Room temperature thermopile THz sensor

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Abstract:

In this paper, we present the conception, fabrication and characterization of a room temperature thermopile designed to detect electromagnetic fields at 3 THz. The absorber consists of a metallic grid made of one of the material of the thin film thermocouples. The design of the grid is based on a theoretical multilayer model using equivalent resistivity and taking into account small diffraction effects. For future work with sub-wavelength resolution, we have also studied the effect of the reduction of the size of the grids on the equivalent resistivity. The grid is deposited on a 1.5 mm-radius SiO_2 circular membrane. The time constant of the sensor is measured with THz and optical sources and it is consistent with finite elements simulations. The sensitivity and the limit of detection are also evaluated. First results at 0.3 THz (and not at the designed frequency of 3 THz, because of limitations in the testing equipment) show a sensitivity of 35 nV/(W/m^2) and a limit detection of the E-field of 23 V/m due to a significant amount of noise. Future perspectives are put forward to increase the sensitivity.

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1. Introduction

The Terahertz (THz) frequency domain is usually defined as ranging from 100 to 10000 GHz. It has long been unexplored because of the difficulties in generation and detection of electromagnetic fields at such wavelengths. Over the past twenty years, considerable improvements have been brought to THz systems [1]. This evolution was initially driven by an increasing need for material characterization methods [2] and for alternative techniques of biological and chemical spectroscopy [3, 4]. Recently, new applications such as robotic vision, traffic control, medicine and biological research, have increased the interest in moderate-sensitive receivers operating at room temperature in the 100 − 3000 GHz frequency range [5].

This work is part of a project concerned in constructing a continuous wave THz near field experiment. The needed THz sensors should have a good spatial resolution (a few wavelengths) and should be easily manipulated (no bulky cryogenic cooling). We designed our own sensor in order to understand all the parameters that will be needed in the future to achieve a spatial resolution smaller than the wavelength. Considering previous knowledge in our team and its ability to be further miniaturized at reasonable cost, a room temperature thermal sensor made of a thermopile was chosen.

This thermal detector measures the electromagnetic radiation power by converting it into heat. The absorber with its thermal bridges and the thermopile are its two key parts. In order to have a relatively simple fabrication process, we chose to build them using a metallic grid and thin film thermocouples. The design is presented in section II. Section III concerns the measurements of the transmission, reflection and absorption of the grids. When grid extensions are far larger than the wavelength λ, experiments are performed at 0.3 THz, whereas experiments are done at microwaves frequencies when grid extensions are smaller than λ. Section IV describes the fabrication process of the THz sensor. Its characteristics in terms of time constant, responsivity, sensitivity and minimum detectable electrical field are introduced in section V. The electromagnetic (EM) map in the H-plane of a horn antenna operating at 0.3 THz (and not at the designed frequency of 3 THz) is also presented with our THz sensor working as the detector.

2. Conception of the THz sensor

2.1. Design of the Absorber

The absorber with its thermal bridges is one of the key parts of the sensor. It absorbs the incident electromagnetic radiation and transforms it into a temperature variation through Joule effect. Metal films can be used as absorbers. However, they must be thin enough to have the best absorption [6], typically a few nanometres or even less. Such a thickness requirement is too drastic to be fulfilled and well controlled with micro-fabrication techniques. Like Bock *et al.* [7], we used instead a structured metallic layer whose optimal thickness is larger. The conception of such structured absorbers is often based on empirical experimentations. We proposed a theoretical approach to design them [8]. It uses a computation of the absorption, reflection and transmission of a plane wave on several dielectric and metal layers, based on the works of Hilsum *et al.* [6] and Hadley *et al.* [9]. A grid can be then implemented as a homogeneous metallic layer with an equivalent resistivity ρ_{eq} depending on the geometry of the grid. It is usually approximated as:

