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Wearable Microwave Radiometers for Remote Fire Detection: System-on-Chip (SoC) Design and Proof of the Concept

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Abstract—**The paper reports the present status of the project aimed at the realization of a wearable low-cost low-power System-on-Chip (SoC) 13-GHz passive microwave radiometer in CMOS 90 nm technology. This sensor has been thought to be inserted into the firemen jacket in order to help them in the detection of a hidden fire behind a door or a wall, especially where the IR technology fail. With respect of the prior art, the SoC is further developed and a proof of the concept is provided by means of a discrete-component prototype.**

I. INTRODUCTION

THE safeguard of the emergency operators is an important challenge, especially when dangerous working conditions are involved. To this purpose the fire brigades are nowadays equipped with cameras working in the mid-infrared (IR) band. Although these devices are well suited to look through the smoke, they fail in the case of the presence of obstacles which mask optically the fire spots (e.g. the walls of building in urban areas or the vegetation in forested areas). In indoor environments, for example, the safety of firemen and the effectiveness of their action could benefit largely if a sensor capable to detect the fire behind a wall or a door was available. A very promising approach for such a problem is given by the microwave radiometry [1-4] and this principle has been exploited by several millimeter-wave imaging systems [5], [6].

The work described in this paper is a part of the ProeTEX project (FP6-2004-IST-4-026987), a European Integrated Project aimed at developing a new generation of equipment for the emergency operators, as firemen and Civil Protection rescuers. In particular, the purpose of the project is to develop a new generation of electronic devices for the mass-market, mainly based on textile technologies, in order to reduce their weight and volume, and then improve their wearability. The final output of the project will be a textile platform where all the monitoring, communication and power management systems are integrated in a fully functional wearable garment.

One of the main innovative aims of the project consists of the research on novel sensors and micro-systems to be integrated in the future prototype. In this framework, the passive microwave radiometry [2] plays a significant role since it makes possible the remote sensing of the environment [3] e.g. the detection of a fire, the pollution release, the ice formation on a road pavement or even the detection of a cancer [4].

In this paper, the idea of the wearable, low-power, low-cost microwave radiometer for fire detection is discussed, showing the developments toward the realization of a SoC fully integrated on silicon. Then a proof of concept is given by means of a discrete-component microwave radiometer. Such an instrument has been used to sense fires behind the walls of buildings.

The adopted research methodology (SoC design and proof of the concept by means of a discrete-component prototype) points-out that microwave radiometers are powerful tools for the fire detection and thus that it makes sense to miniaturize them down to a single chip.

II. 13-GHZ MICROWAVE RADIOMETER ON SILICON

The latest generation of integrated circuits on silicon, especially the sub-micron CMOS technology with a channel length of 90 nm or shorter, provides active devices characterized by very high maximum cut-off frequency and low noise figure. These features are suitable for the realization of sensitive, single-chip, microwave and millimeter-wave receivers. Beside to them, also the calibration circuitry (i.e. switches, noise sources, etc.) and the digital signal processor can be integrated. Finally, it is possible to foresee on-chip thermal control by means of temperature sensors and actuators. All these innovations will led to new concept of System-on-Chip (SoC) microwave radiometers, a possible application of which will be in the field of wearable and low-cost remote temperature sensors.

A. System Overview

The system proposed hereinafter is designed to assist the firefighters in their work, for instance by detecting a fire behind a door or a wall. This sensor is mounted on two textile microstrip board. The former contains the radiometric sensor and it is placed in the front side of the fireman jacket (this in order to detect the fire coming from the front). The latter contains the low data-rate radio transceiver for sending out the information collected by the sensor, and this can be placed in the back side, for instance close to the neck. The system idea is shown in Fig. 1. The radiometer consists of a patch antenna array, a low noise 13-GHz radiometer module and a data acquisition and process unit. It is worth noting that the sensor is mounted on the same microstrip board of

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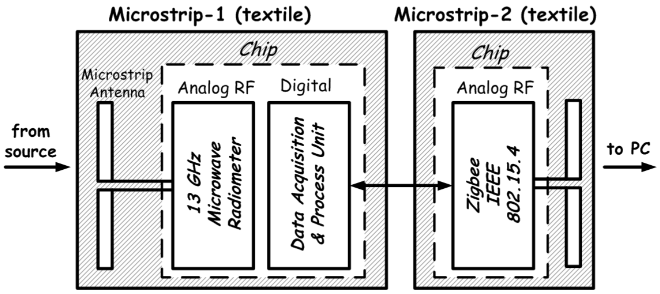


Fig. 1. Block diagram of the overall system

the antenna. The ZigBee transceiver (IEEE 802.15.4) transmits the data to the personal server (or a remote unit as well) of a wireless body area network (WBAN). This wireless platform allows us to collect the data acquired by multiple sensors in order to realize an extended monitoring of the vital and environmental data. Moreover, such a wireless platform allows us to implement re-configurable systems, which can be managed by remote operators addressed to the safeguard of the rescue team.

