TABLE 4-8 Parameters related to the linear interpolation of the peaks of the PSD shown in Figure 4-50.

Frequency [Hz]	**Charge collector / Parameter**	**CC1**	**CC2**	**CC3**
10	α [m/V]	5.2e-5	1.5e-4	2.6e-4
	β $\left[V/\sqrt{Hz}\right]$	7.1e-5	1.6e-4	7.6e-5
100	α [m/V]	3.3e-5	9.3e-5	1.7e-4
	β $\left[V/\sqrt{Hz}\right]$	1.4e-4	-5.1e-5	-2.0e-4
500	α [m/V]	2.2e-5	8.2e-5	1.5e-4
	β $\left[V/\sqrt{Hz}\right]$	1.6e-3	1.5e-3	1.4e-3

6. THE COUPLED CIRCUIT AND THE EXPERIMENTAL RESULTS

Theory underpinning the coupled configuration has been introduced in the first section of this chapter. In section 4 a schematic of the circuit (Figure 4-7) and the related circuital equations have been given.
A detailed description of the circuital implementation of the coupled system will be given in the first part of this section.
In the second part, experimental results showing the suitability of the coupled configuration to sense external target E-fields will be discussed.

6.1 THE COUPLED CIRCUIT IMPLEMENTATION AND ITS BEHAVIOR WITHOUT TARGET E-FIELD

Figure 4.53 shows the schematic of the electronic implementing the coupled circuit. It consist on a ring connection of $N = 3$ elementary cells, discussed in section 3, consisting in a ferroelectric capacitor (the non linear dynamic element) and the Sawyer-Tower conditioning circuit. The unidirectional coupling between contiguous cells is obtained by gain

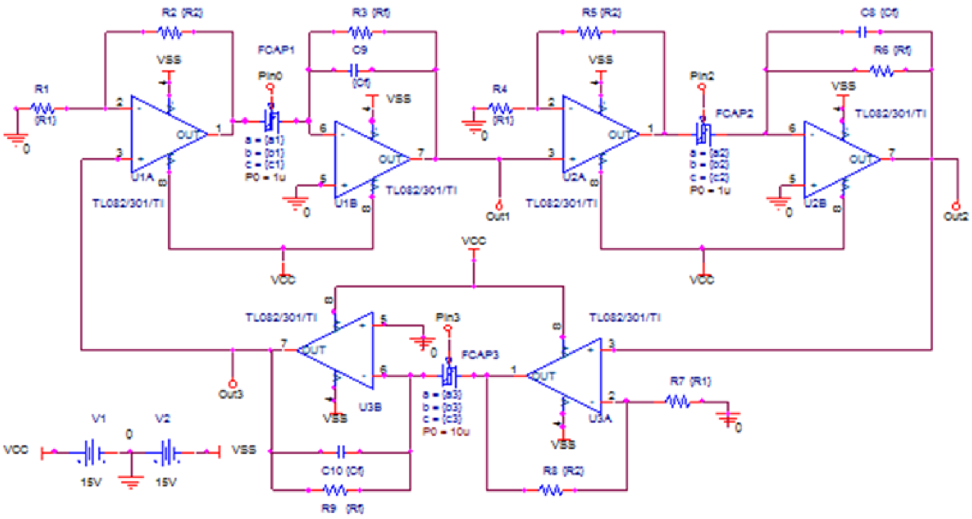


FIGURE 4-53 Schematic of the electronic implementing the coupled circuit.

blocks implemented by simple non inverting amplifiers. Figure 4-54 shows the schematic of the electronic implementing the elementary cell with the gain block. Electronic employs TL082 operational amplifiers and discrete resistances and capacitors apart the ferroelectric capacitors. A picture of the PCB is given in Figure 4-55. Ferroelectric capacitors (yellow caps) are easily recognizable in the upper part of the picture. The circuit has been designed with a modular structure to allow to use the single elementary cell to investigate the behavior of the single capacitor and giving the possibility to add further coupling blocks between two contiguous cells.

The output voltage of the gain block of the elementary cell i is given by

$$V_{G\_out}^{i} = \left(1 + \frac{R_2}{R_1}\right) V_{out}^{i-1} \tag{4.34}$$

where V_{out}^{i-1} represents the output voltage of the cell before the coupling block or rather the input of this latter block, while the factor $K = \left(1 + \frac{R_2}{R_1}\right)$ determines the gain of the block.

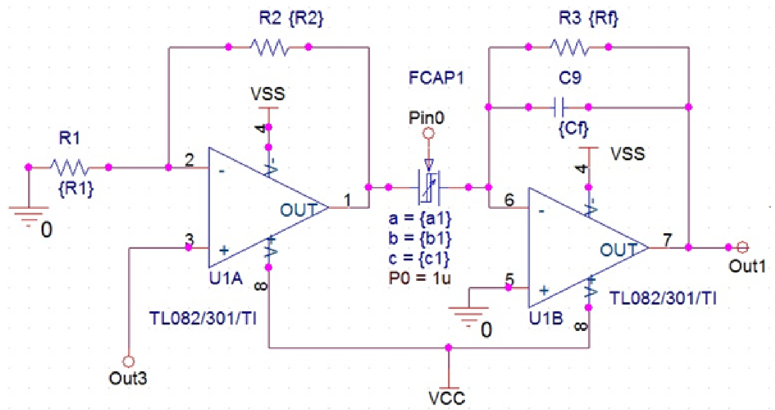


FIGURE 4-54 Schematic of the electronic implementing the elementary cell and the coupling gain block.

