Detection of mechanical resonances of doubly-clamped carbon nanotubes by FM techniques

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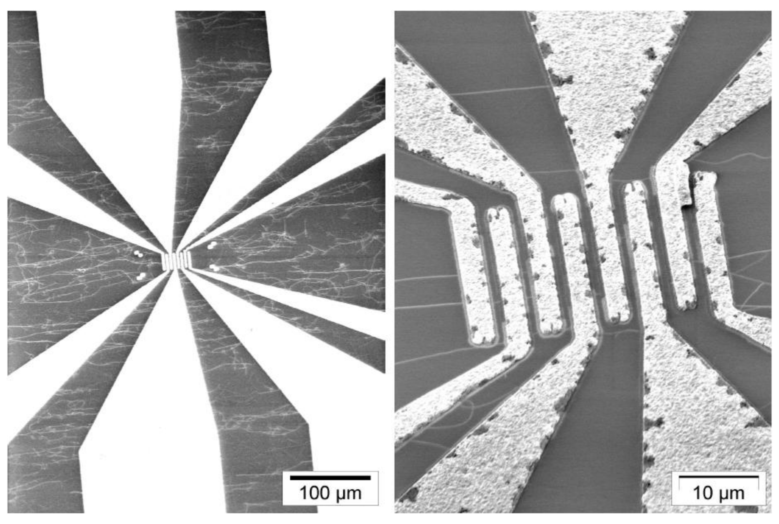
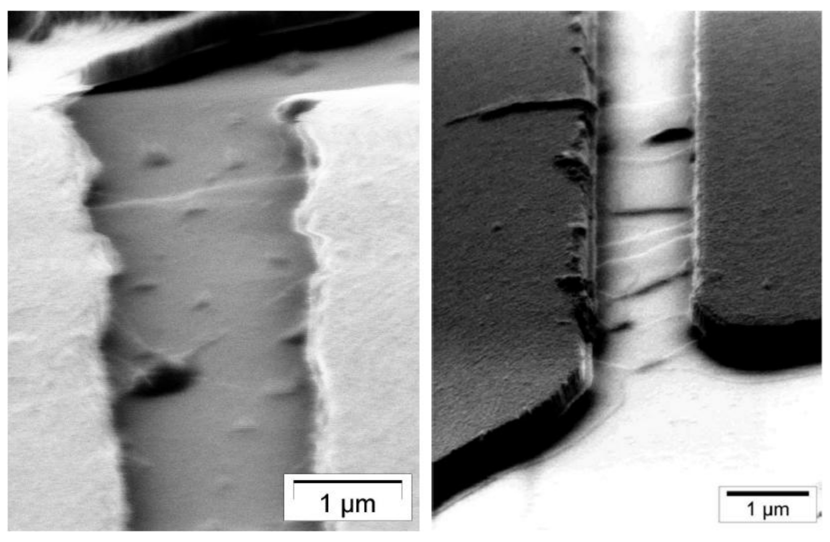
• Detection of the movement of SWNT resonators is an experimental challenge because of their extremely small dimensions.
• Frequency modulated (FM) excitation is shown here to be an efficient technique to detect and measure their mechanical responses.

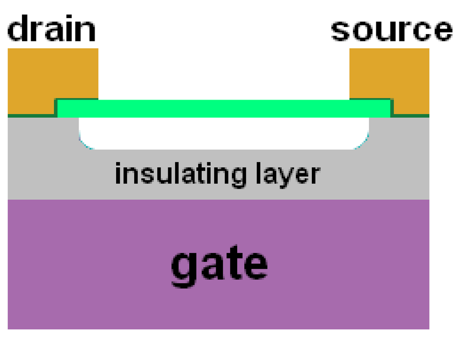
1 Samples : suspended single wall carbon nanotubes



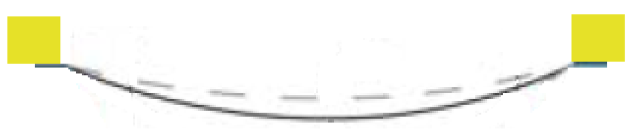
• Gold electrodes on a thin insulating layer
• Underlying substrate used as gate

• Single wall nanotube (SWNT) suspended between two electrodes (~1µm)



