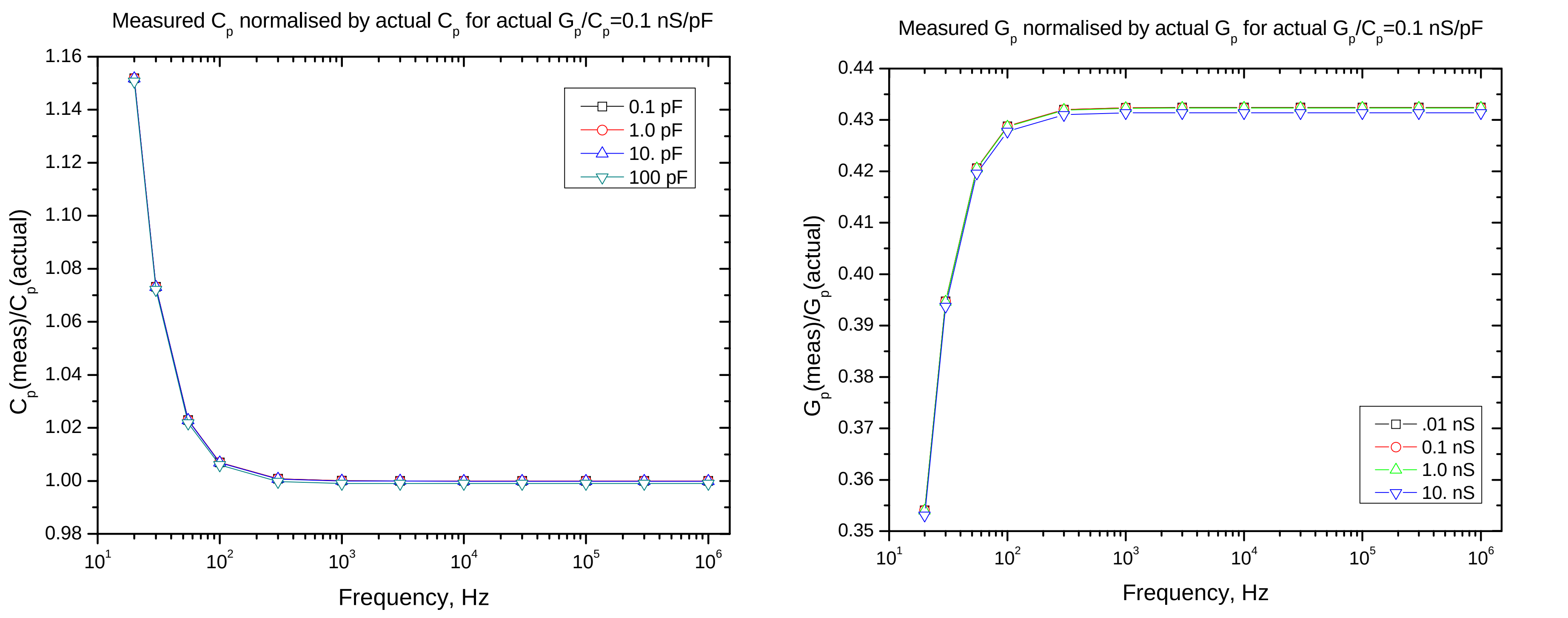
All above conclusions are confirmed by simulation though the simulated circuit is slightly more complicated than the simple case analysed above. Presented here are C_p and G_p measured for a pure capacitor. Scaling of both parameters with C_{pa} and the offset in the asymptotic value of G_{pm} are clearly seen. The latter agrees with expectations. The circuit effects saturate for $\omega(CR)_{aver}$ >10.



