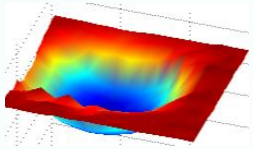
AUTOMATIC OPTIMAL COMMAND FOR THE LINEARIZATION OF THE CMUT OUTPUT

S. Ménigot [1], D. Certon[2], D. Gross[2] and JM Girault[1]

[1] Université François Rabelais de Tours, INSERM U930, 10 Bd Tonnellé, 37032 Tours, France

[2] Université François Rabelais de Tours, GREMAN UMR-CNRS 7347, 10 Bd Tonnellé, 37032 Tours, France



Motivation

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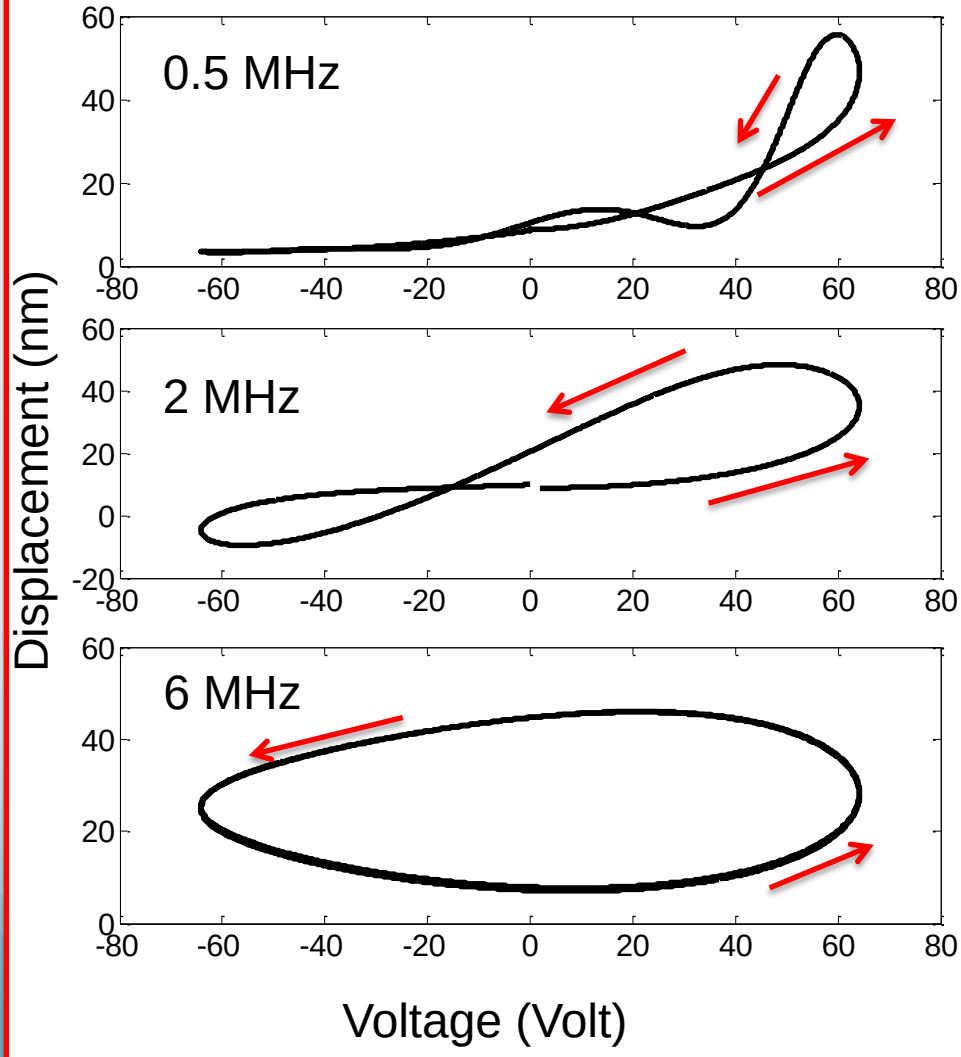
Membrane displacement vs input voltage

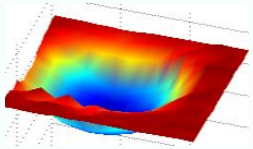


- ✓ cMUTs are nonlinear devices : distortion and asymmetry,…
- ✓ Output waveform depends on the input waveform: frequency, amplitude, shape, …
- ✓ Considerable mean displacement amplitude in a large frequency range

Simulated configuration

2D periodic array with a pitch of 25 µm

Cells	:	$20 \times 20\ \mu m^2$
Gap	:	200 nm
Vc	:	120 V
F0	:	6 MHz
Excitation	:	CW
Amplitude	:	$0.5\ V_c$



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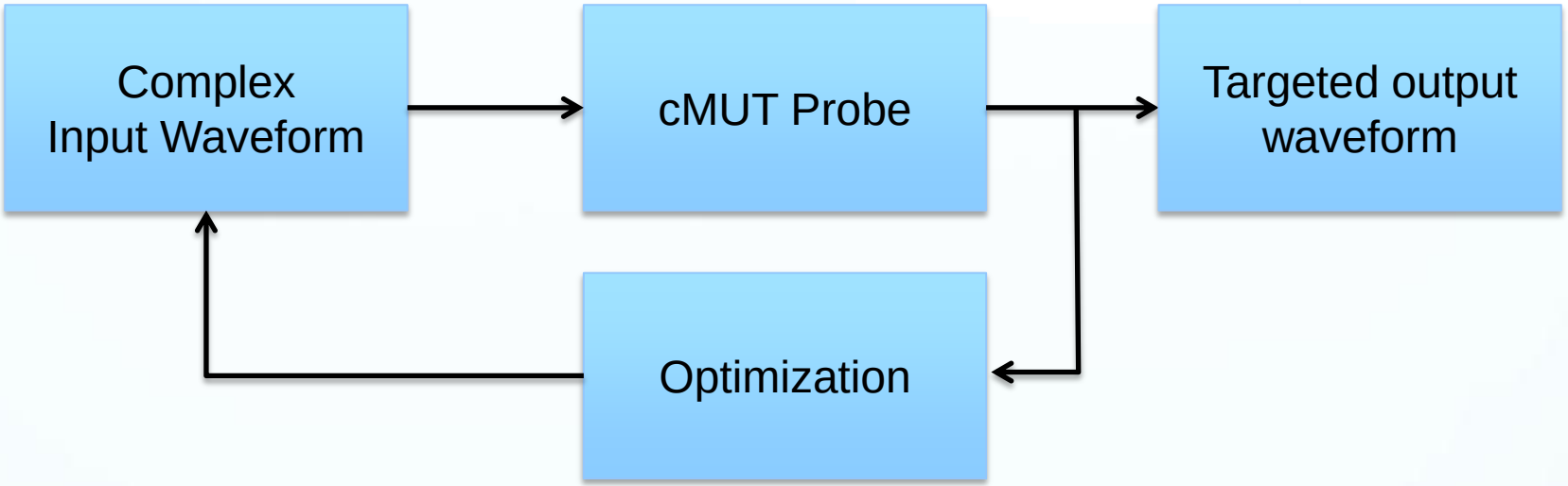
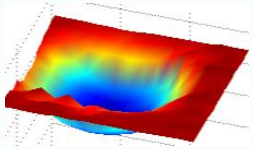
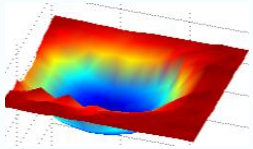


- **<u>The challenge</u>** : to take advantage of the wide cMUT bandwidth and to control the output waveforms , **input waveforms with complex shape are required**
- **<u>Objectives</u>** : development of an automatic procedure to generate the optimal desired output waveform. This implies :
  - Methods for producing new non-standard input waveforms,
  - Implementation of an iterative optimization procedure in order to match the output waveform with the targeted output waveform