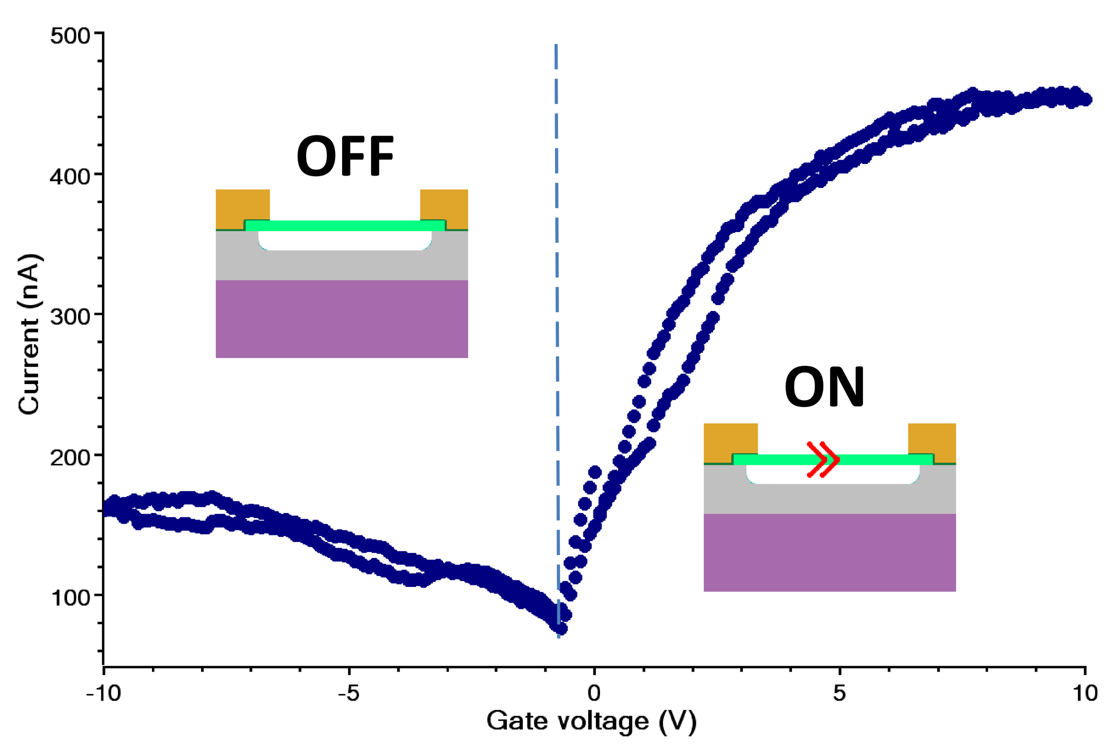


• SWNT as a vibrating string :



• Which excitation signal ?
• How to detect the movement ?

2 Electrical characterization : Field Effect Transistor (FET)



• The suspended semi-conducting nanotube acts as a field effect transistor controlled by the gate voltage.

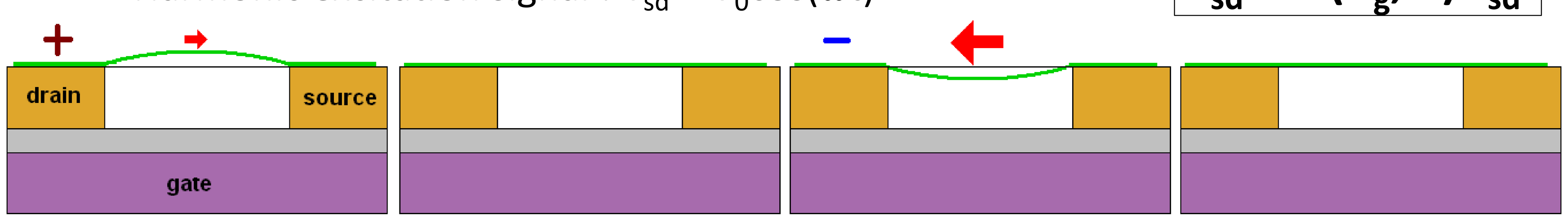
• In a phenomenological approach, one can write the conductivity of the nanotube as a function of the gate voltage :