In the circuit the resistance R_1 has been fixed to 1kΩ while R_2 has been replaced by a potentiometer to the purpose to change the gain of this block.
This allows us to investigate the behavior of the circuit with different values of the gain.

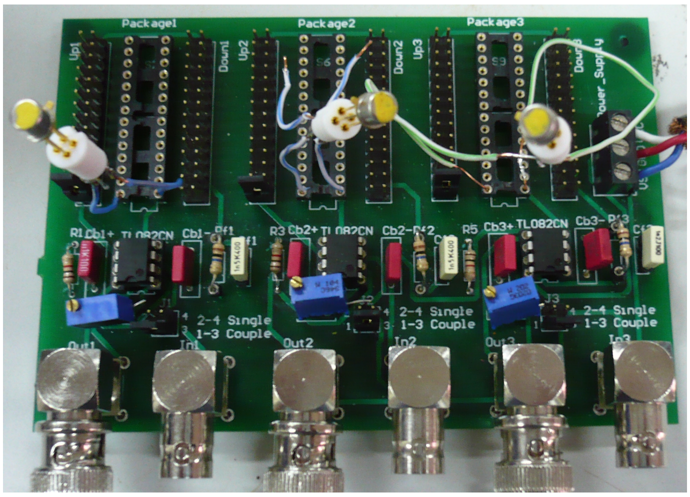


FIGURE 4-55 PCB implementing the coupled circuit with N=3 cells. Ferroelectric capacitors (yellow caps) are easy to recognize in the upper part of the picture.

From (4.34) and remembering equation (4.18) which explicates the value of the coupling coefficient between contiguous cells it readily follows

$$\lambda = c\frac{A_{FE}}{C_f d}\left(1+\frac{R_2}{R_1}\right) \tag{4.35}$$

Then changing the gain of the coupling blocks implies changing the value of the coupling coefficient and then the strength of coupling between contiguous cells. The coupled circuit starts to oscillate when the coupling coefficient exceeds the critical value ($\lambda > \lambda_c$) in (4.20). Above the critical coupling the system is in the self oscillating or supercritical regime.

The frequency of the oscillations depends on the coupling strength and then in last analysis on the gain of the coupling blocks. Changing the gain factor in (4.34) the frequency of oscillations change. This has been experimentally confirmed. Figure 4-56 shows examples of experimental results for different values of the gain factor K in (4.34) obtained changing the value of the resistance R_2 in all the three coupling blocks. Figure 4-56 shows the output voltage signals of the three cells (output voltage of the ST) in the circuit.

A decrease of the frequency is observed increasing the gain K. A comparison of the main peaks of the PSD at the frequency of the oscillation for five values of the gain K is shown in Figure 4-57: a shift in the frequency is clearly visible.

The trend of the frequency of the oscillations as a function of the gain K is shown in Figure 4-58.

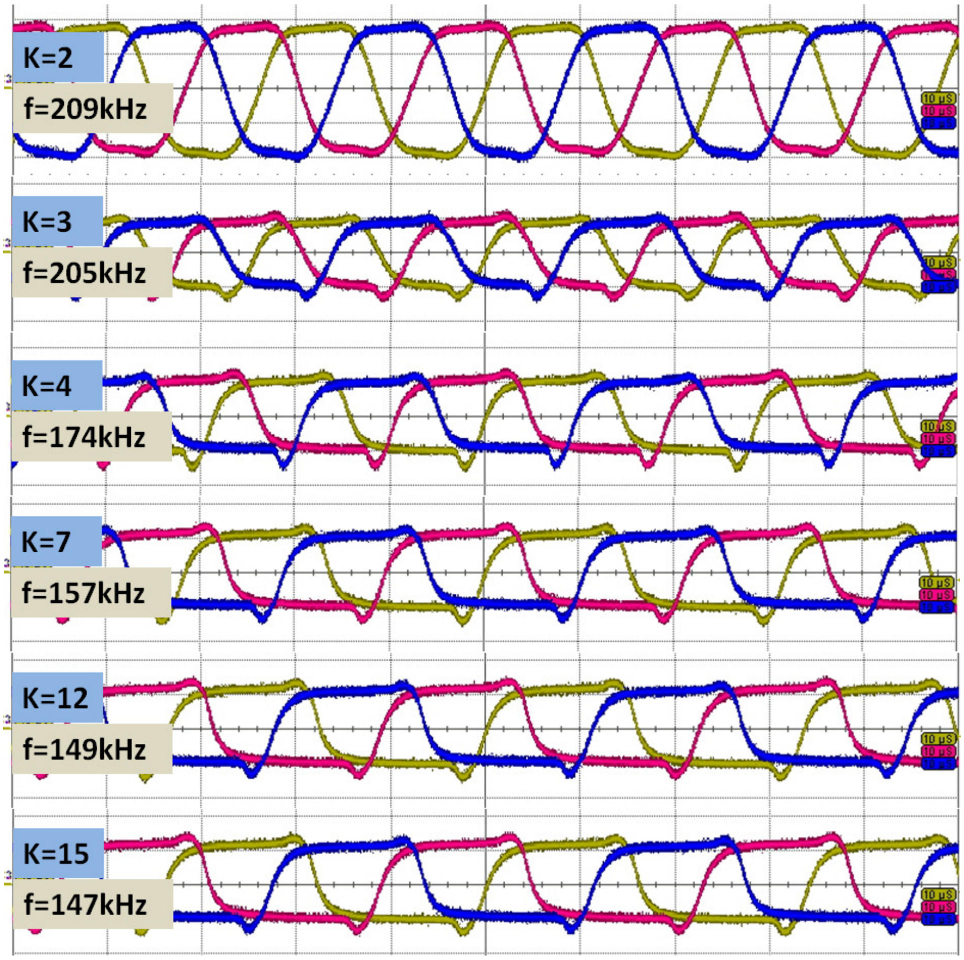


FIGURE 4-56 Examples of experimental signals for different values of the gain *K*. A decrease of the frequency of oscillation is observed increasing the gain.