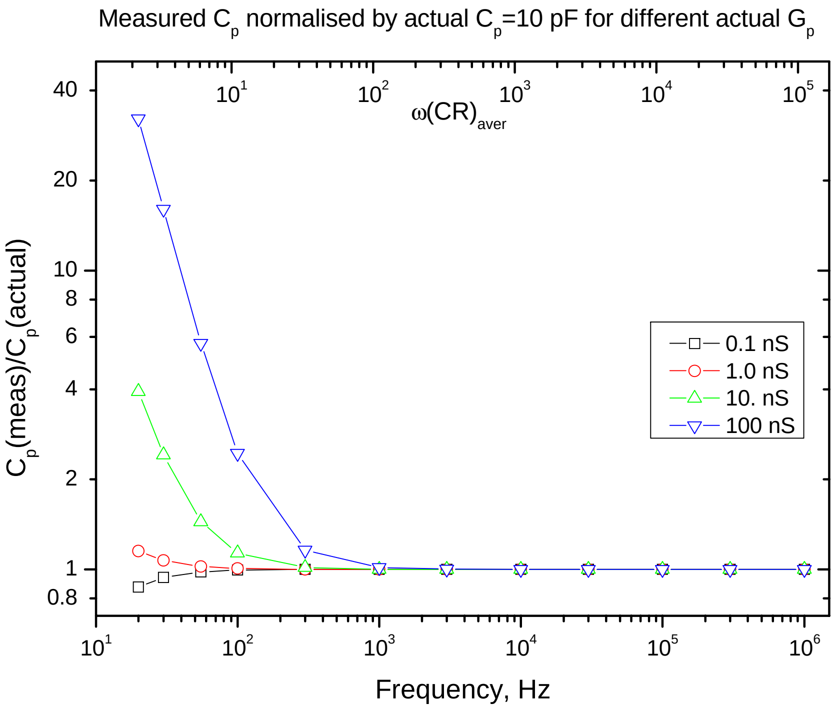


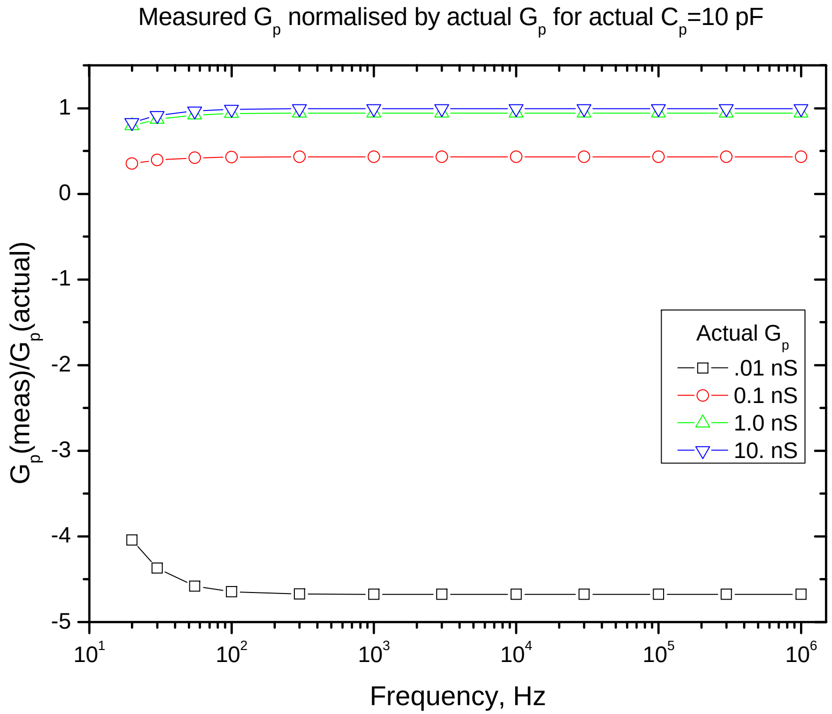


The same C_{pa} set with G_{pa}=1nS. Note the similarity in the G_{pm} shift relative to the case G_{pa}=0 and the variety of shapes for C_{pm}. The value of $\omega(CR)_{aver}$ >30 is needed for C_{pm} to become close to C_{pa}=1pF.

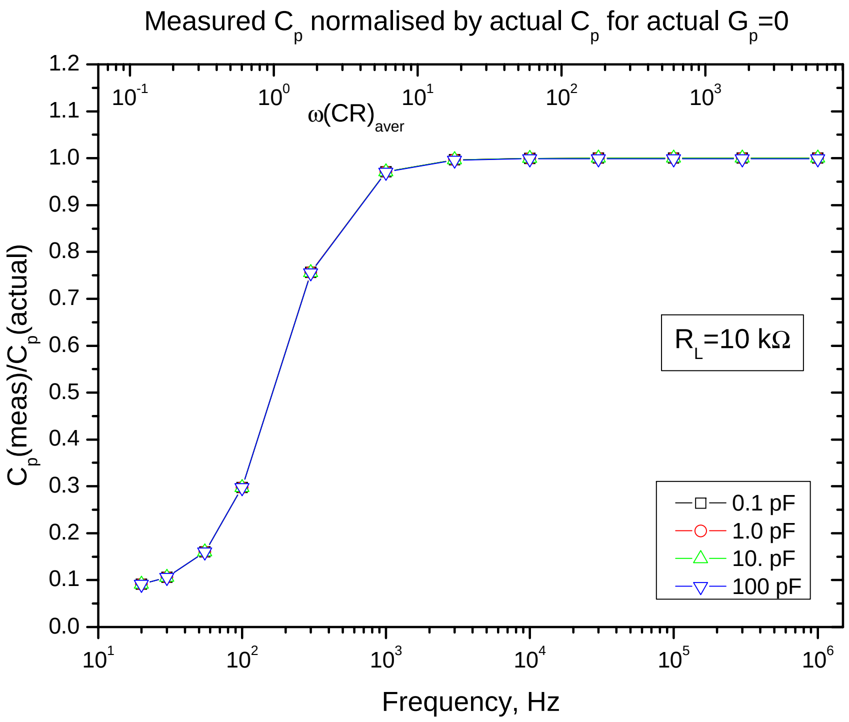


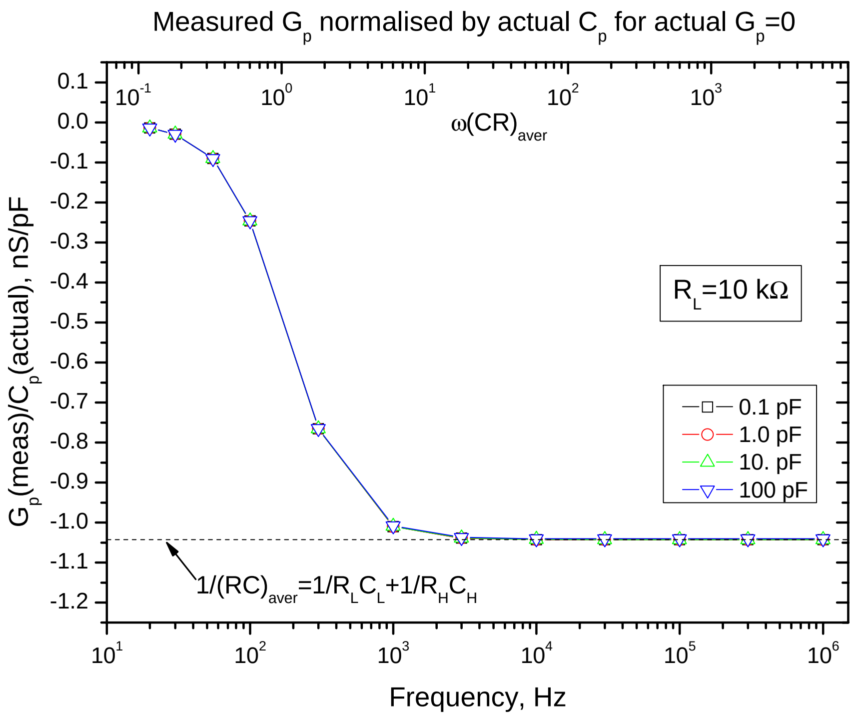
The same set of C_{pa} with proportional G_{pa}. Note the change of the C_{pm} curve shape compared to the case of G_{pa} =0 and ~60% shift in the asymptotic value of G_{pm}.