$$I_{sd} = G(V_g)V_{sd}$$

3 Deformable FET : small offset current for a vibrating nanotube

Harmonic excitation signal : $V_{sd} = V_0\cos(\omega t)$

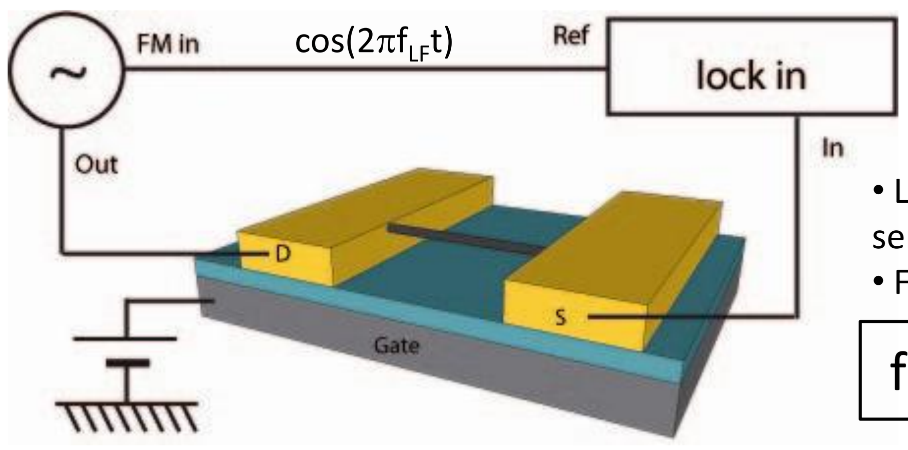
$$I_{sd} = G(V_g, x)V_{sd}$$



• Periodic voltage at the drain excites the oscillation of the suspended nanotube first mode ($f \sim f_0$).
• **Small DC current proportional to the oscillation amplitude.**
• **Only the mechanical oscillation in phase** with the applied voltage gives a **DC current component**.

4 FM excitation : modulation of the offset current

❖ Measurement setup :

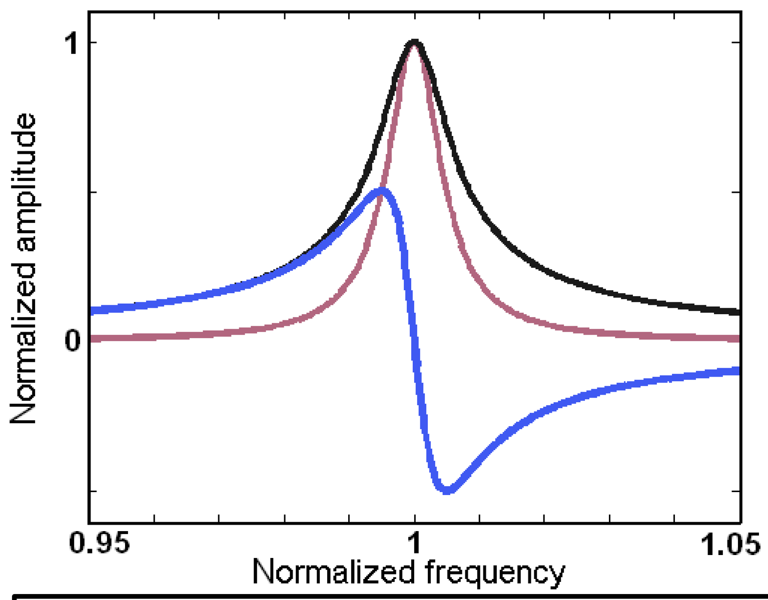


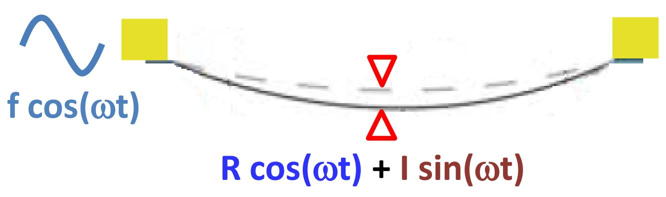
• Low frequency modulation (Ref) signal sent to the FM generator
• FM excitation at drain electrode (D)

$$f_{FM}(t) = f_c + f_{dev}\cos(2\pi f_{LF} t)$$

• Demodulated current at low frequency sent back to the Lock-in (In)