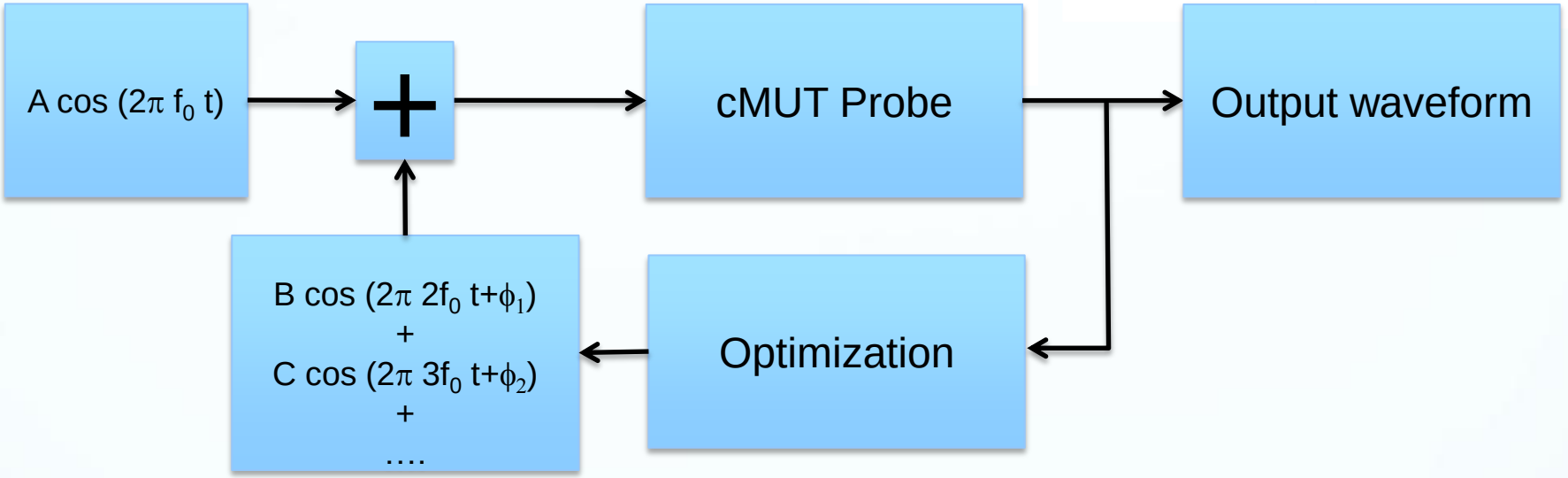


OUTLINE

- Motivation
- Previous literature
- Complex waveform generation with non linear filtering
- Iterative optimization procedure
- Theoretical results : application to the linearization
- Experimental results : application to the linearization
- Summary & conclusions

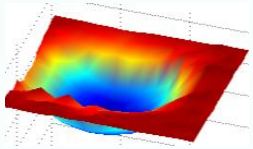


Previous literature



- **Previous works :** Optimal command of cMUT to linearize the output waveform
- High order harmonic components are added to the input sinus waveform
- **Amplitude and phase are tuned in order to cancel out the 2nd harmonic component of the output waveform**
- **Limitations :**
  - **Mainly done** in low frequency bandwidth : application to harmonic imaging
  - **Minimization** error criterion is defined by the harmonic to fundamental components ratio

[1] S. Zhou, P. Reynolds, and J. Hossack, “Precompensated excitatio one parameter : waveforms to suppress harmonic generation in mems electrostatic transducers, ” IEEE T. Ultrason. Ferr. , vol. 51, no. 11, pp. 1564–1574,Nov. 2004.
[2] A. Novell, M. Legros, N. Felix, and A. Bouakaz, “Exploitation of capacitive micromachined transducers for nonlinear ultrasound imaging, ” IEEE T. Ultrason. Ferr. , vol. 56, no. 12, pp. 2733–2743,Dec. 2009.



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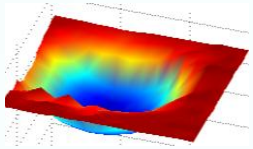
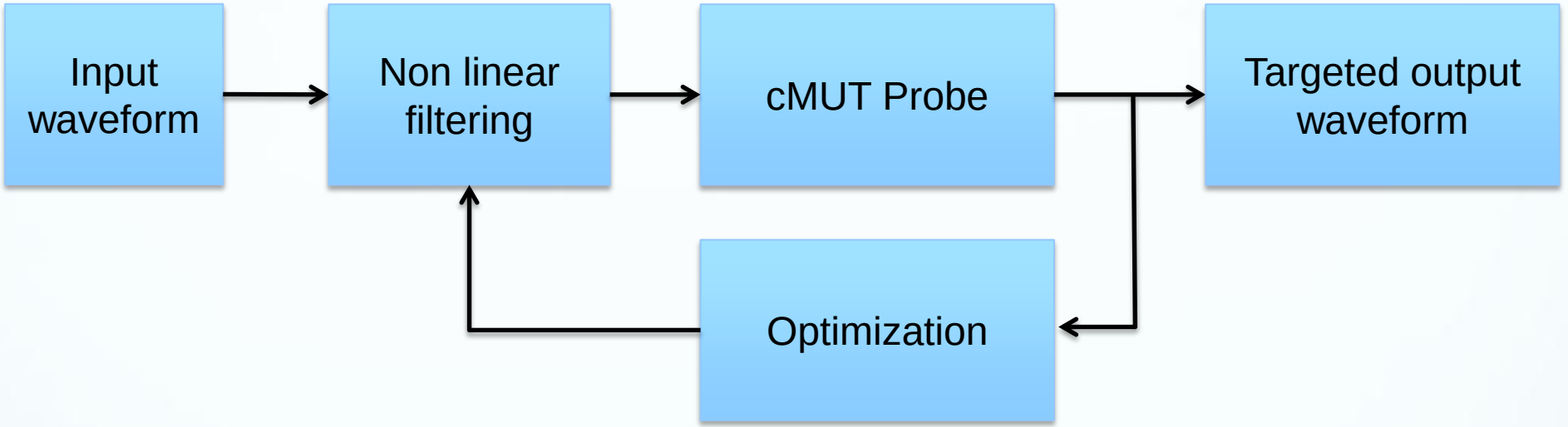
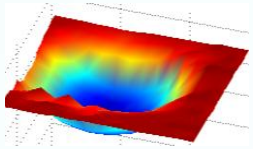


Complex waveform generation



- **Our approach** is an extension of previous works but it is applicable to waveform with any shape
- **a non linear filter** is used to modify the input waveform shape
- **Parameters** of the non linear filter are tuned with a simplex algorithm
- **Non linear filtering** models: Hammerstein, Volterra, Wiener…
- **Applications** : linearisation of loudspeakers, µbubbles driving, all field of physic requiring non linear modelling