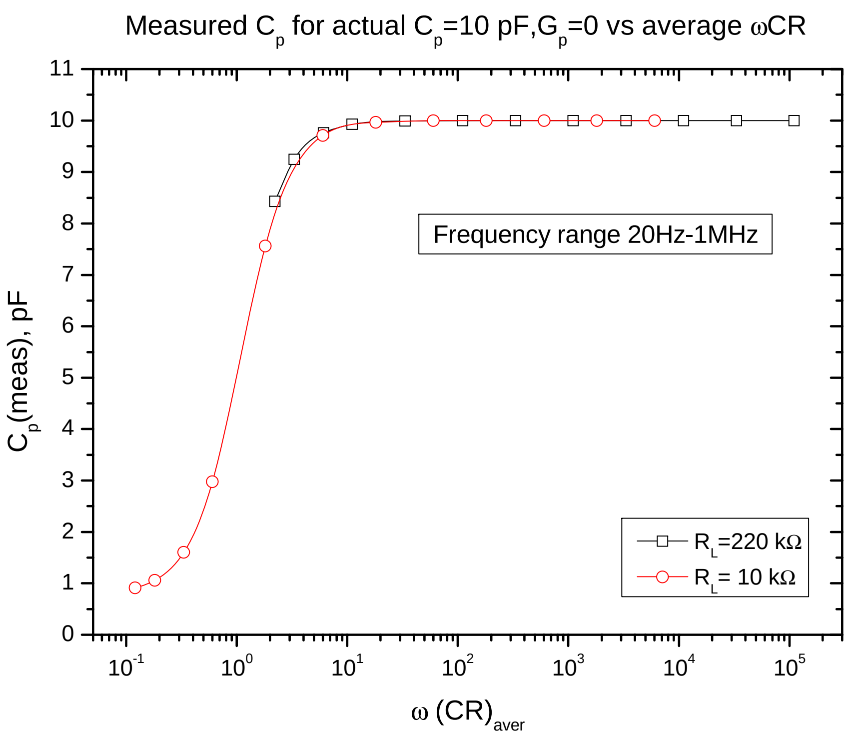


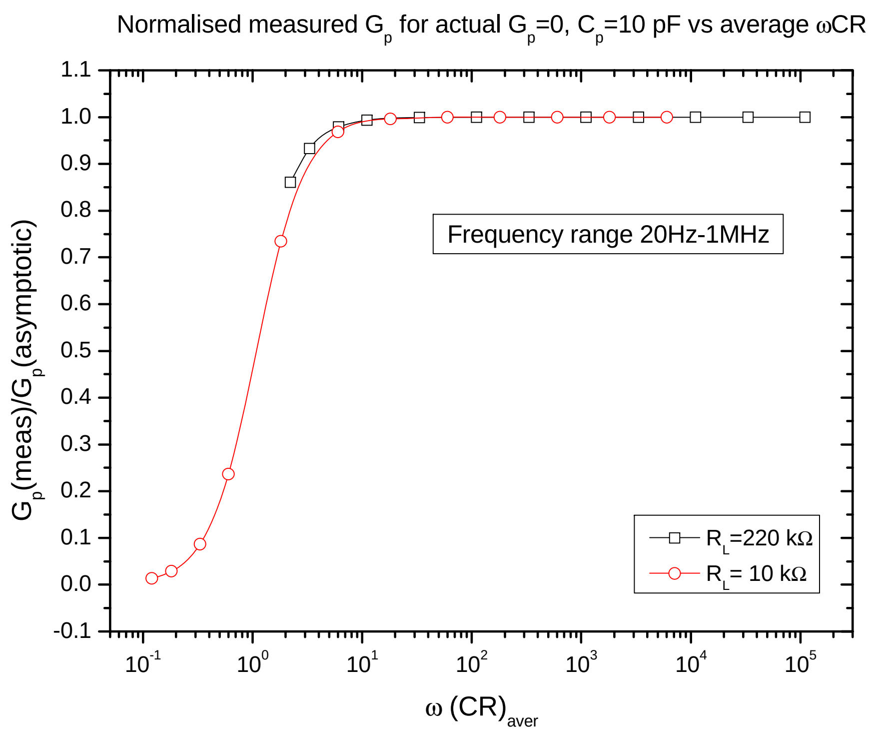
The data for C_{pa} =10 pF with different G_{pa}. Note that for G_{pa}= 100 nS the C_{pm} at low frequency is ~ <u>40 times</u> higher than C_{pa}. The value of $\omega(CR)_{aver}$ >100 is needed for C_{pm} to become close to C_{pa}.





Measured C_p and G_p for a pure capacitive Y_a with R_L=10kΩ instead of standard 220 kΩ. For the same range of frequency the range of $\omega(CR)_{aver}$ extends to much lower values, which increases the C_p and G_p deviations from their asymptotic values. Note also that G_{pm} saturates at the expected level, which is much lower than for R_L=220 kΩ.





To a good approximation C_p measured with different R_L can be regarded as a universal function of $\omega(CR)_{aver}$ that is illustrated above for a pure 10 pF capacitor. To a lesser extent the same is also true for G_{pm} .

Reconstruction of the actual impedance

From the mentioned before equation for the measured impedance Z_m

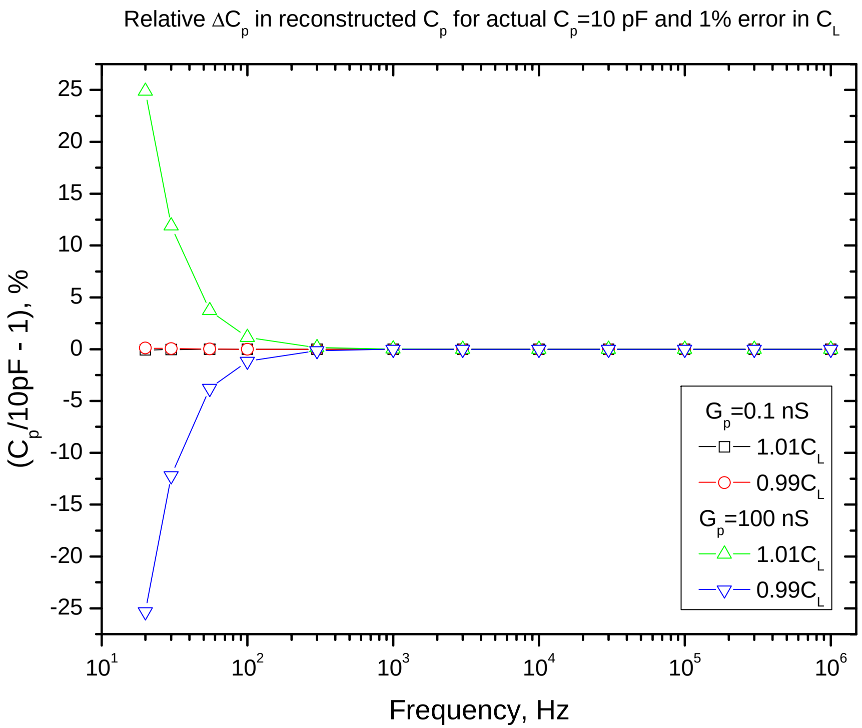
$$Z_m = Z_a F_L F_H + Z_{CH} F_L + Z_{CL} F_H$$