B. System-on-Chip Radiometer

The prototype of the full integrated microwave radiometer proposed herein is shown in see Fig. 2. The receiver consists of: i) a switch; ii) a noise source for the offset/gain calibration; iii) a Low Noise Amplifier (LNA), setting the equivalent noise temperature of the sub-sequent microwave receiver; iv) a mixer for the down-conversion of the incoming signal; v) a local oscillator, PLL controlled; vi) a square-law detector which extracts the information concerning the radiation power; vii) an integrator reducing standard deviation of the measured fluctuations; and viii) an acquisition and processing unit, collecting the data out of the sensor. The latter unit is also used to carry-out the periodic offset/gain calibration. In detail, the system is based on a direct conversion receiver, and exploits a band-pass filter instead of the low-pass one traditionally used, in order to reject the flicker noise contributed by the local oscillator.

TABLE I
SPECIFICATIONS OF THE BUILDING BLOCKS

	Noise Figure	Power Gain
Switch	≤ 1 dB	
LNA	≤ 3 dB	> 20 dB
Mixer	≤ 15 dB	> 4 dB
AFI	≤ 10 dB	> 35 dB

The specifications of the building blocks have been derived (see Table I) by means of a theoretical analysis [2], [3] and a CAD tool system analysis (Ptolemy simulator, by Agilent Technology), both by taking into account the performance expected in the case of practical integration on silicon (CMOS 90 nm by STMicroelectronics) and the microstrip antenna [5]. In detail, we considered non-ideal effects such as physical temperature of antenna, noise contribution, bandwidth and linearity performance limitations of the receiver; all of them obtained by preliminary circuit simulations.

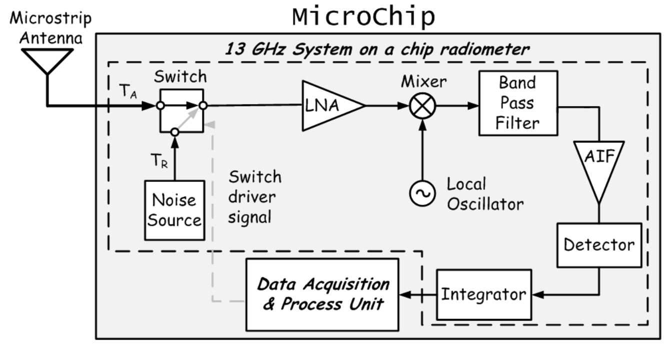
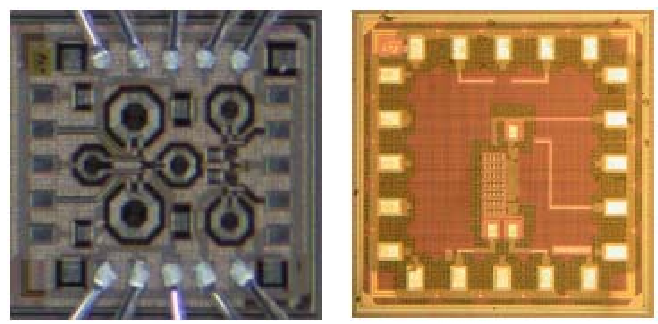


Fig. 2. Block diagram of the 13 GHz microwave radiometer for fire detection, according to a total power architecture.

C. Integrated Building Blocks

The building blocks of the radiometer have been implemented in CMOS 90 nm by STM, in accordance with the specifications derived by the system analysis [6]. Preliminary measurement carried-out on some of the above building blocks (e.g. the LNA and the IF section in Fig. 3) are in agreement with the simulation results.



(a) (b)

Fig. 3. Die micrographs of the (a) LNA and (b) IF-Section, respectively. In both cases the chip size is close to 1mm x 1mm (pad inclusive).