Complex waveform generation

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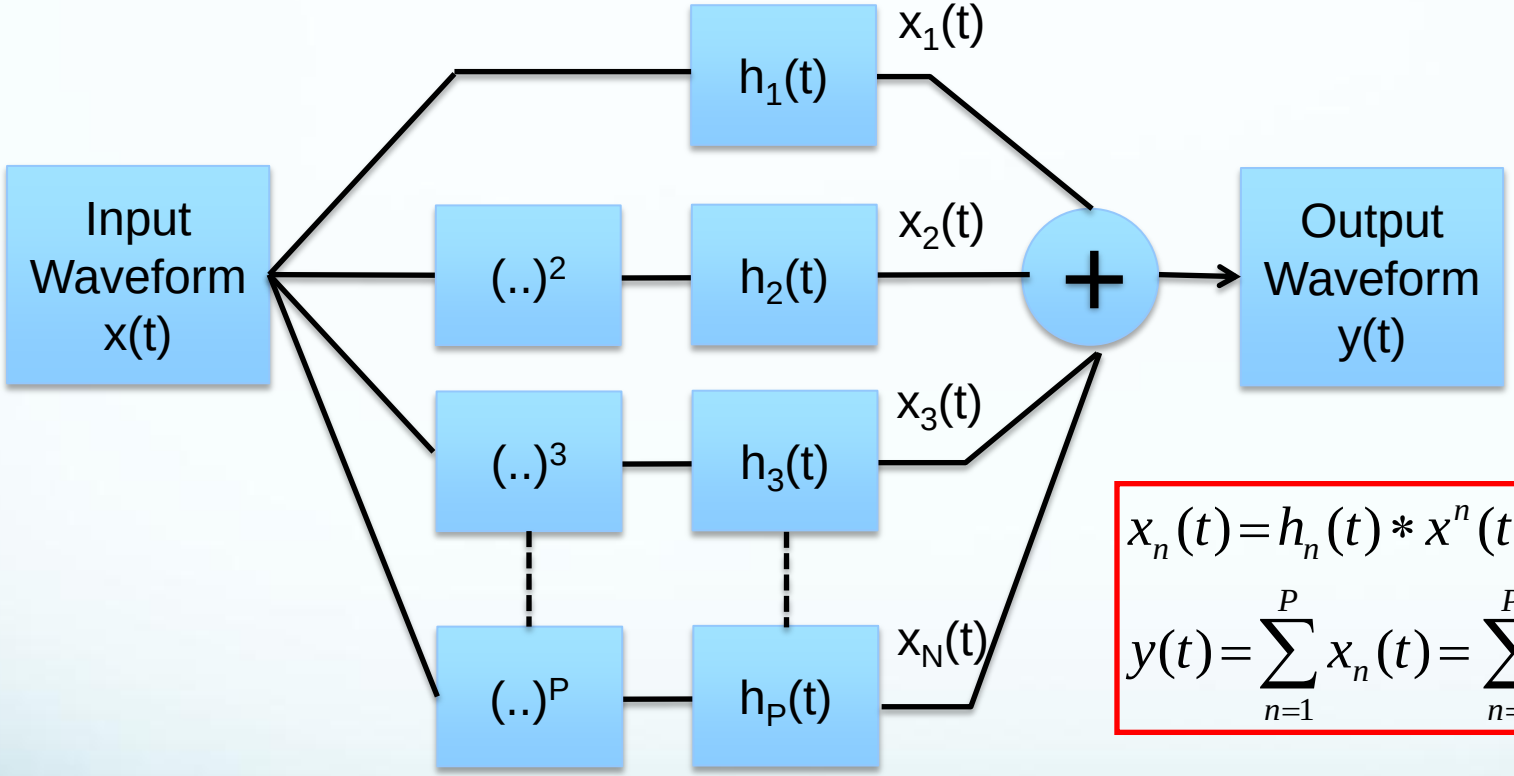
Non Linear Filtering : principle with Hammerstein filter

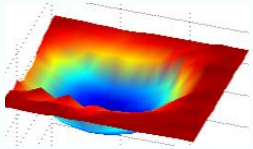


$$x_n(t) = h_n(t) * x^n(t)$$

$$y(t) = \sum_{n=1}^{P} x_n(t) = \sum_{n=1}^{P} h_n(t) * x^n(t)$$

- x(t) is transformed into a polynomial series
- Each ***n*** order component $x_n(t)$ corresponds to the input signal raised to power ***n*** *and* filtered with its own specific linear filter $h_n(t)$
- The polynome order P defines the highest frequency harmonic component (we fix P=3)

Inserm



Complex waveform generation

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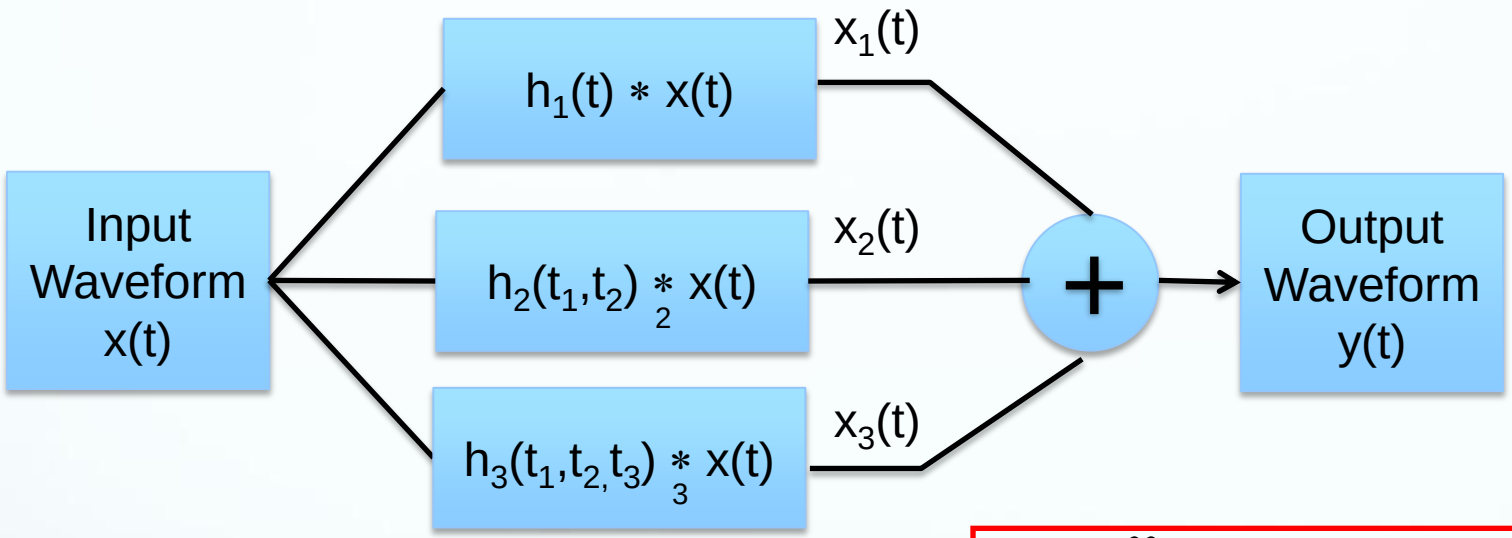
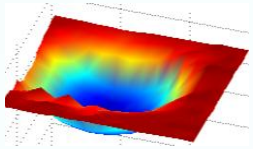
Volterra Filtering : numerical implementation



$$x_2(t) = \iint h_2(\tau_1, \tau_2) x(t-\tau_1) x(t-\tau_2) d\tau_1 d\tau_2$$

- Volterra filtering is preferred : a generalisation of Hammerstein filtering
- Each ***n*** order component is replaced by a ***n-D*** convolution of *x(t)* with $h_n(t)$ filter (dimension ***n) :*** this increases the number of DOF and ensures best convergence