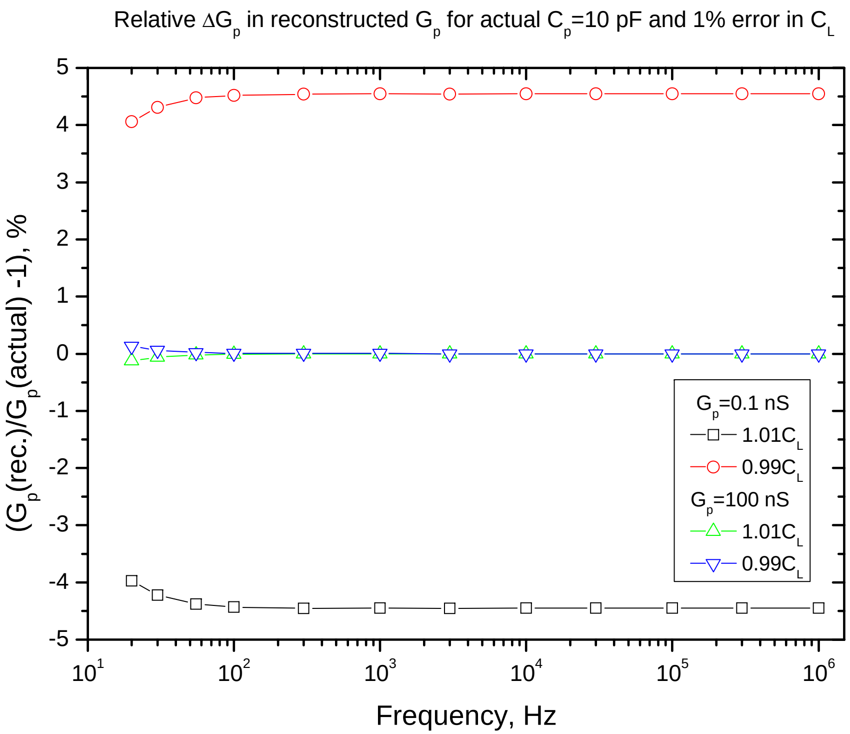
one can easily obtain the actual impedance Z_a

$$Z_a = (Z_m - Z_{CH} F_L - Z_{CL} F_H) / F_L F_H$$

Similarly one can restore the admittance $Y=1/Z$.

However this reconstruction relies on an accurate description of the real biasing circuit especially if the corrections are large compared to the final parameter value.