III. PROOF OF THE CONCEPT

In order to confirm experimentally that microwave radiometers are able to detect fire spots in indoor environments, even behind walls or doors, a proof-of-the-concept has been realized. To this purpose a discrete-component 12.65-GHz radiometer, previously developed by some of the authors, has been used.

A. Discrete-Component Radiometer

The discrete-component 12.65-GHz radiometer has been described in depth in ref. [7]. For the reader's clarity its performances and operation will only be recalled here. The receiver consists of a Low Noise Block (LNB) for Satellite Television (SAT-TV) applications which is characterized by a noise figure of 0.8 dB, a RF-gain of 54 dB and a gain drift versus temperature less than 0.1 dB/K. The LNB converts the RF-signal between 11.65 GHz and 12.75 GHz into an IF-signal signal between 0.95 GHz and 2.05 GHz. The image frequencies are rejected, by a microwave band-pass

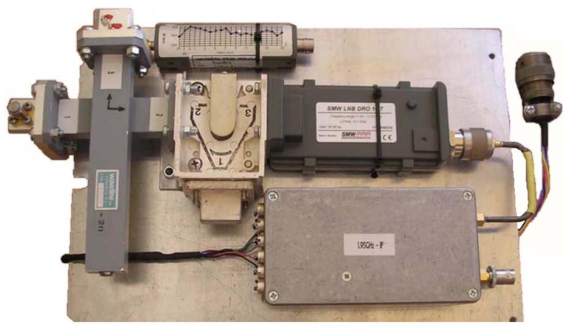


Fig. 4. Assembly of the 12.65-GHz discrete-component radiometer. From the left: input waveguide, 20dB Moreno coupler, isolator, SAT-TV low-noise down-converter, calibration noise source on the top, and 1.95-GHz IF chain on the bottom.

filter, by over 50 dB. The IF chain provides an overall gain of about 10 dB over a IF-bandwidth of 100 MHz. The IF ceramic filter has a center frequency of 1.95 GHz. The main assembly of the sensor is illustrated in Fig. 4.

The antenna noise temperature (T_A) measured by the sensor can be retrieved according to the noise-adding equations [3]:

$$T_A = \alpha \cdot \frac{V_{OFF}}{V_{ON} - V_{OFF}} - \beta \tag{1}$$

where V_{ON} and V_{OFF} are the output voltage obtained when the noise source is switched on/off, respectively, while α and β are the scale factor and the offset of the radiometer respectively. These constants have been determined by suitable calibration procedures, the best estimation of which being: α = 87.4 K, β = 113.0 K. It is worth to note that such an instrument can runs without thermal stabilization producing an absolute error less than 4K; this if the physical temperature of the receiver is in the range 3 – 23 °C.

B. Inter-Wall Fire Detection

The inter-wall fire detection experiments have been carried-out in indoor environment in order to simulate a condition as close as possible to the operative scenario described in the introduction. In particular the set-up shown in Fig. 5 has been used for the proof-of-the concept.

In order to model the scenario sensed by a microwave radiometer, the approach described in [8] has been adopted. This approach is based on the filling factor q, a quantity defined as the ratio between the area of the fire A_{FIRE} and the area of the antenna footprint A_{FOOT}:

$$q = \frac{A_{FIRE}}{A_{FOOT}} \tag{2}$$

By considering Fig. 5, the footprint area can be evaluated approximating the main beam of the antenna with a cone of angular aperture θ (half power beam width) and by cutting this cone with the profile of the illuminated scene, the soil and the furnace in this case.

The radiometric contrast ρ_T is defined as the increase of the antenna temperature due to the fire with respect to the

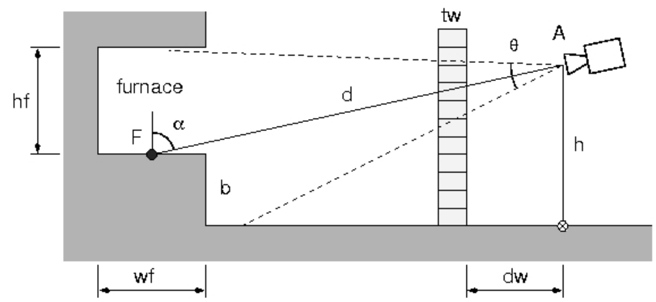


Fig. 5. Basic set-up used for the inter-wall fire detection experiments. The geometry is characterized by: d = 2.40 m, h = 0.49 m, wf = 0.6 m, dw = 0.52 m, tw = 0.125 m, hf = 0.64 m, b = 0.41 m, θ = 30 degrees, α = 78 degrees. A is the antenna position and F is the fire position.

condition without any fire. Applying the radiative transfer theory the radiometric contrast can be derived as follow:

$$\rho_T = \tau \left[\epsilon_F T_F - \epsilon_S T_S - (\epsilon_F - \epsilon_S) \epsilon_W T_W \right] q \tag{3}$$

where τ_W is the transmissivity of the wall, ϵ_F, ϵ_S and ϵ_W are the emissivities od the fire, soil, and wall, respectively, and T_F, T_S, and T_W their physical temperatures.