❖ Mechanical response of damped oscillator : in-phase response

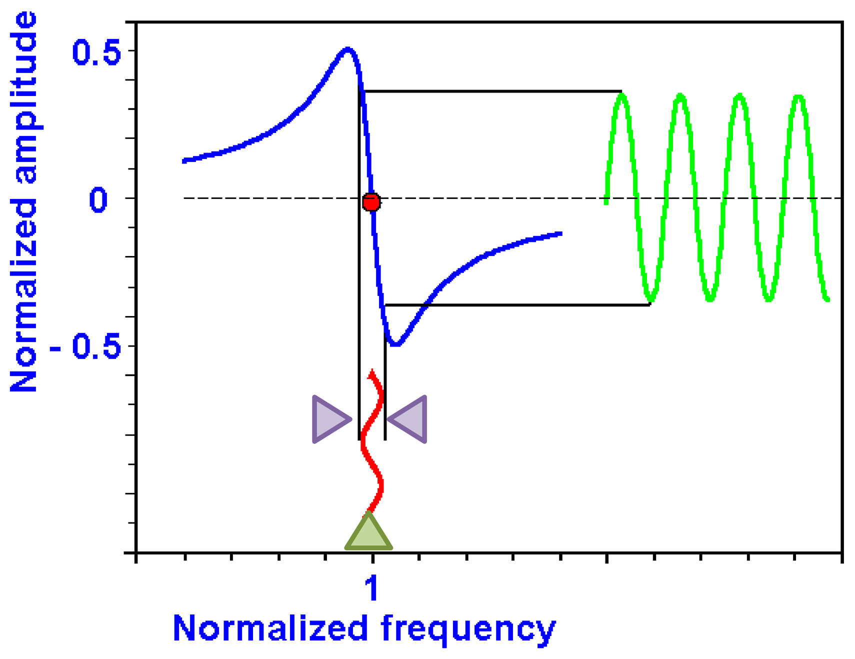




• Oscillation amplitude (total response)
• Out-of-phase amplitude (Imaginary part)
• In-phase amplitude (Real part)

Relevant mechanical response IS NOT the classical lorentzian amplitude ⇨ in-phase response

❖ Frequency modulation and in-phase mechanical response



• FM - AM conversion (frequency discriminator)
• Amplitude modulation proportional to the first derivative of the response function
• 2 parameters :
- Carrier frequency
- Frequency deviation