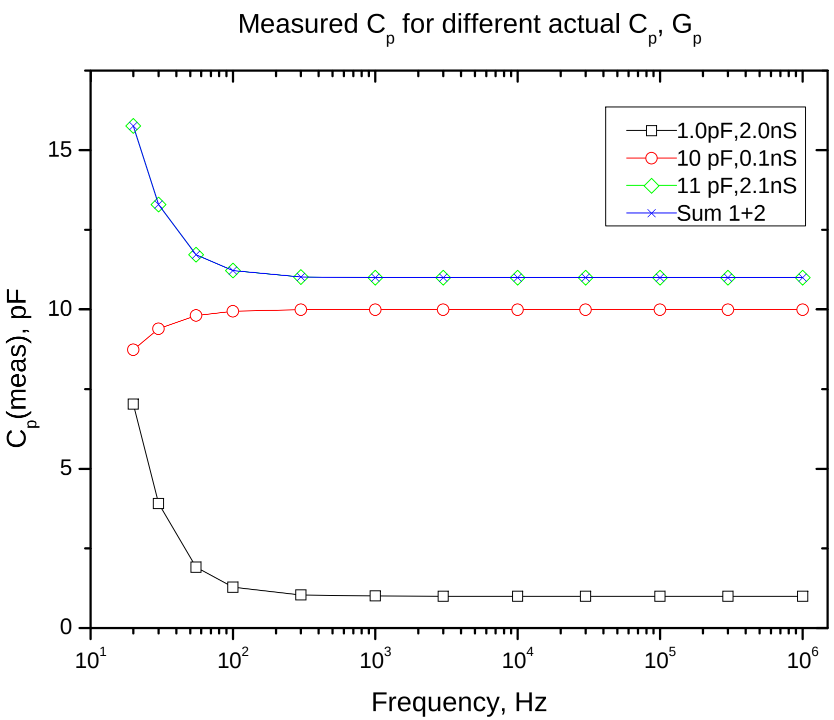


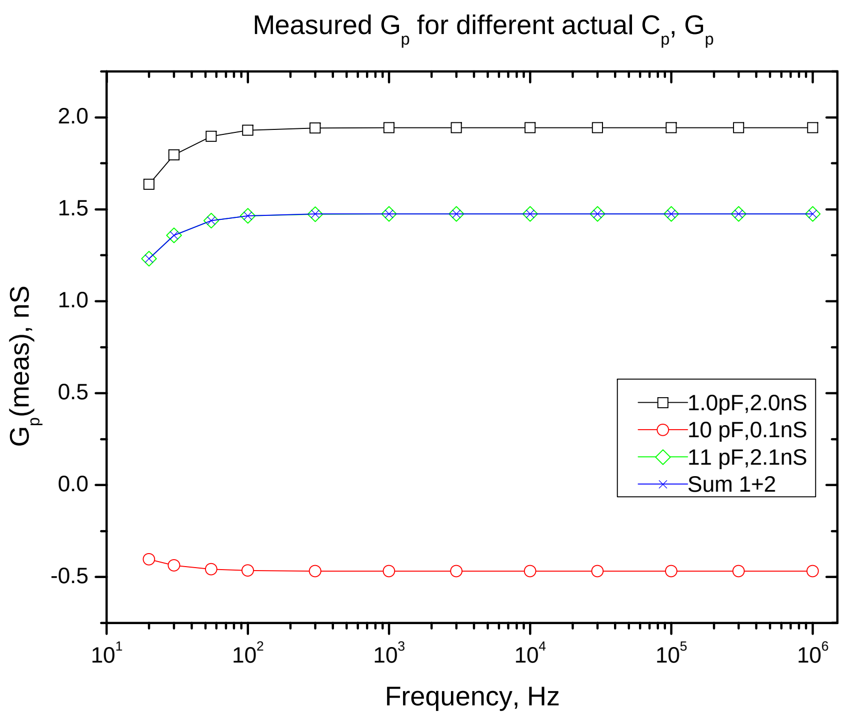


As an example the reconstructed values for C_{pa}=10 pF and two values of G_{pa} are shown for the values of decoupling capacitor C_L used in reconstruction differing by ±1% from its value in the simulation. Note that the deviations in reconstructed C_p and G_p are sometimes >> 1%.

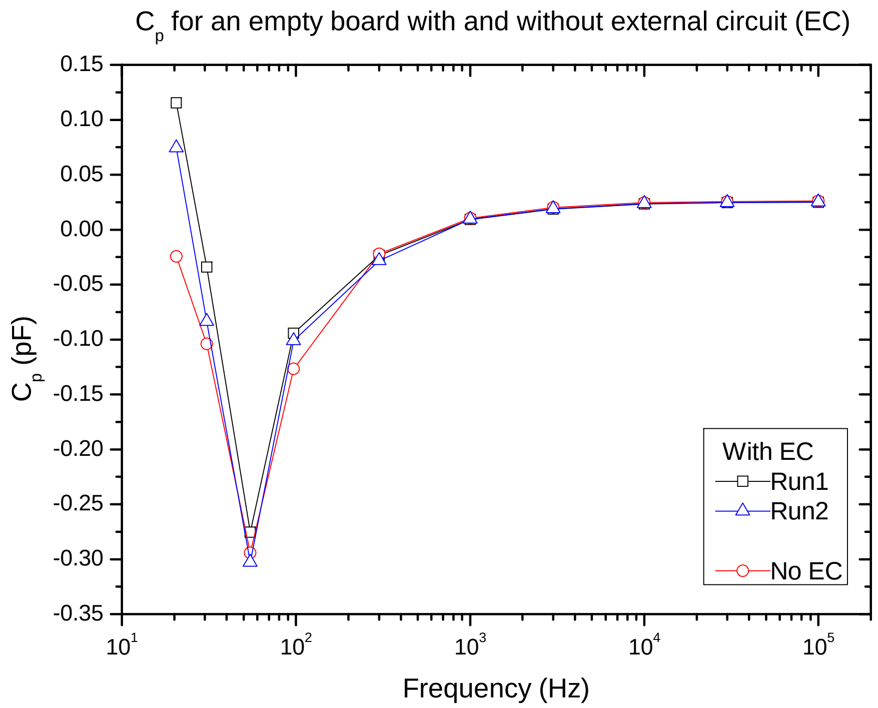
“Open Corrections”

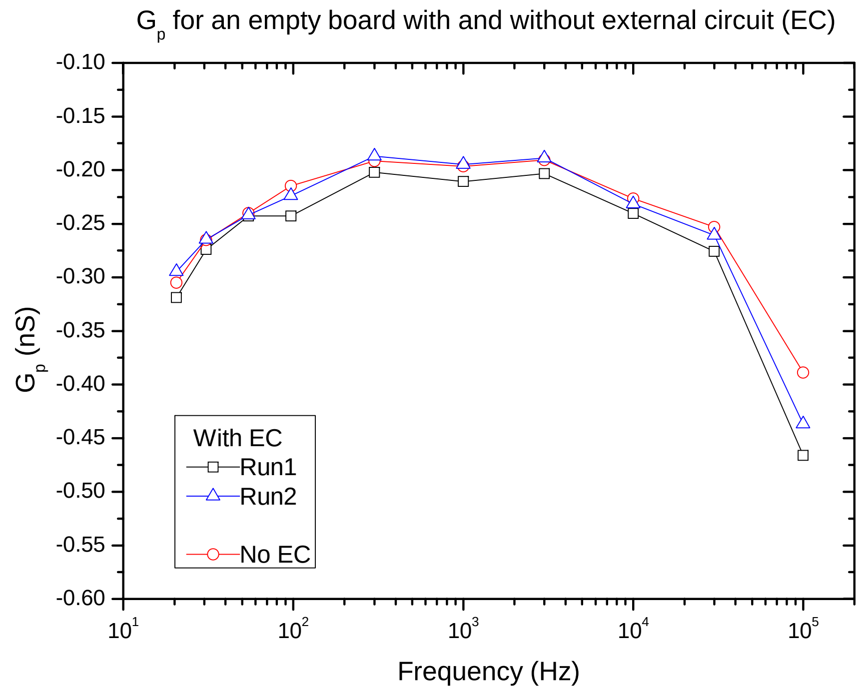
The admittance measured without the DUT consists of the stray impedance (DUT support etc.) and the LCR meter offset values. Due to the mentioned before linearity of the measured admittance vs. the real one $Y_m(Y_a)$ the usual subtraction of Y_{mOC} measured without the DUT (“Open Corrections”) from the total Y_m eliminates simultaneously both the stray impedance and offsets. The linearity is verified in the plots below for typical admittance values.



