Architecture level center frequency drift compensation method for micro-mechanical filters used in IF stages of wireless telecommunication receivers

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ABSTRACT.

A prototype of a 433.92 MHz RF receiver using a micro-mechanical resonator as channel-selection filter in the 2nd IF stage has been realized (94.5 kHz center frequency, 20 Hz bandwidth). A novel approach is used for managing the temperature drift of the center frequency of the micro-mechanical filter. Instead of stabilizing the filter's center frequency by complex device-level and technological modifications (bias voltage tuning, mechanical or thermal compensation), we modified the architecture of the IF stage in order to continuously adapt the IF frequency to the filter's center frequency deviations. This is achieved by periodical real-time measurements of the filter's center frequency and by then generating the appropriate second LO frequency. The measurement of the center frequency is achieved by putting the filter in an oscillating closed loop. The measured relative matching error between the 2nd IF frequency and the filter's center frequency is better than 0.005%.

1. INTRODUCTION.

The point of our work is to demonstrate that a micro-electro-mechanical resonator can be used as an IF bandpass filter in a RF receiver. Compared to discrete SAW filters, MEM filters fabrication technology is compatible with electronic IC technologies. Use of MEMS components in wireless communication systems could allow to design RF receivers completely integrated on silicon. Nevertheless the MEMS components have electrical characteristics quite different from their electronic discrete counterparts, and their use in wireless architectures often requires more than a simple electrical interface management (impedance and signal level adaptation, biasing, …etc). For an optimal integration of MEMS components in RF systems, architecture modifications can be useful and sometimes necessary. A typical example of such a situation is the case of a micro-mechanical filter. The center frequency of such filters depends strongly on the temperature (variation of -4ppm per degree). This instability can not be accepted for an IF filter with narrow band and needs to be compensated in some way.

It is known that the resonance frequency of mechanical resonators can be tuned with the bias voltage applied to its mobile part [4] or by mechanically compensating the temperature [2] and [3]. This feature can be employed for the temperature stabilization of the filter. Nevertheless this method is hard to implement in a RF architecture because these tuning voltages are usually quite high (20-50 V) and difficult to generate and control precisely in mobile devices. Moreover, the bias voltage determines input and output impedances of the filter [4]. Thus modifying the bias voltage for temperature stabilization would affect the impedance matching of the filter. An architecture-level solution is proposed : instead of tuning the resonator's center frequency, the local oscillator's frequency is constantly corrected in order to get the downconverted carrier frequency to be equal to the actual center frequency of the filter. This method allows the use of micro-electro-mechanical filters built in industrially available simple technologies. In this way we transfer the temperature instability managing task from MEMS device level to architecture level, where the mastering of the technologies is much better. Since the center frequency of the filter changes with the temperature, this correction must be done in real-time during the use of the receiver.

This article describes a receiver that uses a micro-electro-mechanical filter as a second-IF channel selection filter. The goal is to demonstrate the use of such a filter as an IF filter and all related architecture issues rather than designing a commercial-use receiver compatible with existing communication standards.

We have used a well-known comb-drive resonator which properties have been described in numerous papers [4]. Principal characteristics of the used resonator are high selectivity (2 to 30 Hz bandwidth depending on the vacuum level), center frequency of 94.510 KHz (at ambient temperature), typical values of bias voltage of 40-60 V and a