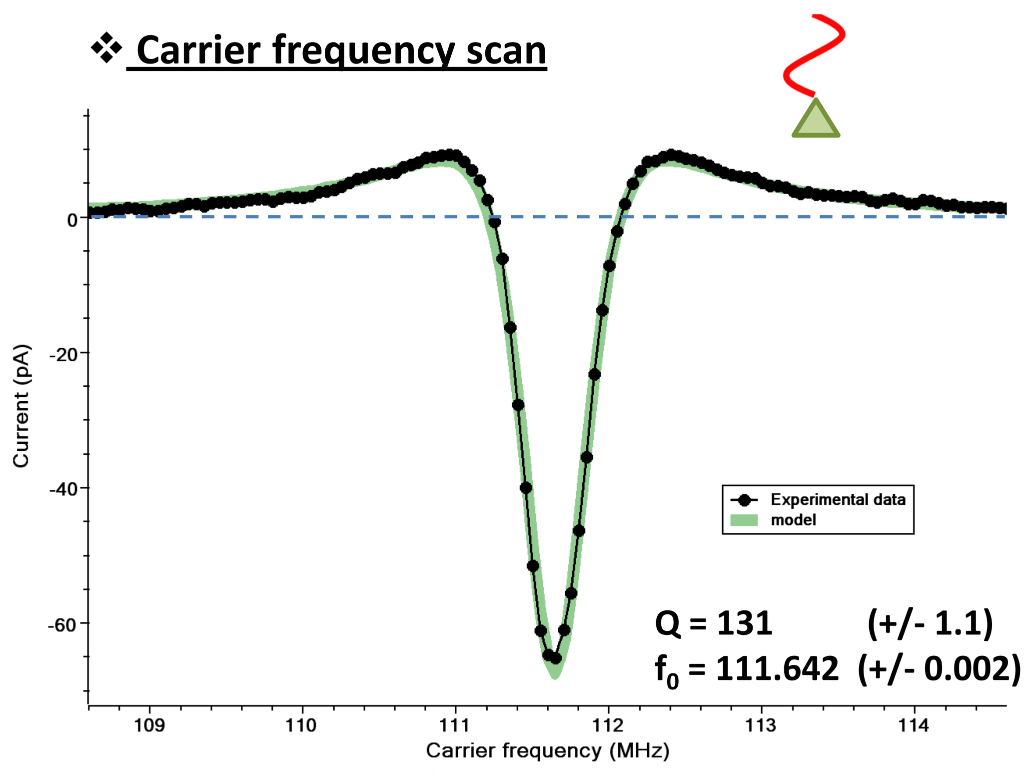
5

Frequency modulation around the mechanical resonance ⇨ Modulation of the amplitude of the mechanical oscillation ⇨ Modulation of the offset current

Mechanical response of the suspended SWNT — Deformable Field-Effect Transistor

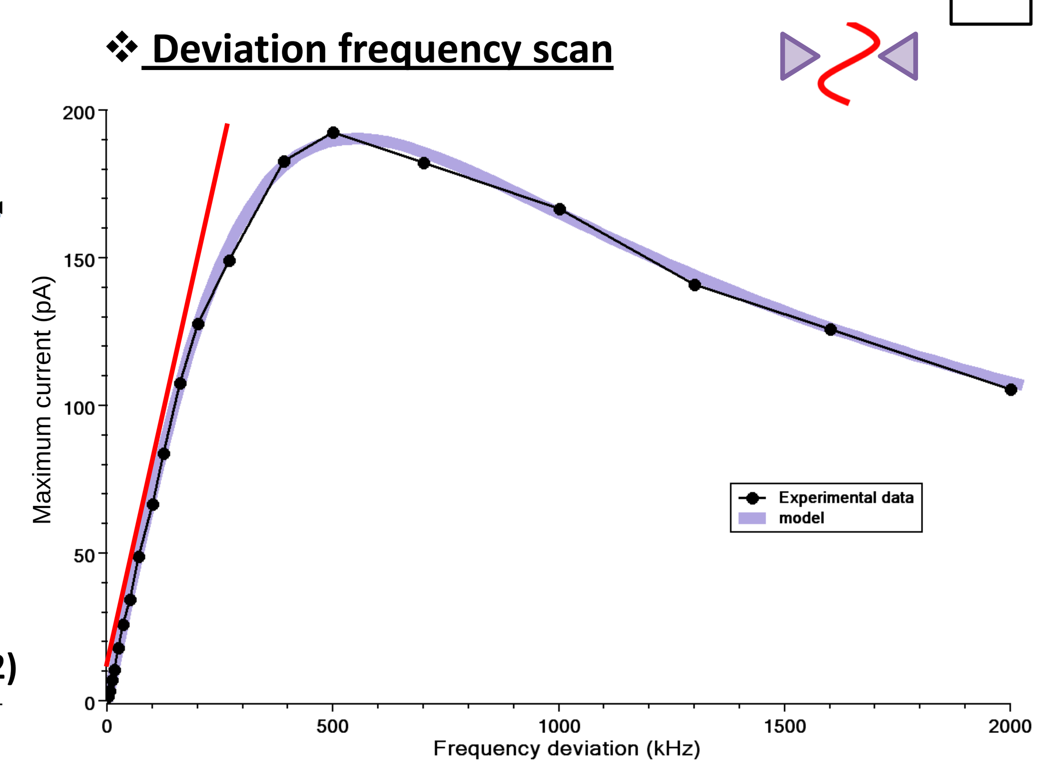
6 Experimental results :