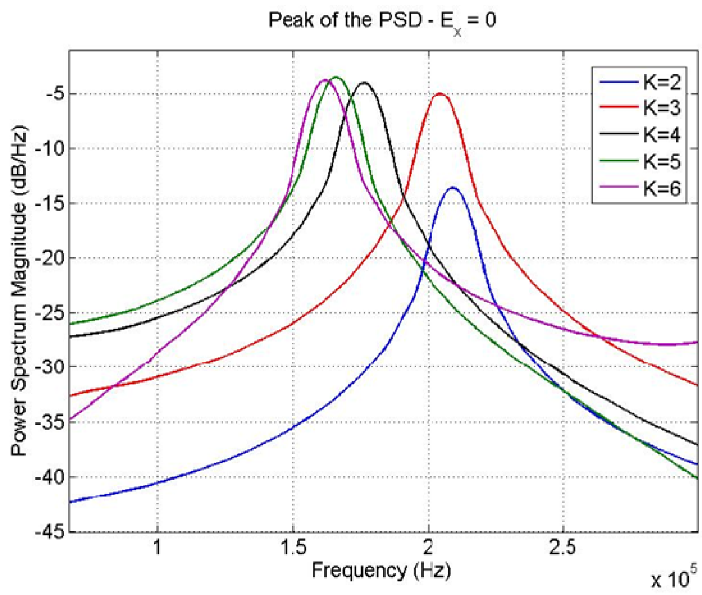


FIGURE 4-57 Comparison of the main peaks of the PSD at the frequency of the oscillation for five values of the gain *K*. A shift in the frequency is clearly visible.

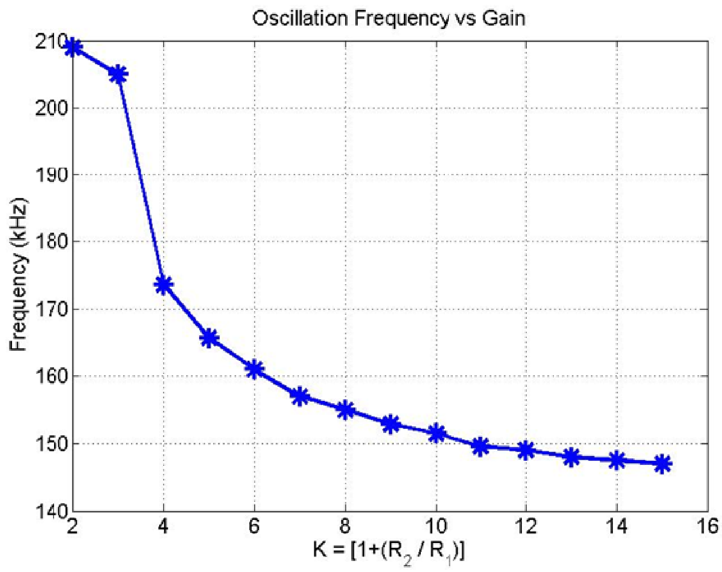


FIGURE 4-58 Trend of the frequency of the oscillations as a function of the gain $K = [1+(R_2/R_1)]$.

6.2 THE COUPLED CIRCUIT AS E-FIELD SENSOR

In the previous section the behavior of the coupled circuit as an oscillator has been discussed. The relationship between the frequency of oscillation and the coupling strength (which depends on the gain of the coupling blocks) has been investigated and experimentally demonstrated. Now the possibility to use the oscillating coupled circuit to sense external static or quasi-static E-field will be discussed hereinafter with experimental evidences.

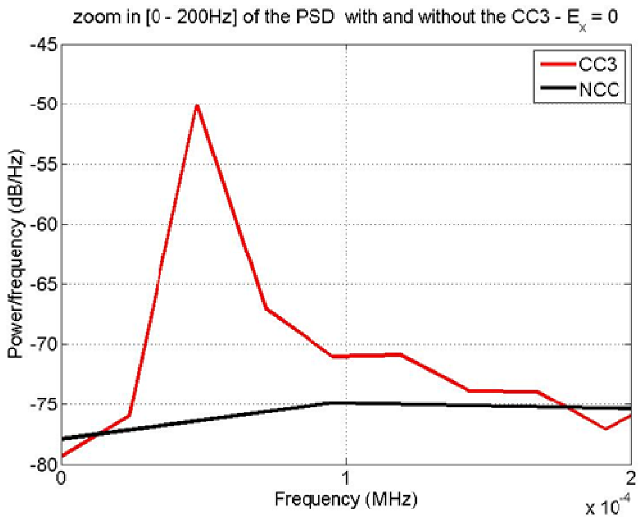
Experiments have been performed with the setup, already described in section 5.3.3, consisting in two sheet electrodes of 50cm x 50cm and a guard chamber to shield the sensor in order to avoid a direct (i.e., bypassing the charge collector) polarization of the ferroelectric. The two electrodes, separated by 10cm, are used to generate a uniform electric field (distance between electrodes can be regulated as you need). An AC voltage is applied to these parallel plates producing the target electric field which, in turn, produces a perturbation of the polarization of the ferroelectric capacitor. As previously discussed AC E-fields are employed to mimic the effect of a field-mill which converts a static or quasi-static target field in a AC voltage. Then the frequency of the target E-field could be fixed once and for all, anyway experiments for different frequencies of the target E-field have been carried out to the purpose to investigate the behavior of the circuit.