frequency temperature drift of -4 ppm/°. Its general view and biasing scheme in filtering mode are presented in fig. 1. The filter has been fabricated in a thick epi-poly technology provided by ST Microelectronics.
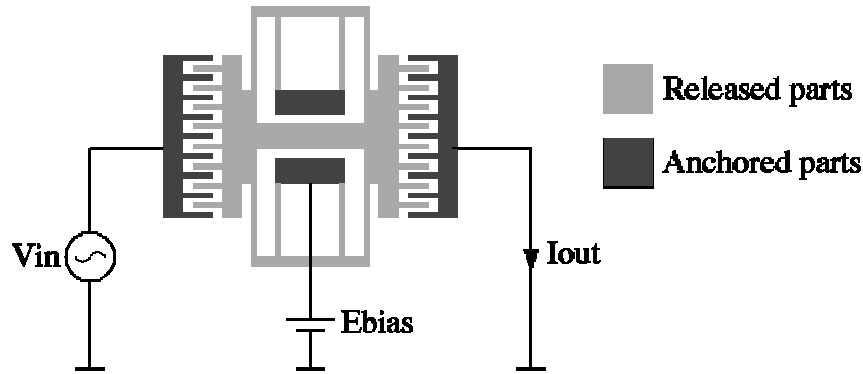

Fig. 1. General view of a micro-mechanical comb-driven filter [4].

The overall architecture of the realized receiver prototype is presented in the fig. 2. The receiver works in the 433.92 MHz frequency band (ISM). Since the center frequency of the micro-electro-mechanical filter used as channel selection filter is quite low, we have decided to build a triple conversion super-heterodyne receiver and to use the mechanical filter in the second-IF stage. The first intermediate frequency has been chosen equal to 10.7 MHz.

The whole receiver architecture is presented on the fig. 2. The RF and 1st IF part is implemented with a standard heterodyne receive module that won't be described in this paper. The frequency of the second local oscillator is constantly corrected according to the measured value of the filter's center frequency. The signal issued from the output of the filter can be downconverted to the baseband if mixed with a 3rd LO signal, that must also be variable and track the measured center frequency of the 2nd IF filter. The 3rd IF blocs are not included in the prototype, since they are not necessary to demonstrate the principles of the frequency shift correction.
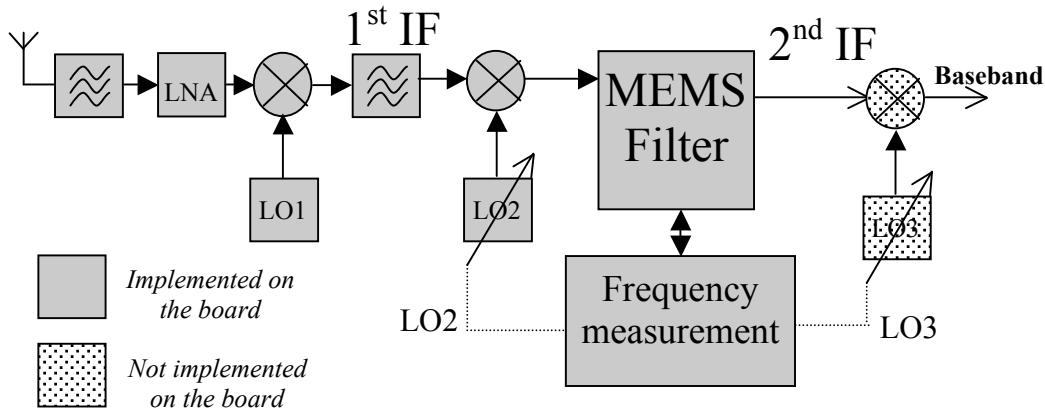

Fig.2. Overall receiver architecture.

2. CENTER FREQUENCY MEASUREMENT.

There are several approaches to measure the center frequency of a bandpass filter. The classical approach is to excite the filter with a pulse signal and to analyze the output impulse response. Since the tone corresponding to the central frequency of the filter will dominate the output response, a measurement of this frequency is possible. This approach is used for the measurement of the center frequency of a Gm-C band-pass filter [1]. A step signal is applied to the input and the frequency of output transient oscillations is measured.

This method is difficult to apply to a comb-driven filter, because of its high quality factor. As the bandwidth is narrow, using a step input signal doesn't produce enough output signal since there is far too less power from the input signal concentrated in the filter's bandwidth.