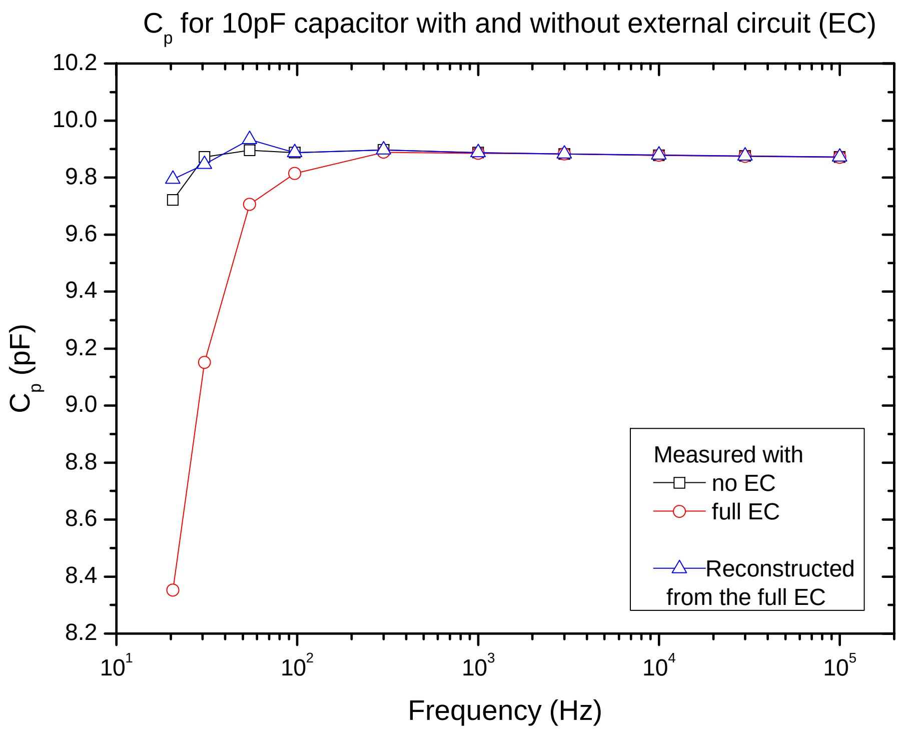


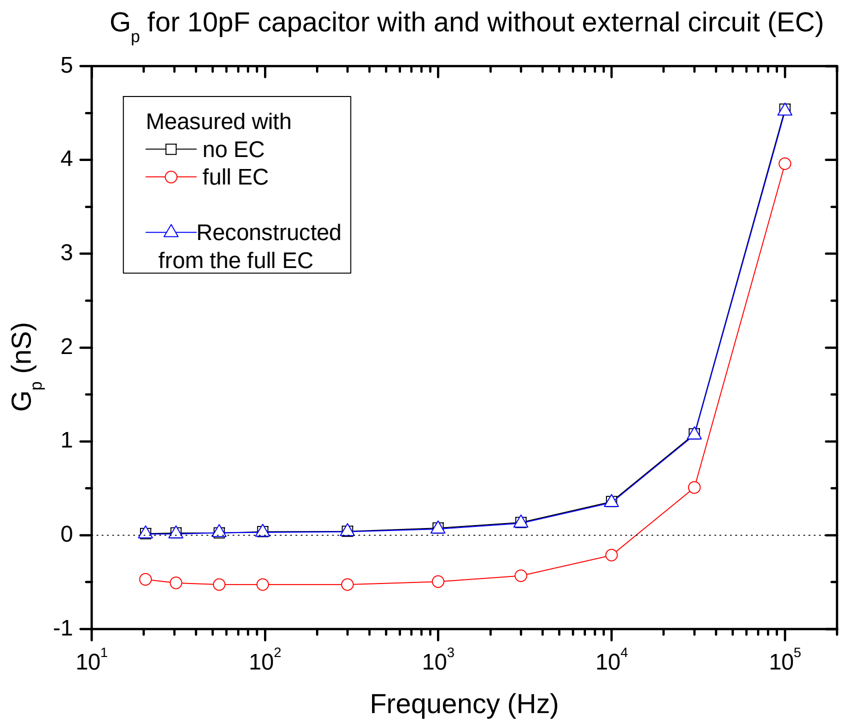
4. Experimental results



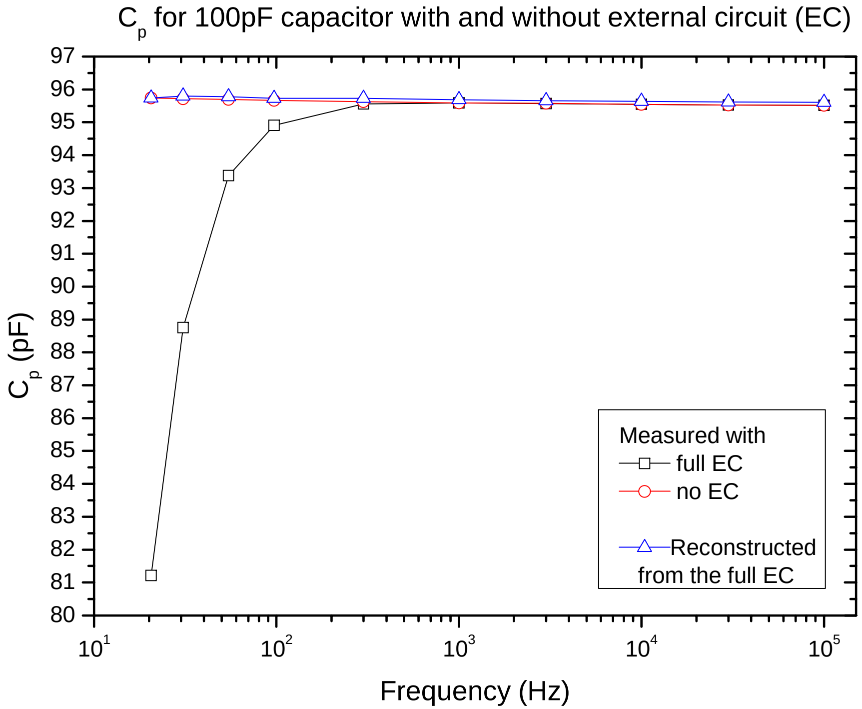


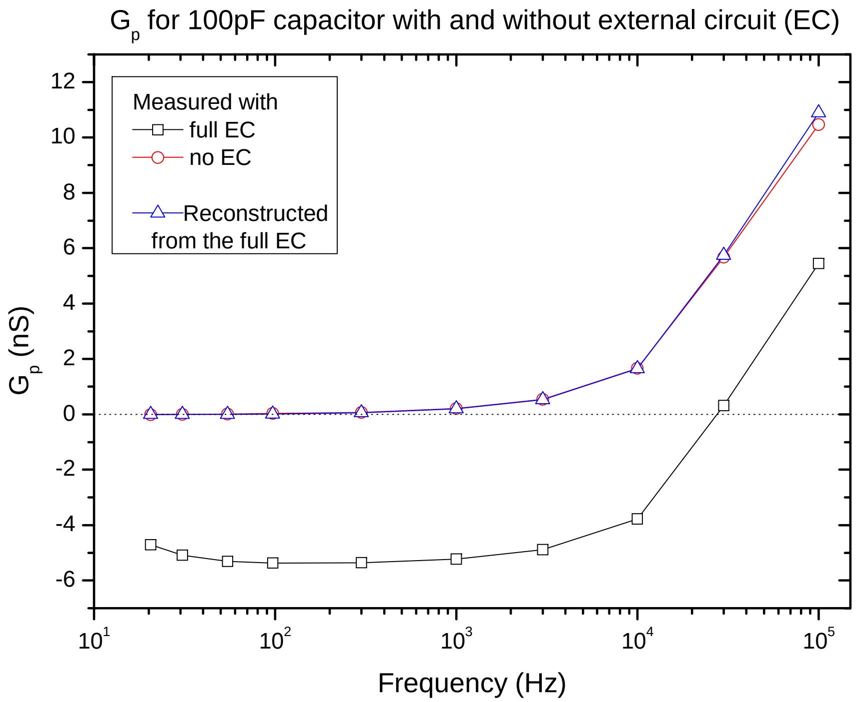
C_p and G_p measured for an empty support board with the full DC bias circuit (two independent runs) and with disconnected resistors. The similarity between the latter and the former shows that the results are dominated by the LCR meter offsets. Note the very fine *y*-scale in both plots.