The experiments involve subjecting one of the capacitors in the coupled circuit to a target E-field having different intensities and frequencies, while also varying the dimensions of the charge collector. Specifically, the voltage (producing the target E-field across the capacitor) applied to the electrodes has been varied in amplitude from $100mV_{pp}$ to $20V_{pp}$ and its frequency varied from 100Hz to 1kHz. Treating the two large electrodes as a parallel plate capacitor, the target electric field amplitudes were 1V/m, 5V/m, 10V/m, 50V/m, 100V/m and 200V/m.

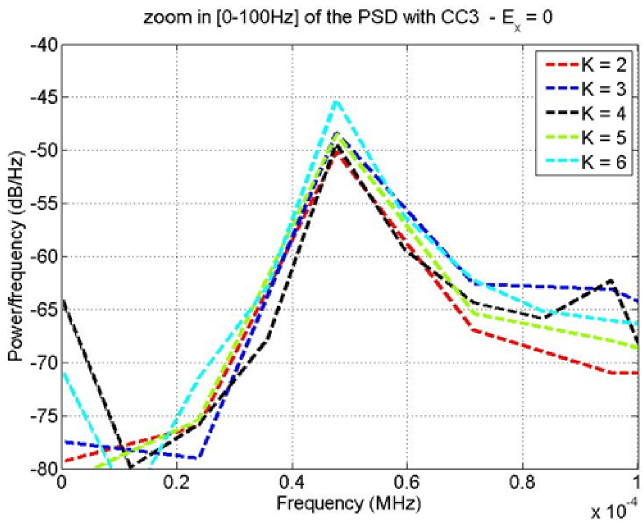
All the experiments have been repeated with three charge collectors, CC1, CC2 and CC3 having dimensions 9cm x 9cm, 20,5cm x 16cm and 25,5cm x 25,5cm, respectively, and for different values of the coupling gain.

6.3 EXPERIMENTAL RESULTS

To start with, the benefit of the charge collector strategy will be immediately demonstrated by experimental evidences. Figure 4-59a shows a zoom in the range 0 -200 Hz of the PSD of the output voltage of a cell of the coupled circuit with and without the charge collector linked to the sensing electrode of the ferroelectric capacitor. No external target E-fields was generated. A peak in the PSD at 50Hz, due to environmental electromagnetic fields, appears when the charge collector is connected. Figure 4-59a refers to the case of a set gain $K = 2$. A comparison of the peak of the PSD at 50 Hz for five values of the gain K and for the same charge collector CC3 is given in Figure 4-59b. Essentially the comparison highlights that there is no evident advantage choosing one or the other value of gain. Anyway the main results in this first evaluation is that the charge collector makes the circuit sensitive to an external target E-field producing a perturbation on its dynamic by perturbing the polarization state of the ferroelectric. Established that the system is sensitive to external E-fields an analysis of the circuit response for different amplitudes and frequencies of the target E-field has been performed. Figure 4-60 shows some examples of the output signals of a cell of the circuit for two values of the amplitude (50V/m and 100V/m) and of the frequency (500Hz and 1kHz) of the target electric field. Superimposed to the main oscillations of the circuit a low frequency perturbation is clearly visible. The frequency of this perturbation is that of the target E-field and the amplitude of this perturbation (which resemble an amplitude modulation) is proportional to the E-field intensity. In addition to the target E-field another field at 50Hz is always detected and its effect is visible in Figure 4-60 as a second order low frequency perturbation. This latter component can be easily removed by filtering the voltage signal. Signals shown in Figure 4-60 have been obtained with a gain K=2 and the small charge collector CC1. A comparison of the peaks of the PSD at 500Hz for all the amplitudes of the E-field is shown in Figure 4-61 with the charge collectors CC1 and CC2 and a coupling gain K=2. The value of the peak of the PSD at the frequency of the target E-field is proportional to the amplitude of the E-field.



(a)



(b)

FIGURE 4-59 Effect of the charge collector. (a) zoom in the range 0 -200 Hz of the PSD of the output voltage of a cell of the coupled circuit with and without the charge collector. No external target E-fields was generated. A peak in the PSD at 50Hz, due to environmental electromagnetic fields, appears when the charge collector is connected. (b) comparison of the peak of the PSD at 50 Hz for five values of the gain *K* and for the same charge collector CC3.