Finally, the best way to measure the micro-mechanical center frequency in this case is to make it oscillate by putting it into a positive feedback loop with high gain and 0° phase shift. In this case free oscillations will be produced at the ringing frequency of the filter. Moreover, if the gain is high enough, the oscillation's settling time diminishes and the output signal's amplitude rises quickly to a detectable level. Then, by means of a comparator, it is possible to convert the oscillations in a TTL signal, which can be computed by a micro-controller in order to measure its frequency.
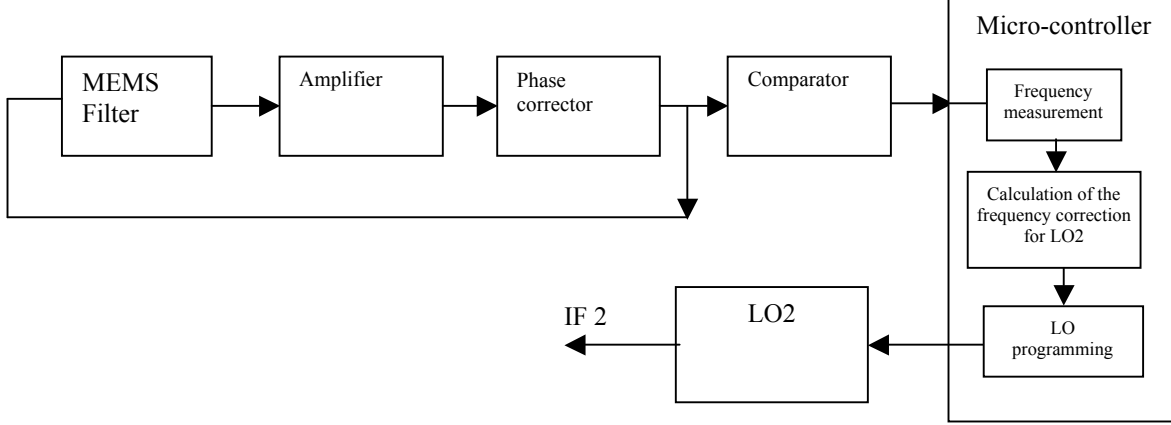

Fig. 3. Operation of the 2nd IF stage in the measurement phase.

The micro-controller used is a PIC16F74 from Microchip, operating at 20 MHz (which means a clock frequency of 5 MHz, i.e $T = 2.10^{-7} s$) using a 32 bits floating point library (taken from an application note) in order to increase computing accuracy.

The frequency measurement is based on two simultaneous-running processes. The micro-controller increments a clock cycles counter while a constant number (N, which value depends on the accuracy needed) of oscillations cycles are counted. Once N oscillations cycles have been counted, the process stops, M is assigned the number of counted clock cycles and the measured frequency is computed with the following formula :

$$f_{measured} = \frac{N}{M} * \frac{1}{T}$$

Fig. 4. shows the two simultaneous-running processes that are used to make the frequency measurement.
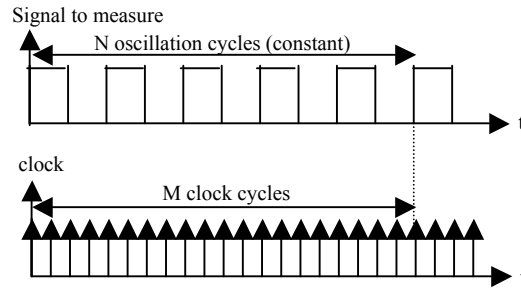

Fig. 4. Principle of measurement.