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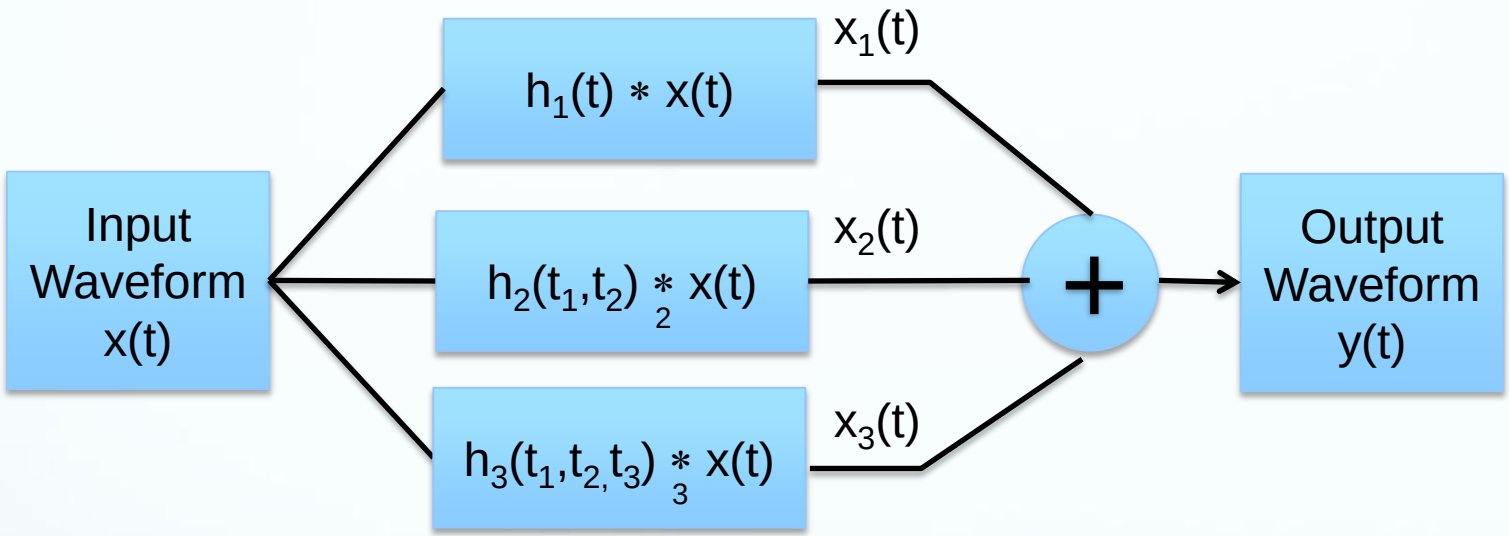
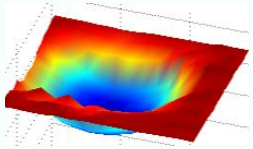


$$y(t)=\sum_{i=1}^{M} h_1(i)\,x(t-i)+\sum_{i=1}^{M}\sum_{j=1}^{M} h_2(i,j)\,x(t-i)x(t-j)+\sum_{i=1}^{M}\sum_{j=1}^{M}\sum_{k=1}^{M} h_3(i,j,k)\,x(t-i)x(t-j)x(t-k)$$

- ***n***-Dimension convolution with ***n***-Dimension $h_n(t)$ filter
- $h_{1,\,2,\,3}(t)$ are three numerical Finite Impulse Response Filters with a memory length of **M=3 : 19 parameters have to be determined**

Inserm



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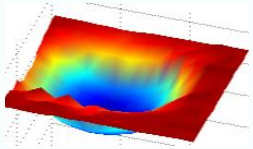

Optimization procedure

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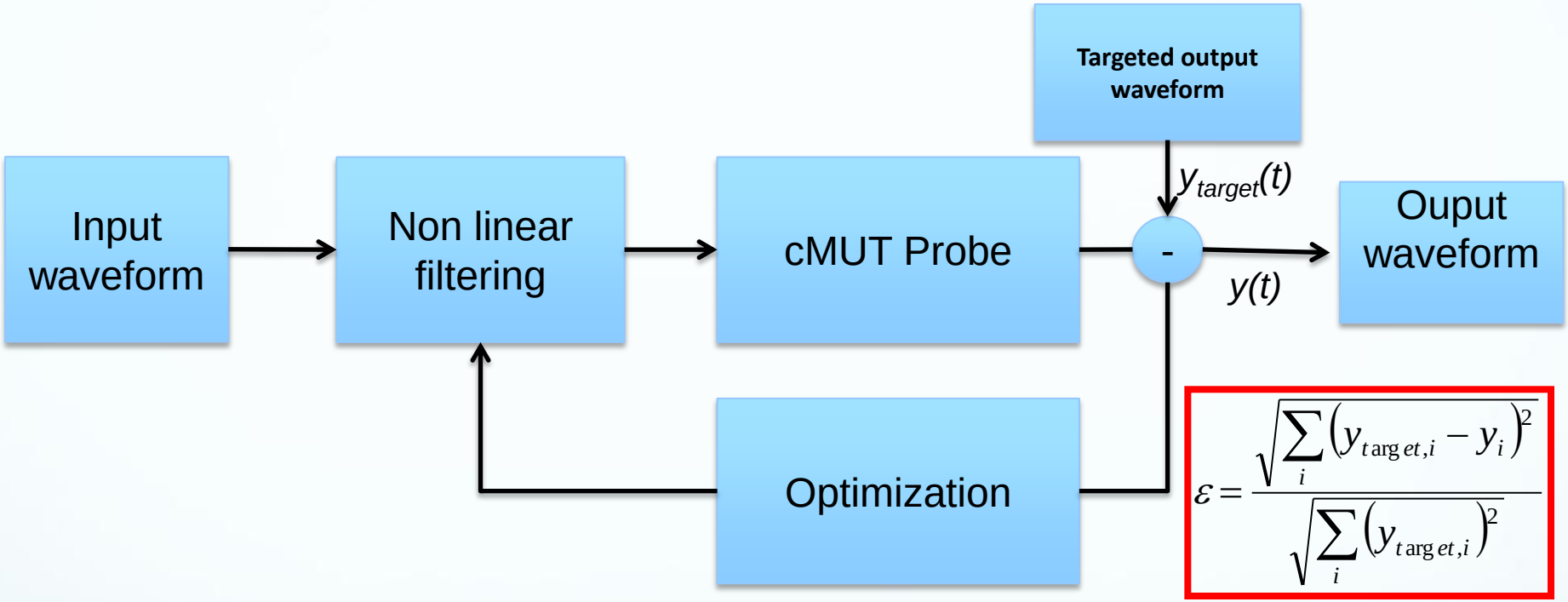
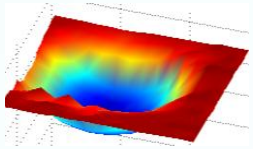


- **Optimization procedure** is done with the simplex algorithm defined by Nelder-Mead
- **Cost function** : the relative error between the targetted signal and the output signal
- The 19 parameters of the non linear filter are set to minimize cost function
- **Initialization of iterative procedure**
  - ✓The input waveform shape is similar to the targetted output waveform shape.
  - ✓ Amplitudes of the input waveform are fixed after a first experiment or with *a-priori* knowledge of the device
  - ✓Filter Parameters ≈ arbitrary very low values , typ. 1%



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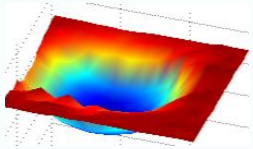
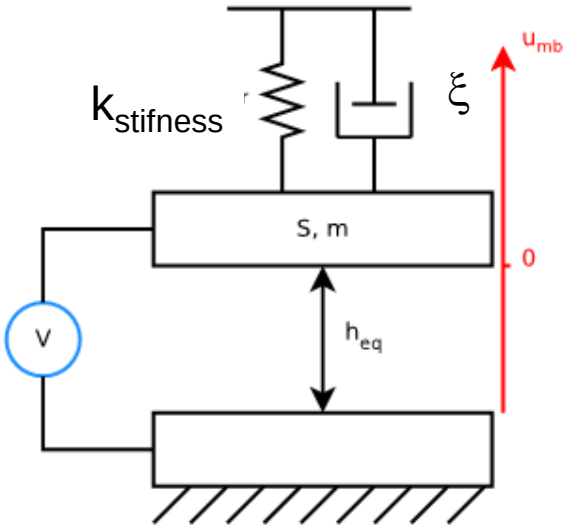