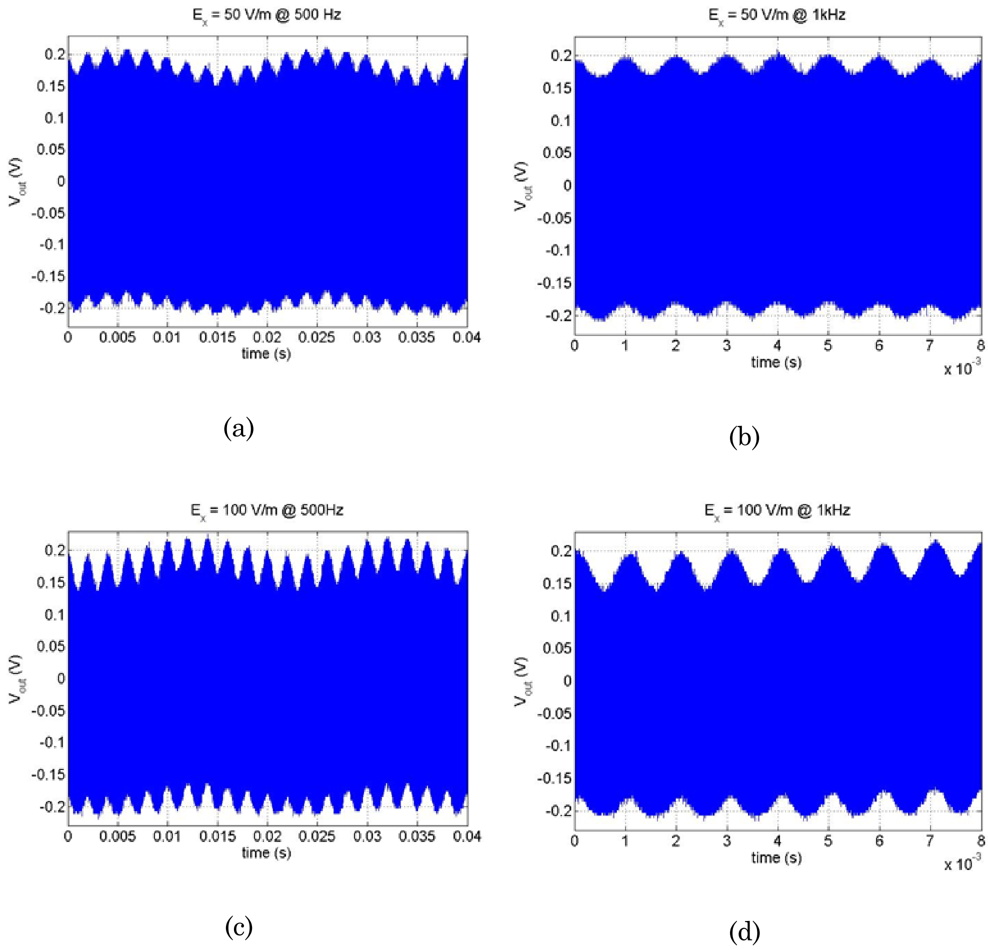
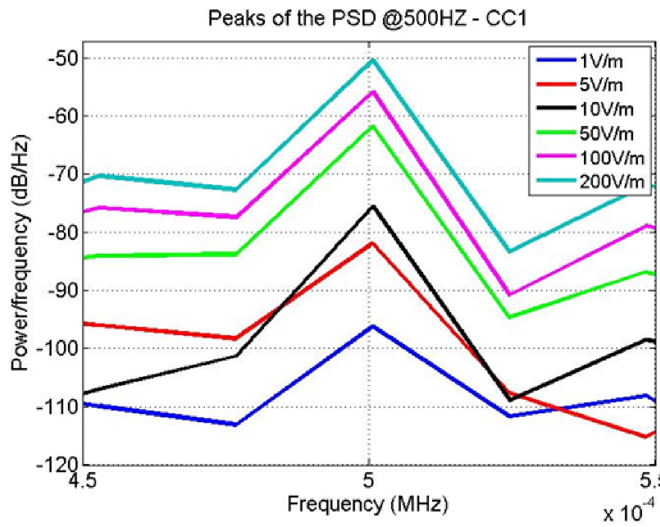
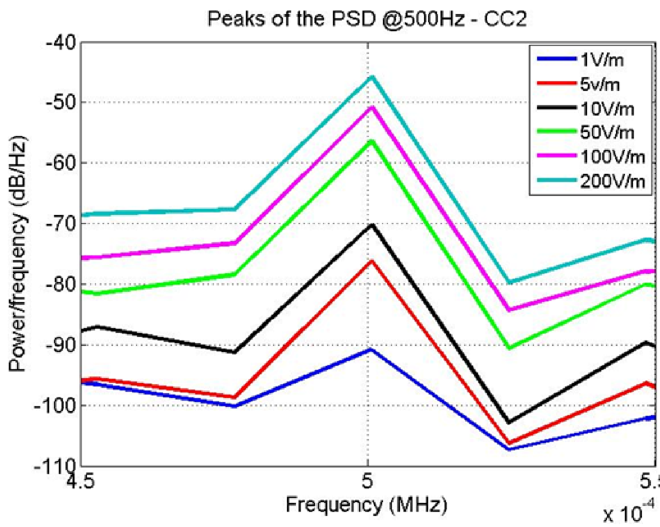


FIGURE 4-60 Examples of the output signals of a cell of the circuit for two values of the amplitude 50 V/m (a) and (b) and 100 V/m (c) and (d) and two values of the frequency 500Hz (a) and (c) and 1kHz (b) and (d) of the target electric field. Superimposed to the main oscillations of the circuit (high frequency) a low frequency perturbation at the frequency of the target E-field is clearly visible. The amplitude of this perturbation (which resemble an amplitude modulation) is proportional to the E-field intensity. In addition to the target E-field another field at 50Hz is always detected and its effect is visible as a second order low frequency perturbation. This latter component can be easily removed by filtering the voltage signal