A rising edge of the comparator's (oscillator's) output is actually detected on the next rising edge of the reference clock. The delay between the two edges is unknown, as it depends on the oscillator frequency and phase relation with respect to the reference clock. This gives rise to a measurement uncertainty equivalent to one reference clock period (see Fig. 5.). Thus, taking into account this uncertainty, the actual frequency is comprised in an interval bounded by f_{min} and f_{max} given by :

$$f_{\min} = f_{measured} = \frac{N}{M} * \frac{1}{T}$$

$$f_{\max} = \frac{N}{M-1} * \frac{1}{T}$$

Signal to measure

Last oscillation
period to count

t

clock

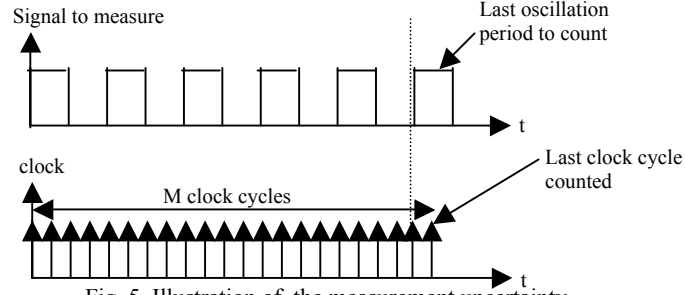Last clock cycle
counted

M clock cycles

t

Fig. 5. Illustration of the measurement uncertainty.

The maximum error being one clock cycle, the resulting error on the measured frequency can be bounded by :

$$\Delta f = \left| f_{\min} - f_{\max} \right|$$

$$\Delta f \leq \left| \left(\frac{N}{M} * \frac{1}{T} \right) - \left(\frac{N}{M-1} * \frac{1}{T} \right) \right| = \left| \frac{N}{T} * \left(\frac{1}{M} - \frac{1}{M-1} \right) \right| = \left| \frac{N}{T} * \frac{-1}{M(M-1)} \right|$$

At the end, we obtain :

$$\Delta f \leq \frac{N}{T} * \frac{1}{M(M-1)}$$

For example, if a frequency of 94.5 kHz is measured, we have got the following configuration :

$$T = 2.10^{-7} s$$
$$N = 13520$$
$$M = 715344$$

We can verify that effectively :

$$f_{\min} = 94499.98882 Hz$$
$$f_{\max} = 94500.12092 Hz$$

In this case, $\Delta f \leq 0.1321 Hz$

It is important to notice that this error doesn't take into account the calculation approximations made by the micro-controller during multiplications and divisions. In order to know the effective value of Δf, the following test has been performed (see Fig. 6.).

1st IF
generated by a
HP 33120A

MEMS
Filter
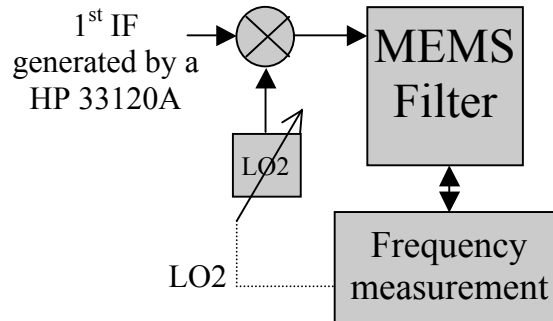
LO2

LO2

Frequency
measurement

Fig. 6. Measurement protocole.

A 10.7 MHz frequency is generated by a HP 33120A generator in order to allow the measurement of the MEMS's center frequency (assuming that the whole system's temperature and pressure are steady).

Because of jitter, 2nd LO frequency synthesis precision and uncertainty about the test-frequency generator, the effective Δf measured is ±5 Hz maximum.

3. SWITCHING BETWEEN THE MEASUREMENT AND RECEIVING MODES.

The 2nd IF stage has two operating modes: receiving and measurement. The measurement mode has been described in the preceding section. The receiving mode is standard like in classic IF stage, the only difference is that the frequency of the local oscillator is updated at the beginning of every receiving phase.

During the receiving phase, the phase corrector and the amplifier used to measure the ringing frequency of the filter must not stay connected to the resonator in order to prevent any perturbation on the received signal. Thus, the switching between measurement and receiving modes is made by use of bilateral switches that allow a digitally programmable architecture and that can be driven by the micro-controller.