Theoretical results

Model

- Assessment of the procedure performed with theoretical model before experiments
- Simple mass spring-model with losses to

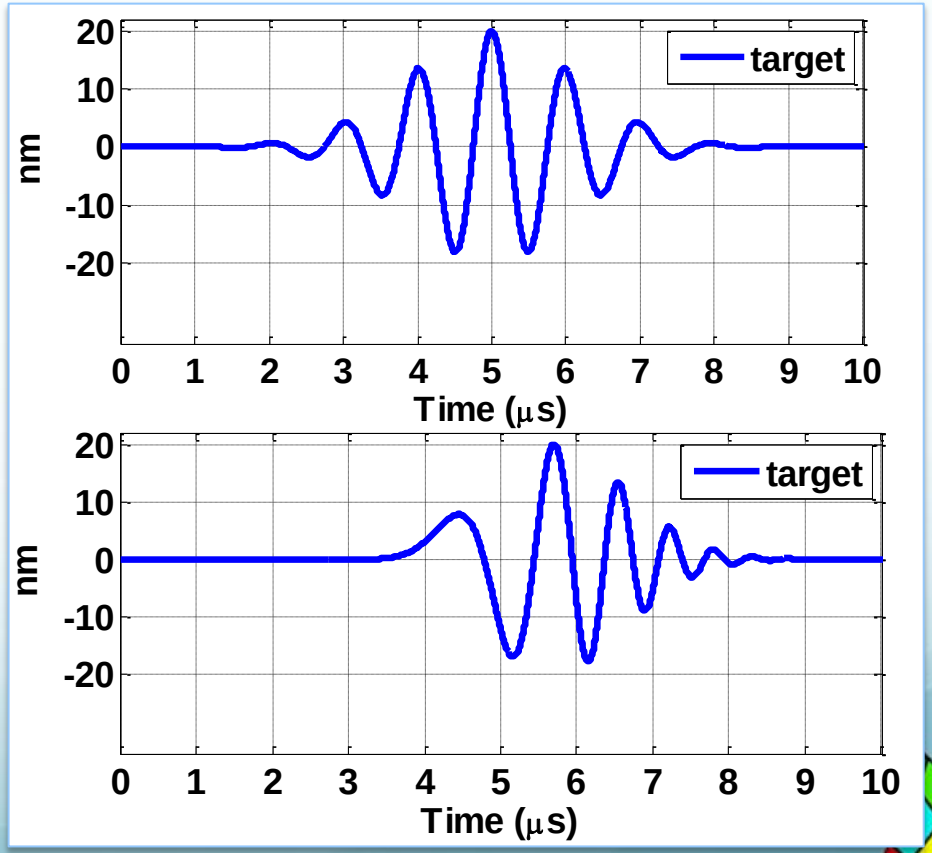


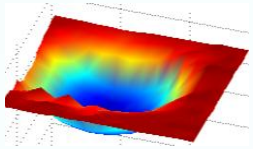
- h_{gap}= 200 nm - Vc = 110 V
- f_0 = 5.5 MHz
- Vbias = 65 V = 0.7 Vc

Note: input voltage >0 : the membrane is stretched
input voltage <0 : the membrane is released

Experiments

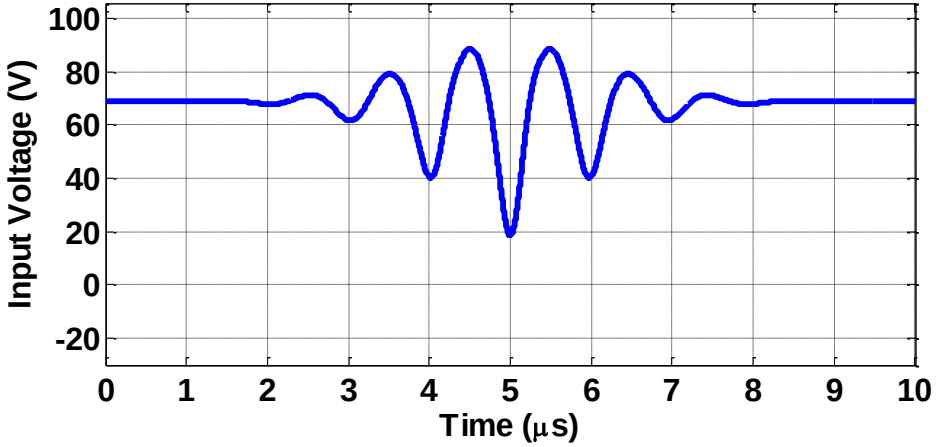
- Output waveform : mechanical displacement
- Two targetted signals
  - a burst with 5 periods at 1 MHz : BW_{-6dB} (%) ≈ 30 %
  - a chirp at 1 MHz : BW_{-6dB} (%) ≈ 100 %