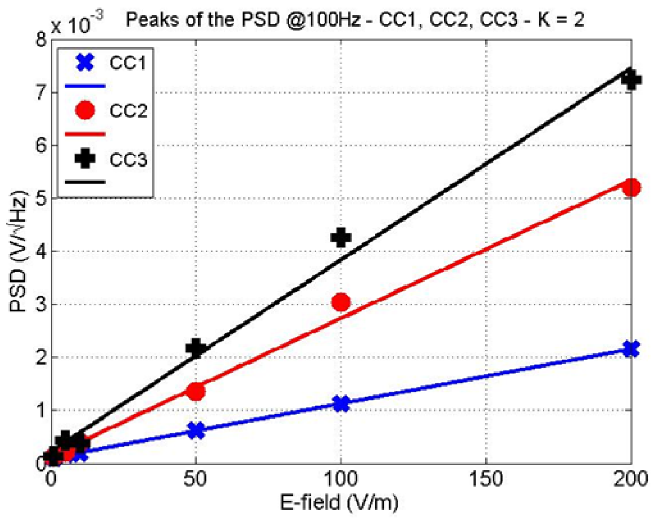
(a)



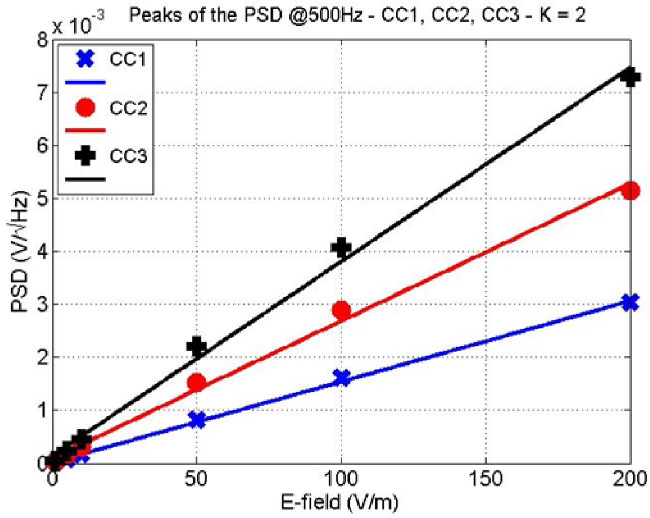
(b)

FIGURE 4-61 A comparison of the peaks of the PSD at 500Hz for all the amplitudes of the target E-field with the charge collectors CC1 (a) and CC2 (b) and $K = 2$.

A reliance on the size of the charge collector is also evident. A large charge collector enhances the perturbation on the polarization of the ferroelectric and then the sensitivity of the coupled system. As a consequence it is possible to enlarge the operating field of the system toward weak electric field by choosing a large charge collector.
A linear relationship between the amplitude of the target E-field and the peaks of the PSD (converted in V/√Hz) of the voltage output signals at the frequency of the target E-field can be arose from. Figure 4-62 shows the comparison of the peaks of the PSD for two frequencies of the target E-field (100Hz and 500Hz) with the three charge collector for $K = 2$. The enhancement due to the increasing size of the charge collector is highlighted. A linear interpolation of the values of the peaks of the PSD leads to the value of the parameters (α, β) reported in Table 4-9.
In addition, a reliance between the sensitivity and the coupling gain K can be arose from observing the linear interpolation of the values of the peaks of the PSD for increasing values of K. Figure 4-63 shows the comparison of the peaks of the PSD for a target E-field at 100Hz with the three charge collector and for two values of the coupling gain K ($K = 3$, and $K = 5$). A linear interpolation of the values of the peaks of the PSD leads to the value of the parameters (α, β) reported in Table 4-10. An increasing on the sensitivity can be observed at increasing the coupling gain K.
A further information arise from Figure 4-63: increasing the coupling gain K the system reaches a saturation state over that no particular benefits derive from increasing the size of charge collector. This statement is demonstrated by the fact that the linear interpolation for the charge collectors CC2 and CC3 are close together.
This leads us to concluded that increasing the gain K makes the system more sensitive to lower electric fields and a modulation of the sensitivity can be further produced by increasing the size of the charge collector until the system reaches a saturation state.

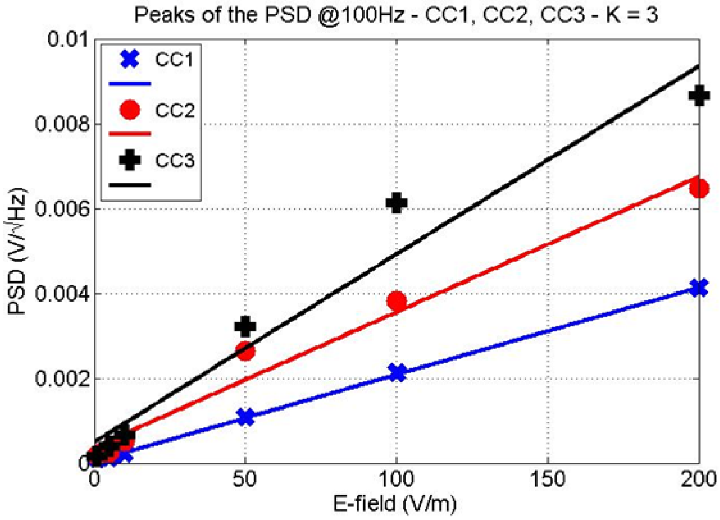


(a)