C. Experimental Results

All the experiments have been carried-out keeping constant the fire spot size and material. The fire has been produced by 21 pine-wood sticks forming a pile of 0.25m base side. The total mass of the wood is 1.18 kg while A_{FIRE} = 0.0625 m^2. Since the estimated footprint area (A_{FOOT}) is equal to 2.01 m^2, the resulting filling factor is q = 3.2%.

The measured results are reported in Fig. 6. In particular such a figure shows: i) a reference experiment with no wall, ii) an experiment with a light plasterboard wall and iii) a test with heavy concrete wall. The radiometric contrast is computed as the antenna temperature difference between the measured value at each time instant minus the values recorded at the begin of the experiment, i.e. when no fire is

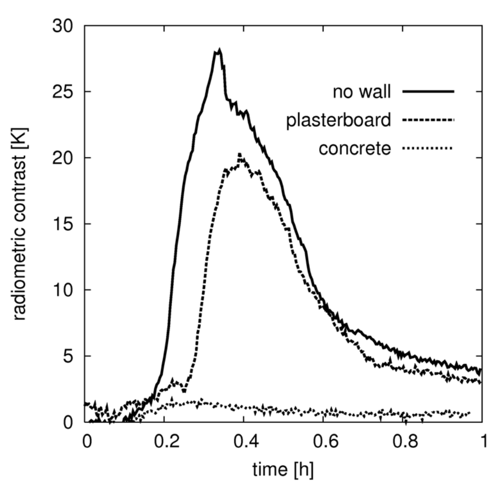


Fig. 6. Radiometric contrast measured during the inter-wall fire detection experiments. The results without the wall are compared with that of plasterboard and heavy concrete walls. Although heavy concrete wall cause a significant attenuation, the microwave emission is clearly captured with a radiometric contrast of about 1.4 K.

present. In particular, using the radiometric contrast $\rho_T = 27$ K obtained without the wall, the term $\epsilon_F T_F$ has been estimated to be around 1100 K. By inserting the plasterboard wall a radiometric contrast $\rho_T = 17$ K is measure, leading to $\tau_W = 0.63$. Finally, in the case of the heavy concrete wall, the contrast amounts to only 1.4 K and τ_W drops to 0.05.

It is worth noting that the above transmissivity values are correlated with the density of the wall material, as reported in Table II.

TABLE II
WALLS PARAMETERS

Material	Average density [kg/m^3]	t_W [m]	d_W [m]	ρ_T [K]	τ_W
Plaster-board	112	0.125	0.52	17	0.63
Concrete	2063	0.125	0.52	1.4	0.05

Moreover, in spite of a concrete wall introduces a significant attenuation, the microwave emission peak is clearly captured with a radiometric contrast of about 1.4 K, whereas typical IR sensors fails even behind the plasterboard wall.

IV.CONCLUSIONS

This paper reports the progress toward the realization of a system-on-chip (SoC) 13 GHz radiometer, fully integrated on a commercial CMOS 90 nm technology. Such a sensor is intended to the temperature remote sensing, paying special attention to the detection of fire spots behind the walls of buildings. The basic building blocks have been realized and preliminary tested.

In parallel to such a IC design activity, a proof-of-the-concept has been obtained exploiting a 12.65 GHz radiometer already built by some of the authors. As a result it emerges that microwave radiometric sensors can be effectively used to detect small fires masked by the walls of a building. In the worst case, the measured radiometric contrast is 1.4 K for a 0.0625 m^2 wooden fire placed behind a 0.12 m concrete wall. The distance between fire and sensor is 2.4 m and the estimated wall transmissivity is 0.05.

In conclusion, the innovative low-cost, system-on-a-chip microwave radiometer could represent a very promising solution for the realization of a next-generation of wearable sensors. The SoC microwave radiometer will allow an extended detection capability in the cases where traditional devices, like IR devices, fail.

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