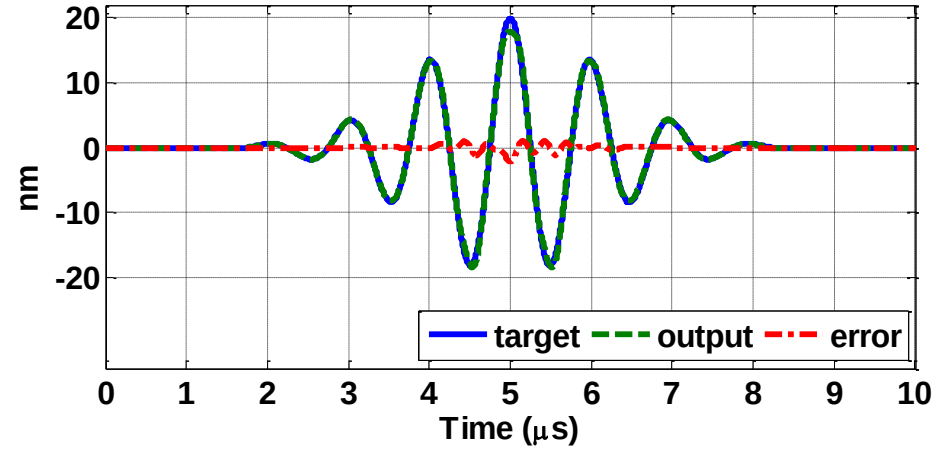




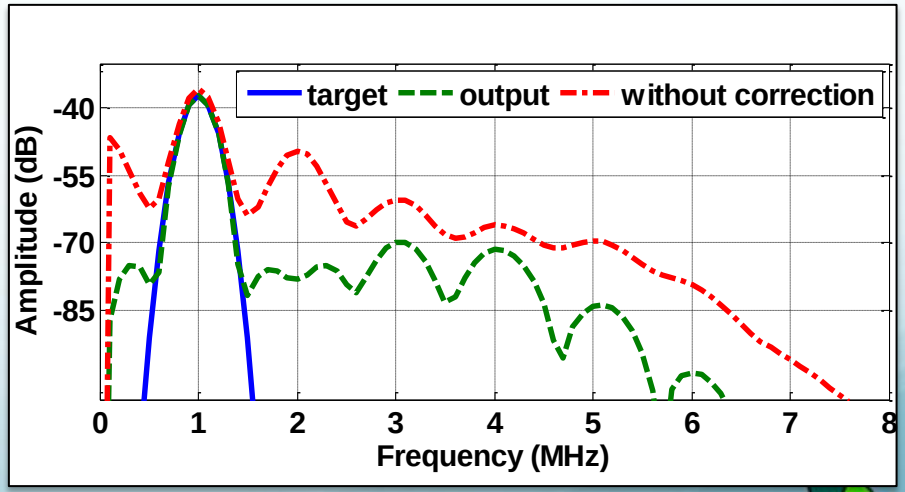
Theoretical results

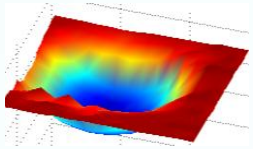
1 MHz toneburst with 5 periods





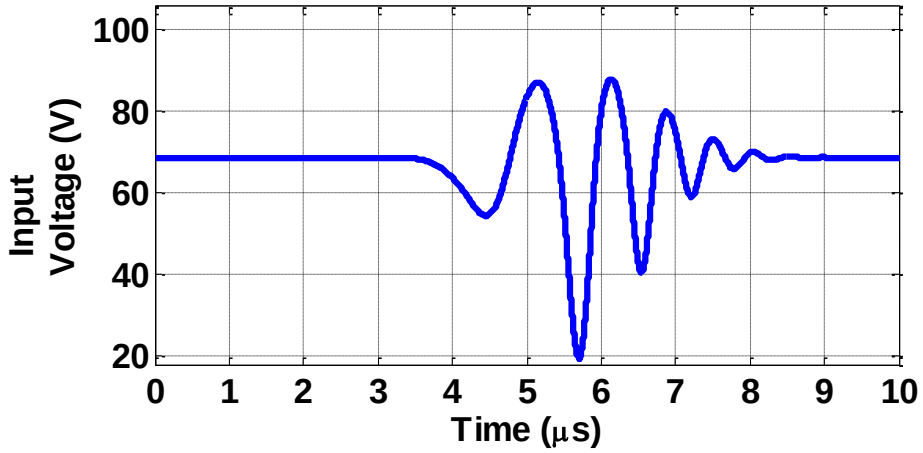
- Final relative error ≈ 0.5 % with 400 iterations
  ≈ 0.1 % with 800 iterations
- The output signal matches very well with the targetted signal (temporal waveform and spectrum)
- The input waveform signal is similar with results published in the previous literature
- Strong dimininution of the 2nd and 3rd harmonic



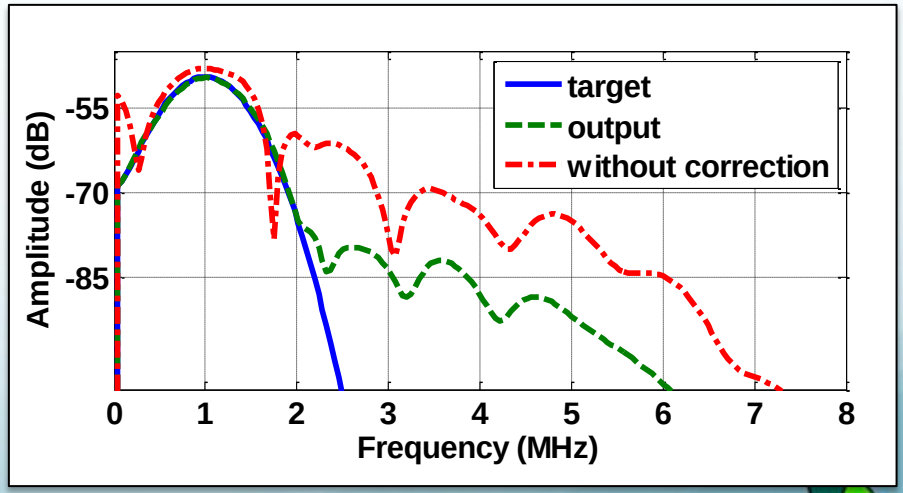


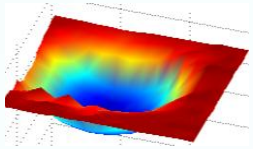
Theoretical results

1 MHz CHIRP signal with 100% BW_{-6dB}



- Basic test signal for coded imaging techniques
- 100 % Bandwidth signal : the output signal matches very well with the targetted signal (temporal waveform and spectrum)
- Final relative error ≈ 0.5 % with 200 iterations
  ≈ 0.1 % with 500 iterations
- **Higher convergence speed** ! The desired signal shows less distortion ?





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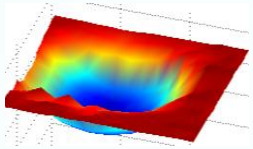

Experimental results

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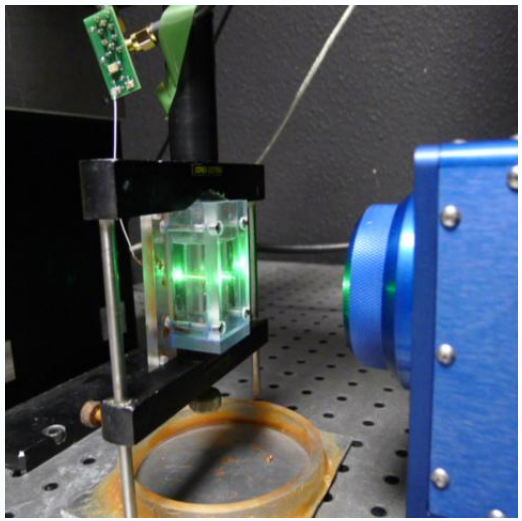
Experiment : displacement measurement

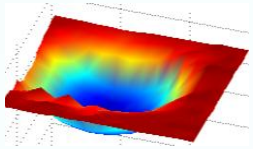


- Array was loaded with water
- 30 µm laser spot size
- **Input signal generation** : arbitrary waveform generator drived with a PC computer
- **RF amplifier** : 150A100B, Amplifier Research
- **Output signal** : mechanical displacement in front of the excited emitter

Device

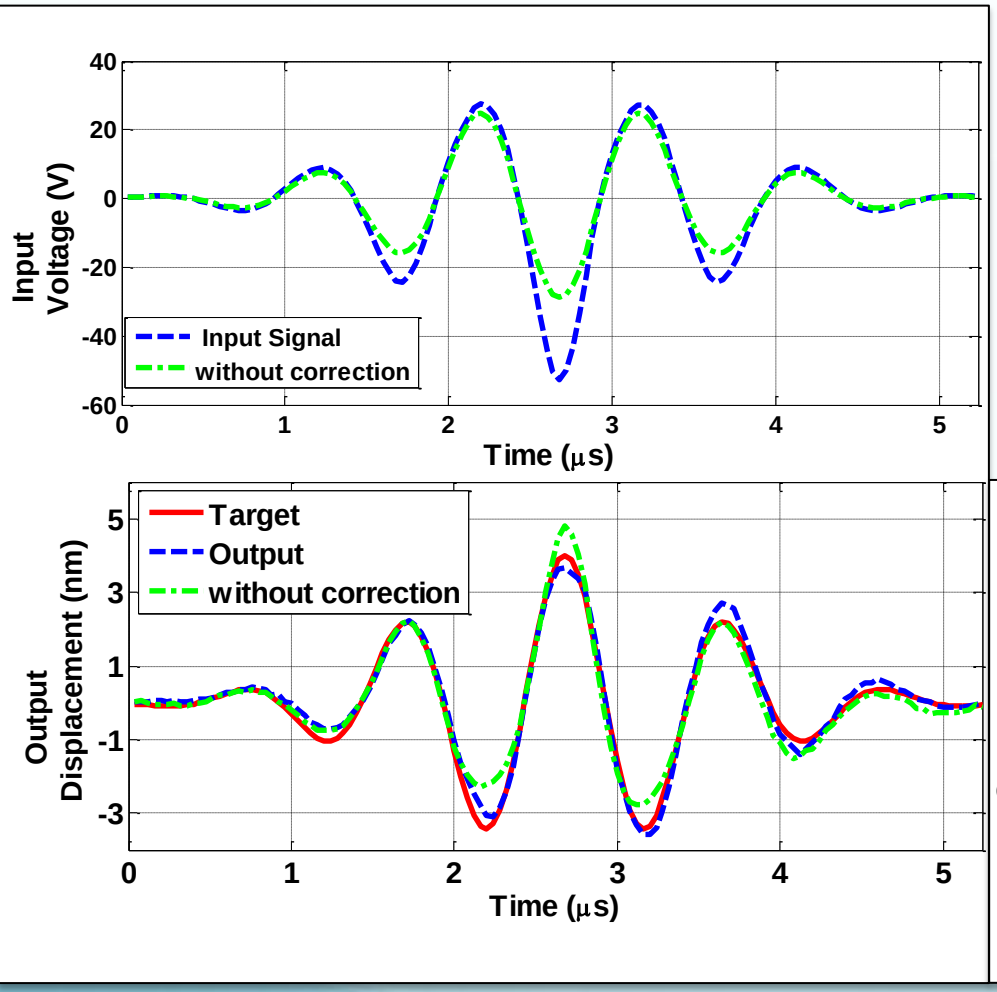
- Surface micromachining process
- 128 elts probe
- Pitch 200 µm
- Cells : $35 \times 35\ \mu m^2$
- H_{gap} : 200 nm
- $V_{collapse}$ = 70 V
- $f_0 \approx 2.8$ MHz
- Array covered with a 500 µm silicone layer
- A mylar film is stuck onto the silicone layer to reflect light beam
- For all experiments : $V_{bias} \approx 70\%$ Vc – **50 V**