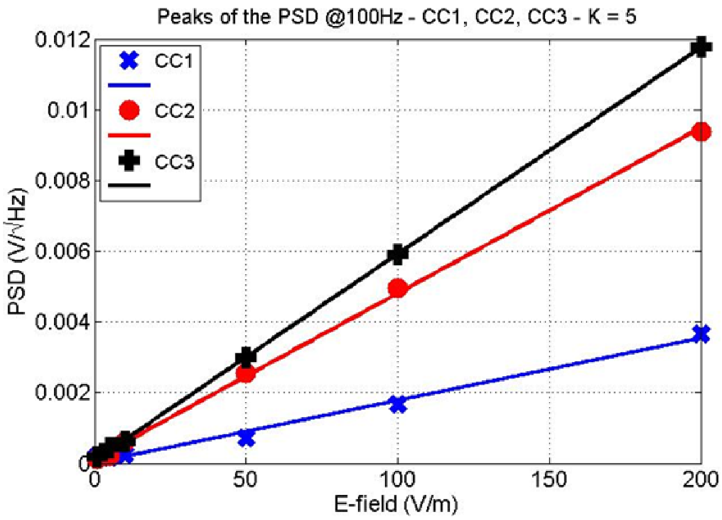


(b)

FIGURE 4-62 Comparison of the peaks of the PSD for two frequencies of the target E-field 100Hz (a) and 500Hz (b) with the three charge collector for $K = 2$. A linear relationship between the amplitude of the target E-field and the peaks of the PSD (converted in V/√Hz) of the voltage output signals at the frequency of the target E-field can be arose from. The values of the parameters (α, β) of the linear interpolation are reported in Table 4-9.



(a)



(b)

FIGURE 4-63 Comparison of the peaks of the PSD at 100Hz with the three charge collector and for K = 3 (a), K = 5 (b).

TABLE 4-9 Parameters related to the linear interpolation of the peaks of the PSD at 100 Hz, 500 Hz and 1kHz for the three charge collector CC1, CC2, CC3 and a coupling gain $K = 2$.

Frequency [Hz]	Charge collector / Parameter	CC1	CC2	CC3
100	α $\left[m/\sqrt{Hz}\right]$	1.0e-5	2.6e-5	3.6e-5
	β $\left[V/\sqrt{Hz}\right]$	1.0e-4	1.4e-4	2.3e-4
500	α $\left[m/\sqrt{Hz}\right]$	1.5e-5	2.6e-5	3.7e-5
	β $\left[V/\sqrt{Hz}\right]$	2.5e-5	9.4e-5	1.5e-4
1000	α $\left[m/\sqrt{Hz}\right]$	5.9e-6	9.4e-6	1.4e-5
	β $\left[V/\sqrt{Hz}\right]$	2.1e-6	5.3e-5	5.5e-5

TABLE 4-10 Parameters related to the linear interpolation of the peaks of the PSD at 100 Hz for the three charge collector CC1, CC2, CC3 and for $K = 3$, $K = 4$ and $K = 5$.

K	Charge collector / Parameter	CC1	CC2	CC3
3	α $\left[m/\sqrt{Hz}\right]$	2.0e-5	3.2e-5	4.4e-5
	β $\left[V/\sqrt{Hz}\right]$	5.0e-5	3.7e-4	5.0e-4
4	α $\left[m/\sqrt{Hz}\right]$	1.4e-5	4.9e-5	5.5e-5
	β $\left[V/\sqrt{Hz}\right]$	1.4e-4	3.2e-5	1.3e-4
5	α $\left[m/\sqrt{Hz}\right]$	1.8e-5	4.7e-5	5.8e-5
	β $\left[V/\sqrt{Hz}\right]$	3.2e-5	1.3e-4	1.0e-4

6.4 CONCLUSIONS

In this chapter two systems employing the charge collector strategy to perturb the polarization state of a ferroelectric capacitors have been presented together with experimental evidences. Experimental results show the suitability of both the investigated systems to sense external target electric fields.

A comparison of the performances of both the single capacitor device and the coupled system in the actual operating conditions does not make sense. Actually, the ferroelectric capacitor in the two systems is forced by different dynamics, in the single device the capacitor is driven @ 1kHz while in the coupled system the driving frequency is around 200kHz. As it can be observed by Figures 4-48 and 4-60 also the forcing term amplitude is quite different in the two cases.

Being the hysteresis loop in the two cases very different, the effect of a target field on the two devices (single and coupled) will be different. Anyway the coupled circuit presents more freedom of tuning its performance than the single capacitor by changing either, or both, the size of the charge collector and the coupling gain of the cells.

CHAPTER

5

CONCLUSIONS

It is a paradox typical of the human mind to catch the elements without being able to embrace the summary: an epistemological paradox of a science certain in the facts, but anyway insufficient.
- Albert Camus

This thesis deals with the exploitation of ferroelectric material properties and nonlinear dynamics behavior with emphasis on the realization of an innovative transducer.
The focused approach is based on the exploitation of circuits made up by the ring connection of an odd number of elements containing a ferroelectric capacitor, which under particular conditions exhibits an oscillating regime of behavior. For such a device, an external target electric field interacts with the system thus inducing perturbation of the polarization of the ferroelectric material; the target signal can be indirectly detected and quantified via its effect on the system response. The conceived devices exploit the synergetic use of bistable ferroelectric materials, micromachining technologies that allow us to address charge density amplification, and implement novel sensing strategies based on coupling non-linear elemental cells.