❖ Carrier frequency scan



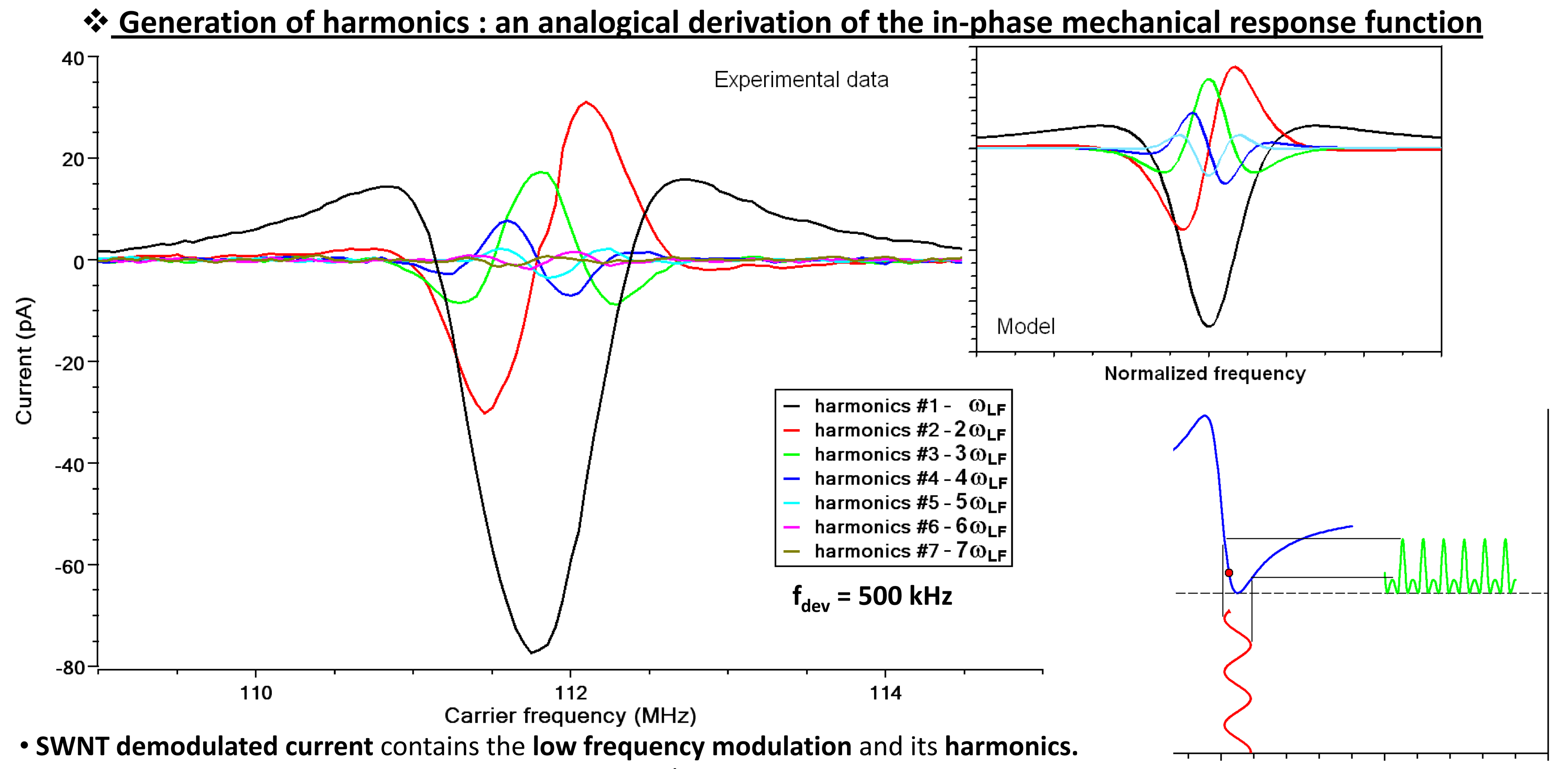
• Not the classical lorentzian resonance curve
• Good agreement with our model (3 fit parameters)
• Resolution in frequency much higher than the quality factor
• **No out-of-resonance demodulation** selectivity

❖ Deviation frequency scan



• Expected behavior given by our model
• Range of linear response f_{dev} = 0 – 150 kHz

❖ Generation of harmonics : an analogical derivation of the in-phase mechanical response function



• **SWNT demodulated current** contains the **low frequency modulation** and its **harmonics.**
• Large frequency deviation : measurement up to the **9th harmonics of the low frequency modulation signal.**
• **nth harmonic of the low frequency signal** matches with the **nth derivative of the in-phase mechanical response** of the SWNT.

Conclusion
- FM excitation is a **selective method** to detect the **mechanical resonance of suspended SWNT.**
- Suspended SWNT acts as an **FM demodulator** where **mechanical properties** play a central role.
- Our **model** fits the experimental data giving access to **resonant frequency and quality factor** of the resonator.
- **Generation of harmonics** interpreted as derivatives of in-phase **mechanical response function**.

Gouttenoire *et al.* to be published