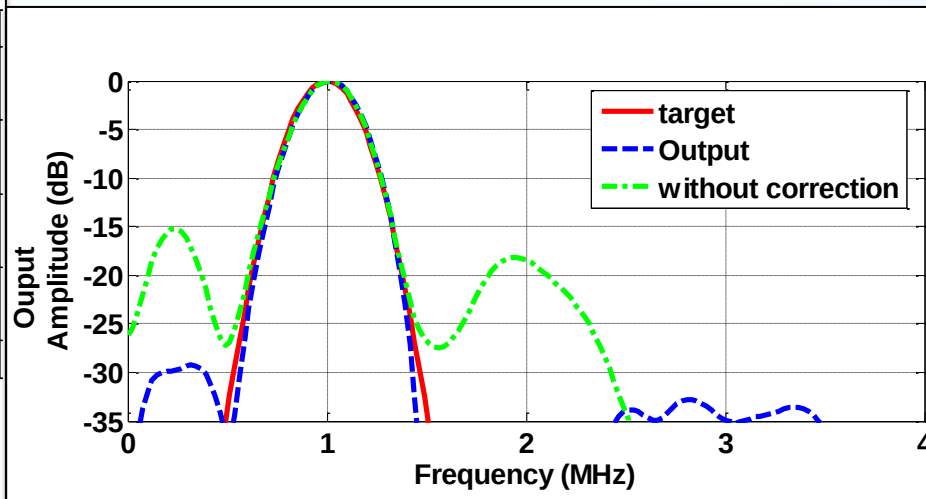
Note: input voltage >0 : the membrane is stretched
input voltage <0 : the membrane is released



Experimental results

1 MHz toneburst with 5 periods



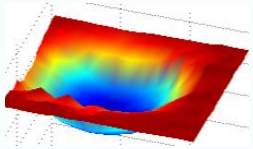


- The output signal matches very well with the targetted signal (temporal waveform and spectrum)

- **2nd harmonic component is « *cancelled out* »** :
  - ✓ without creating 3rd harmonic component - main risk
  - ✓ without reducing the output displacement amplitude

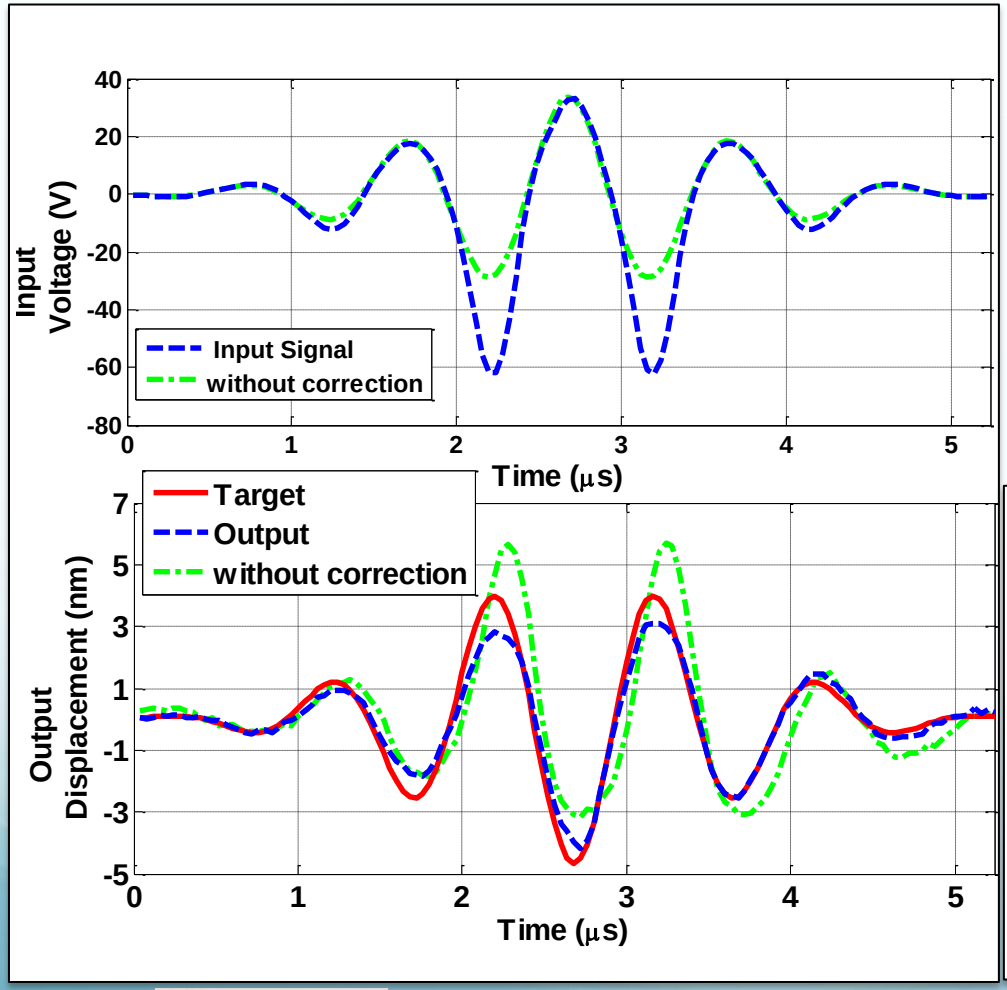
- Final relative error ≈ 3 % with less than 10 iterations : High convergence speed !