Fig. 7. shows the schematic of the complete 2nd IF stage and Fig. 8. the different elements used in each operating mode.
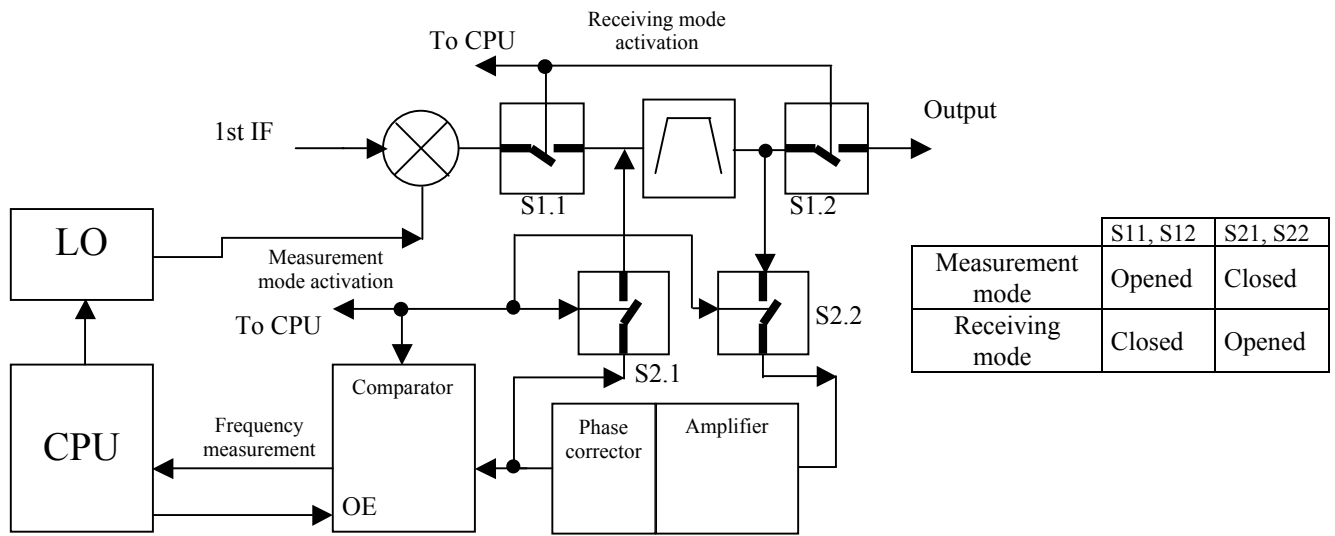

	S11, S12	S21, S22
Measurement mode	Opened	Closed
Receiving mode	Closed	Opened

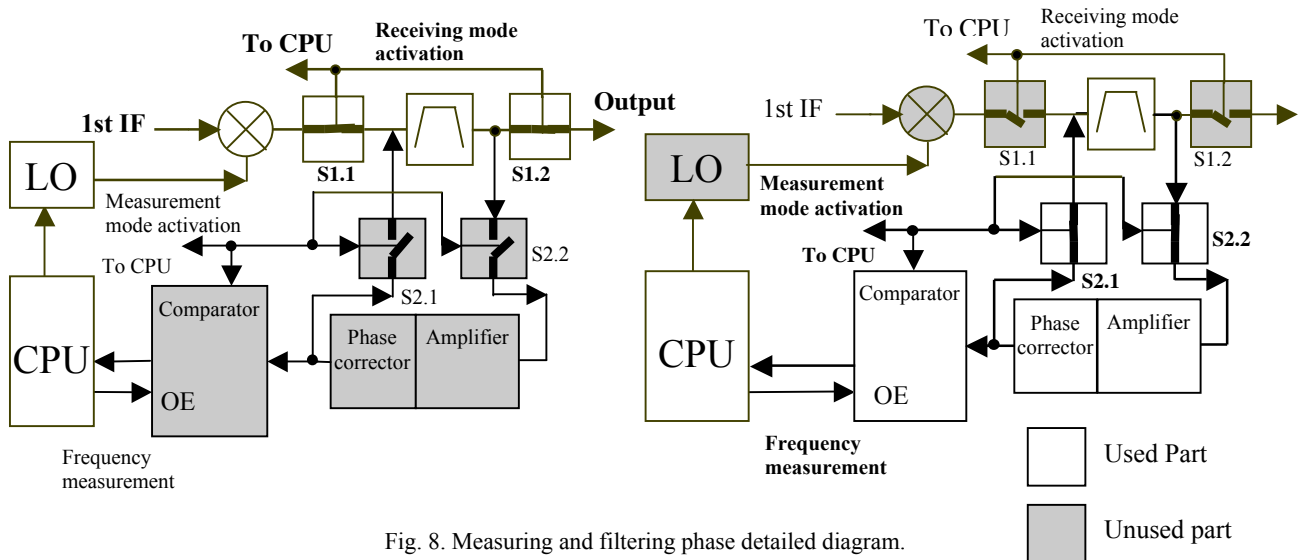Fig. 7. Complete schematics of the 2nd IF stage.