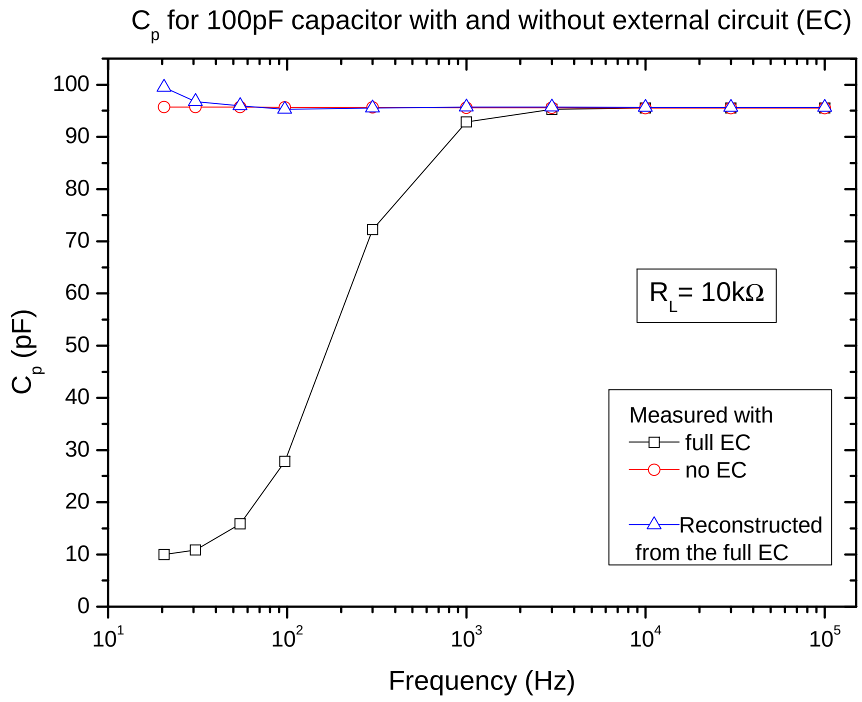


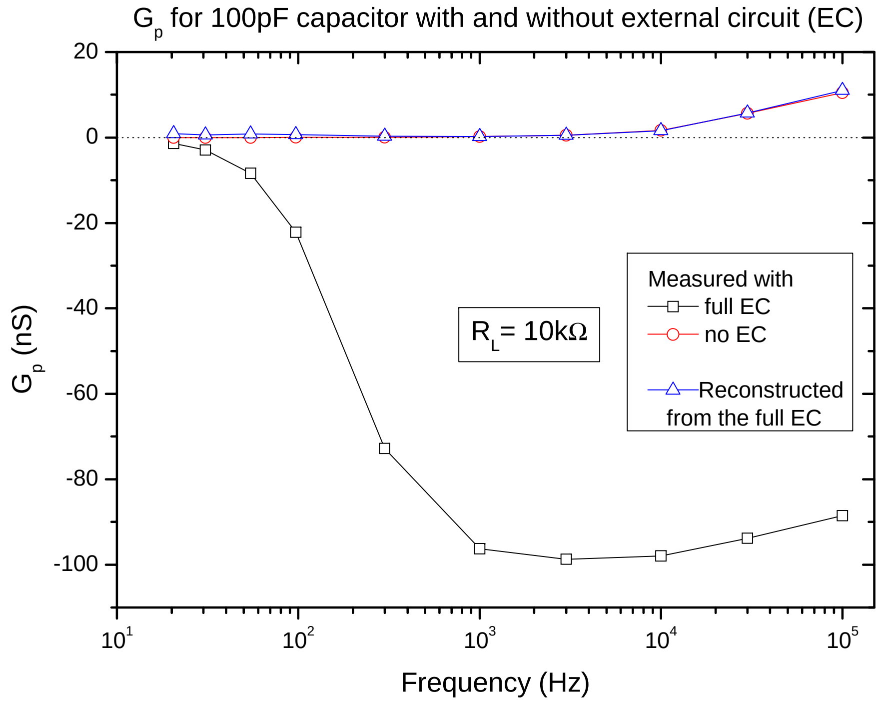
C_p and G_p measured for a 10 pF test capacitor with the full DC bias circuit and with disconnected resistors. The latter gives the actual admittance which is successfully reconstructed from the measured values. Note the conductance increase at high frequency due to the AC losses in the capacitor.