- **Optimal input signal** reaches maximum amplitude when membrane is released and not streched -> there is less distortion



Experimental results

1 MHz toneburst with 5 periods : impact of the phase inversion



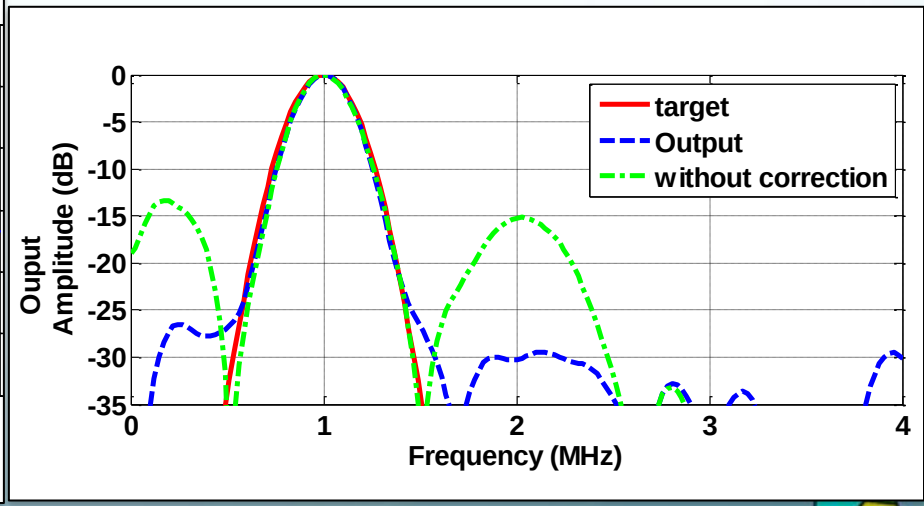
•A basic technique to increase contrast in ultrasonic imaging

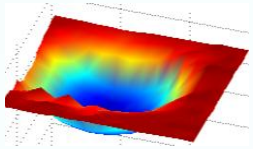
• **the 180° output signal is not the inversion of the 0° phase signal** : when the input signal reaches the maximum voltage the membrane is stretched and not released

• **2nd harmonic level :** +5 dB - a reduction of 15 dB for a loss of 1 nm on the displacement (not significant)

• Output signal matches with the target signal : relative error of 5 % (10 iterations).

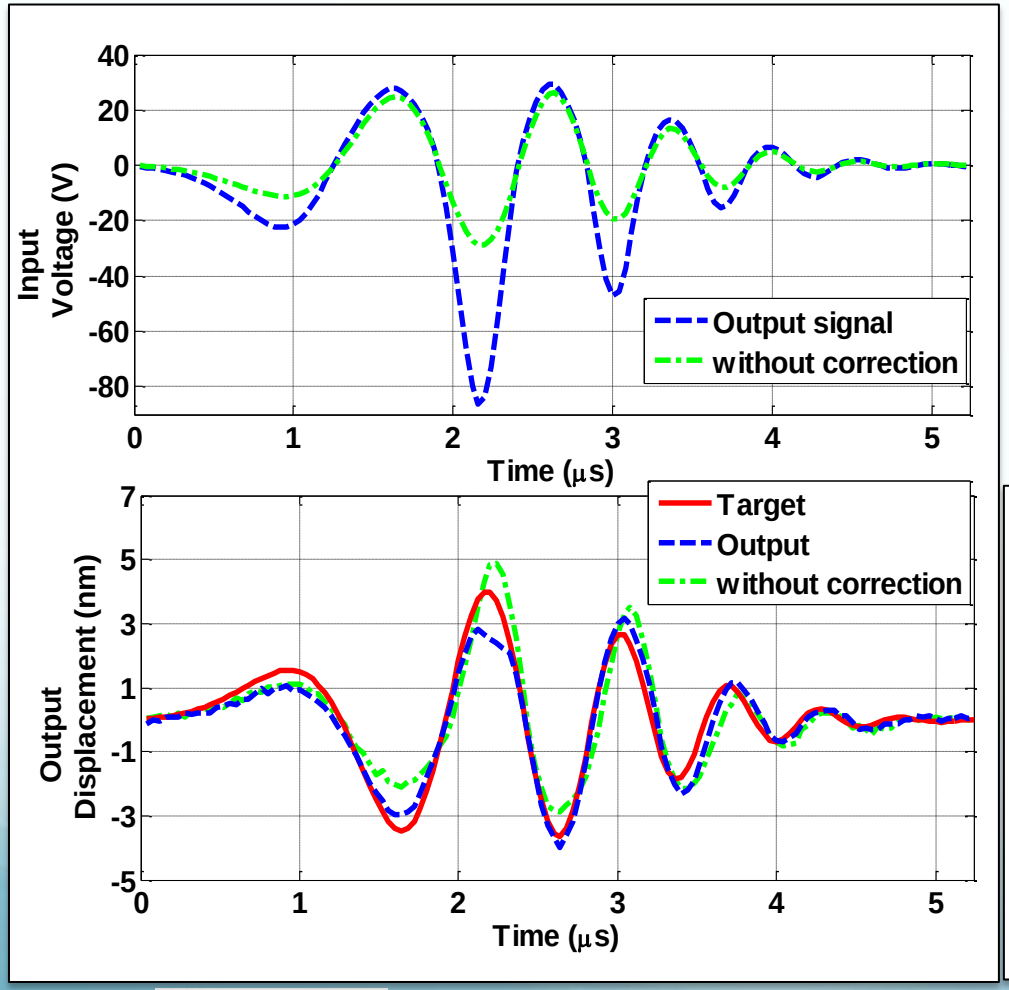
• Note the shape of the optimal solution



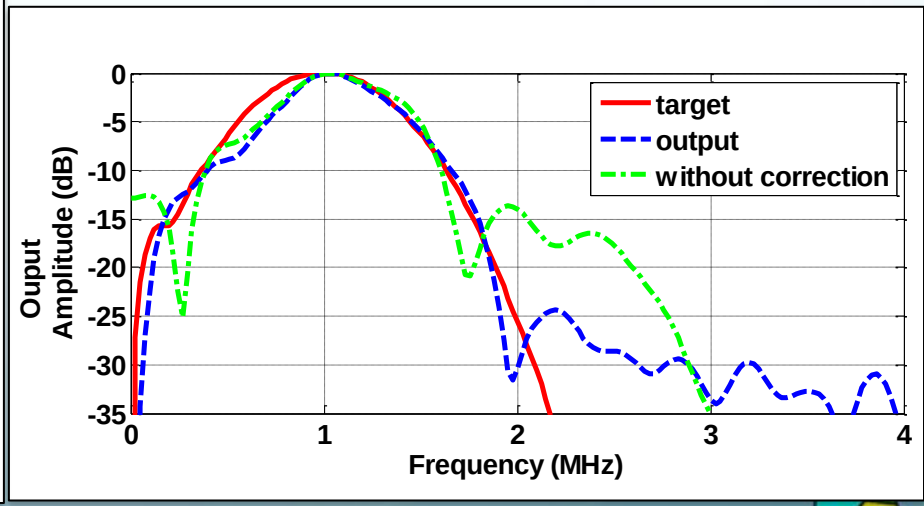


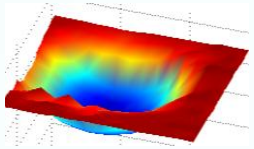
Experimental results

1 MHz CHIRP signal with 100% BW_{-6dB}



- Output signal matches with the target signal : relative error of 5 % (10 iterations).
- **Distorsion level :** a reduction of 10 dB (spectrum) for a loss of 1 nm on the peak-to-peak displacement
- Note the shape of the optimal solution





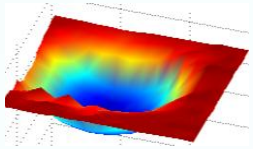
Conclusion & prospects

- Efficiency of optimal command method to control the cMUT output was demonstrated (experiments)

- Optimisation of the temporal waveform :
  - Previous literature focused on minimisation of the second harmonic level
  - The method can be applied to a large range of waveforms and so to coded imaging
  - Other shapes are actually under test

- The procedure is automatic and shows high convergence speed : applicable to industrial devices

- Prospects - application to therapy
  - How these techniques could be used to increase the volume of fluid swept by the membrane without collapsing ?
  - Implementation of non linear filtering models taking into account the collapse event (similar with the modelling of gate function used in electronic)



Acknowledgement

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l'Europe s'engage en région Centre avec le FEDER

Thanks !

QUESTIONS ?

- COSTUM ANR-09-TECS-005
- THERANOS ANR-10-TECS-007
- FEDER COSTUM II 2657-33868

•Vermon SA for the fabrication of the cMUT array