Fig. 8. Measuring and filtering phase detailed diagram.

4. SECOND OSCILLATOR'S FREQUENCY SYNTHESIS.

As the theoretical error on frequency measurements is ±1 Hz around the filter's center frequency (equal to 94.5 kHz in our case), the second oscillator's frequency must be generated with at least a precision of ±1 Hz around 10.6 MHz.

Precise frequency synthesis is usually achieved with a PLL which can generate variable frequencies by means of a multi-bit programmable divider. However, in our case, because of the accuracy needed in the frequency variations (at least 1 Hz step around a 10.6 MHz frequency, i.e a precision of 0.00001%) and due to the high number of bits needed to control the output frequency, a PLL architecture is not a good solution. We chose to generate the second oscillator's frequency with a digital component from Analog Device called DDS (Direct Digital Synthesis) that allows a step of 11 mHz for 0 to 15 MHz frequencies and which can be controlled with 3 pins of the micro-controller (serial data, clock and frequency update).

5. MICRO-ELECTRO-MECHANICAL FILTER INTERFACE.

The mechanical filter bloc is realized on a printed circuit board separate from the main receiver board since for experimental operation the filter has to be placed in a vacuum chamber. The schematics of the filter board is presented in the fig. 9.

A capacitive coupling between the input and output electrodes of micro-mechanical filter reduces the attenuation at out-of-band frequencies [5]. In order to maximize the out-of-band attenuation, we have used the method described in [5]. The parasitic coupling current present in both resonators is canceled, only the motional signal of the biased resonator is present at the output.

A heating element is placed near the biased resonator to adjust approximately the operating temperature of the system during the test process.
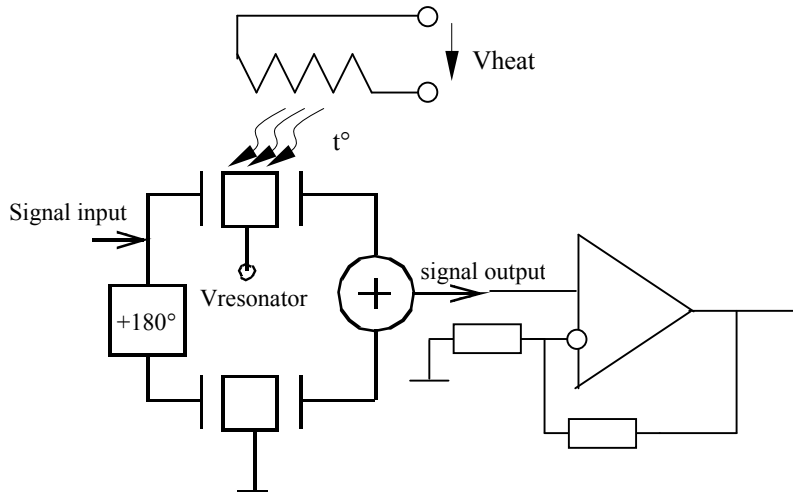

Fig. 9. Compensation of parasitic input-output coupling in the micro-mechanical filter.