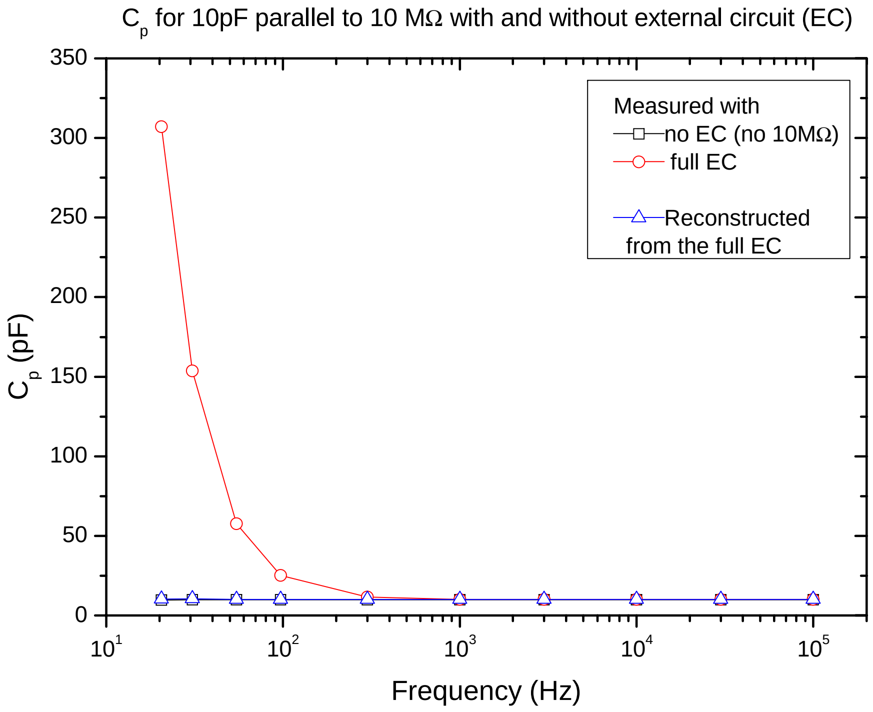


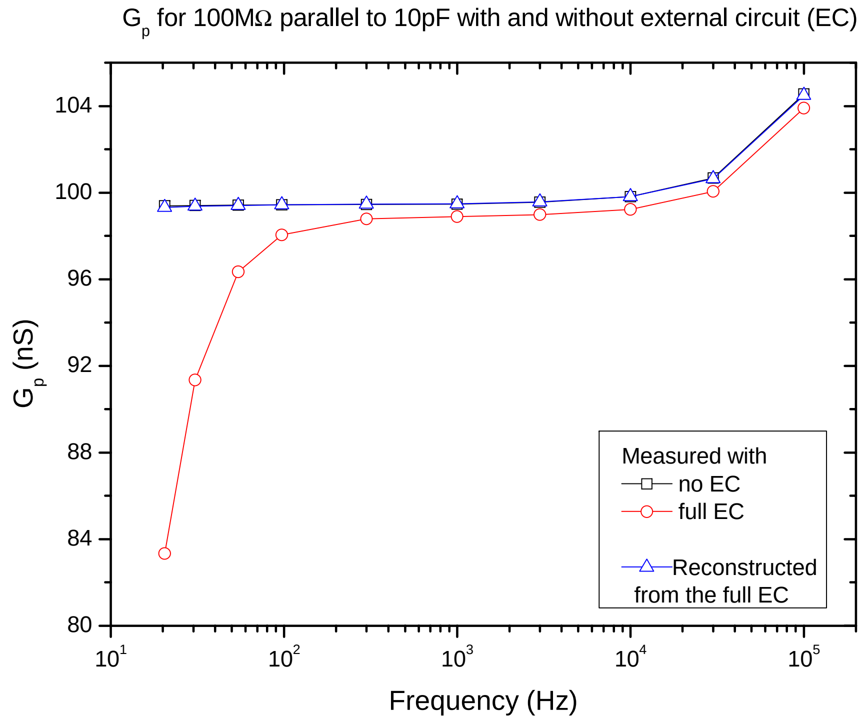
Very similar results were obtained for a 100 pF test capacitor. Note the large shifts in measured parameters successfully eliminated by the reconstruction procedure.





The same 100 pF test capacitor measured with R_L=10 kΩ. The shifts in measured parameters are very large and the reconstruction is less accurate especially at lowest frequencies.





The same 10 pF test capacitor as above in parallel with a 10 MΩ resistor. Note very large deviations in the measured C_p from the actual 10 pF. The reconstruction works reasonably well for both C_p and G_p.

5. Conclusions

1. When biasing of the tested device (DUT) during CV measurement is provided by an external DC circuit and the capacitors are used to decouple the input of the LCR meter from the DC potential, the measured DUT parameters may differ significantly from their actual values.
2. The effects disappear (apart from the shift in G_{pm}) when ωRC>10 for the minimum RC, but in some situations ωRC>100 may be needed.
3. The actual DUT parameters can be reconstructed from the measured values. However for large corrections the reconstruction accuracy may deteriorate due to insufficient precision of the circuit description.

Conclusions (continued)

4. Tests with several known typical impedances (with and without the external circuit) in the whole range of the frequencies planned to be used are strongly recommended during commissioning of the CV set-up.
5. It is better to make “Open Corrections” off-line than to subtract them at the hardware level. In this way one can see explicitly what the corrections are and how reproducible are they.
6. In all our results the frequency of 10 kHz is high enough to eliminate DC bias circuit effects for capacitance.