An experimental characterization of the circuit, including three cells coupled in a ring configuration has also been carried out with and without the target E-field.

The results confirm the reliance of the circuit oscillation frequency on the coupling factor, as expected from the mathematical and numerical models.

Experimental results with external target E-fields have been presented and discussed. A relationship between the sensitivity of the coupled circuit and the size of the charge collector as been demonstrated. In addition a reliance with the coupling gain has been observed. Both the two factors allow to enhance the sensitivity making it sensitive to lower electric fields.

A comparison between the coupled circuit and the single elemental cell containing a single ferroelectric capacitor, used as E-field sensor has been carried out to the purpose to show the benefits of the coupled circuit.

Of course, this activity needs further investigations and validations. A more accurate validation of the models and of the underpinning theory by simulations and comparisons with the experimental results is mandatory. Moreover further experiments are necessary to re-validate the results here presented and to investigate the behavior of the system with lower electric fields. Experiments should be performed to observe the response of the system to static target electric fields with and without a field mill device.

Finally, further analysis of the output voltage signals of the cells of the coupled circuit to investigate possible relationships between the target electric field and other properties of the signals, such as the duty cycle, could be carried out.

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APPENDIX

A summary of all the ferroelectric capacitors designed together with the list of groups and the number of replica of capacitors in the group is given in the following.
For the sake of convenience an example of the layout of the designed capacitor is reported in Figure A-1 with highlighted the three electrodes: the top and the bottom driving electrodes and the central sensing electrode. The relation between the sizes indicated in the upper part of the die and the geometrical features is also shown.

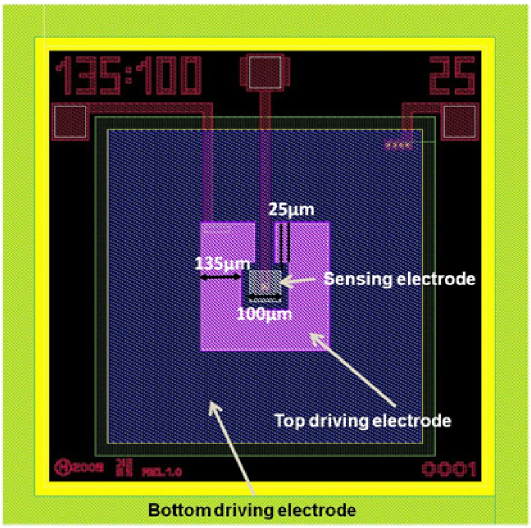

FIGURE A-1 Example of layout of the designed capacitors

Code	Group	N° of elements	Total
110:150:25	0001	10	40
	0010	6	
	0011	8	
	0100	6	
	0101	10	
135:100:10	0001	15	58
	0010	10	
	0011	8	
	0100	15	
	0101	10	
135:100:25	0001	10	48
	0010	10	
	0011	8	
	0100	10	
	0101	10	
135:150:100	0001	10	44
	0010	8	
	0011	8	
	0100	8	
	0101	10	
160:50:25	0001	10	42
	0010	7	
	0011	8	
	0100	7	
	0101	10	
160:50:10	0001	10	53
	0010	12	
	0011	9	
	0100	10	
	0101	10	

Code	Group	N° of elements	Total
160:100:100	0001	10	51
	0010	11	
	0011	9	
	0100	11	
	0101	10	
170:150:15	0001	10	48
	0010	10	
	0011	8	
	0100	10	
	0101	10	
185:50:25	0001	10	41
	0010	13	
	0011	4	
	0100	4	
	0101	10	
185:50:100	0001	10	48
	0010	10	
	0011	10	
	0100	8	
	0101	10	
195:100:15	0001	10	48
	0010	10	
	0011	8	
	0100	10	
	0101	10	
220:50:15	0001	10	42
	0010	7	
	0011	8	
	0100	7	
	0101	10	

Code	Group	N° of elements	Total
225:150:10	0001	10	48
	0010	10	
	0011	8	
	0100	10	
	0101	10	
235:150:50	0001	10	47
	0010	6	
	0011	5	
	0100	6	
	0101	10	
	0110	10	
250:100:10	0001	10	44
	0010	8	
	0011	8	
	0100	8	
	0101	10	
250:100:20	0001	10	46
	0010	10	
	0011	8	
	0100	8	
	0101	10	
260:100:50	0001	10	42
	0010	7	
	0011	8	
	0100	7	
	0101	10	
280:150:5	0001	10	48
	0010	10	
	0011	8	
	0100	10	
	0101	10	

Code	Group	N° of elements	Total
275:50:10	0001	10	51
	0010	6	
	0011	6	
	0100	6	
	0101	10	
	0110	13	
285:50:50	0001	10	47
	0010	11	
	0011	5	
	0100	11	
	0101	10	
305:100:55	0001	10	46
	0010	10	
	0011	6	
	0100	10	
	0101	10	
330:50:5	0001	10	52
	0010	12	
	0011	8	
	0100	10	
	0101	12	