6. EXPERIMENTAL RESULTS.

To test the receiver, the filter has been placed in the vacuum chamber with 3 Torr air pressure, so the -3db bandwidth was 20 Hz. To test the receiver, we have used an amplitude-modulated signal with 5 Hz modulation frequency and 50% depth. The receiver test has shown a 0.005% matching precision between the 2nd LO frequency and the filter's center frequency. To test the reliability of the IF stage operation, we have heated the filter in the way that his center frequency was shifted by 400Hz (4% of the central frequency). To better observe the 2nd IF correction, we have set the time interval between measurements (and so between 2nd IF corrections) equal to 8 s, in order to have a big frequency deviation between two measurement (10-30 Hz depending of the heating rate). The amplitude of the AM signal at the filter output decreased considerably between two measurements, since the filter center frequency was changing and the signal became out of band. After each measurement the amplitude jumped back to the value corresponding to the filter transmission at the resonance frequency.
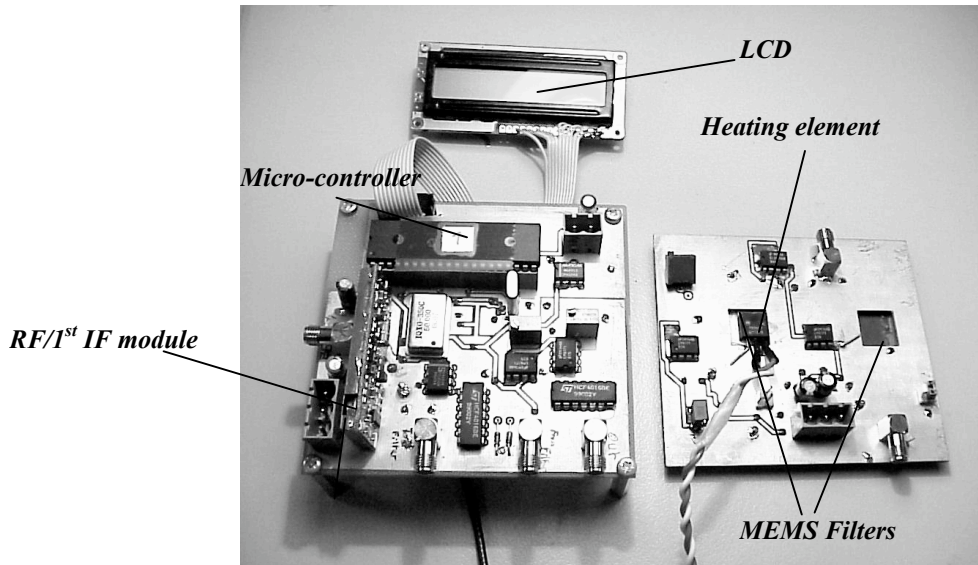
Fig. 10. General overview of the complete RF receiver.

The measurement phase time is about 143 ms. Although it seems to be high, we should take into consideration that in real RF systems the center frequency of the micro-electro-mechanical filter would be much higher (aimed values are about several hundred megahertz), so the measurement time will be considerably decreased.

7. CONCLUSION.

The achieved receiver prototype demonstrates a way of use of micro-electro-mechanical filters in an IF stage and a possible solution for such a fundamental problem of micro-electro-mechanical filters as the temperature frequency drift. The prototype filter has a center frequency at 94.5 kHz, but the demonstrated principle can be applied to filters operating at much higher frequencies.

The case of a micro-electro-mechanical resonator has shown that sometimes architectural-level solutions are more efficient and easier to implement than technology level or than modifications on the device.

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