$$\rho_{eq} = \rho_m \, . \, (g / 2a) \qquad (1)$$

with ρ_m the resistivity of the metal, g the pitch of the grid and 2a the width of the grid lines. Figure 1 shows the advantage of the use of a metallic grid in terms of thickness. The used parameters are g = 20 µm, 2a = 2 µm and ρ_m = 5.4 10^{-7} Ωm. The film and the metallic grid being unsupported (no dielectric), this result does not depend on the THz wavelength λ (as long as it is far greater than g). To improve the absorption (cf. Figure 1) a dielectric layer can be placed before the grid. With its thickness a quarter of the wavelength λ/(4n) (refractive index n), the reflected waves are in-phase and increase the absorption.

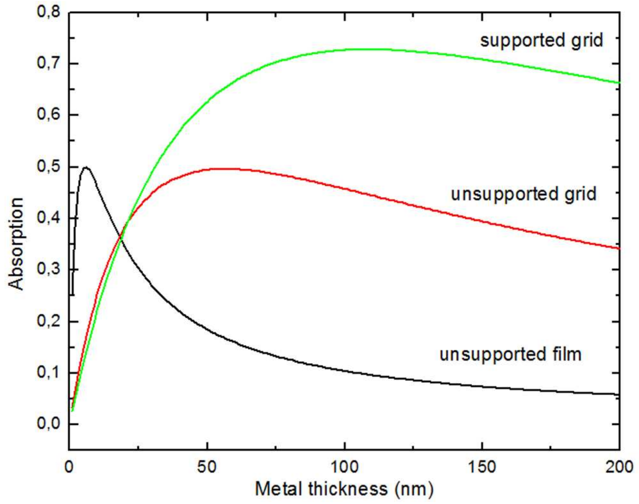

Fig. 1: Absorption of an unsupported metallic film, an unsupported metallic grid, and a grid with a λ/(4n) thick dielectric placed before; ρ_m = 5.4 10^{-7} Ωm, g = 20 µm , 2a = 2 µm, n = 1.7

Ulrich's work [10] was used to take into account the diffraction when the pitch of the grid becomes comparable to the wavelength. Our model shows in particular that the optimal thickness of the dielectric layer used to enhance the absorption can be slightly different from the quarter of the wavelength because of these diffraction effects [8].

Our sensor was initially designed to work at 3 THz, which corresponds to a wavelength of 0.1 mm in the vacuum. The size of the absorber and the membrane on which it rests is a trade-off between the spatial resolution and the sensitivity. It is chosen to be 3 mm. The chosen pitch g and the width of the track 2a of the grid are 20 and 2 µm respectively. To improve the absorption and to protect the membrane, a dielectric layer is added. However, its benefit is reduced by the higher thermal capacity. The grid thickness is computed with our model according to the dimensional parameters and metal resistivity.

2.2. Thermopile

To sense the variation of temperature due to the absorption of the THz wave, we have built thin film thermocouples that are highly compatible with micro-fabrication processes and that take full benefit from the previous knowledge of our team regarding this technology [11-12].

Thin film Seebeck coefficients are known to be usually lower than bulk coefficients and technology dependent. We then decide to measure the Seebeck coefficients of many thin film couples available for fabrication within our lab. The most interesting sets that we measured are Ti/Al (7.4 µV/K), Bi/Cr (70 µK/K) and Ti/doped Si (190 µV/K). Although the latter exhibits the highest Seebeck coefficient, its use of doped silicon makes the fabrication process more complicated. Bi/Cr couple also has a high coefficient but Bismuth is a soft material and it is difficult to use with precise lift-off and not easy to etch. Among the sets of "machining-friendly" metals tested, Ti/Al has the highest coefficient. Hence, the first prototype of the THz sensor uses it. The second prototype that will be published later will use the Ti/doped Si couple. A major advantage of our present choice is that titanium is used at the same time for the thermocouple and for the absorber grid.

To increase the sensitivity, thermocouples are connected in series. In a first approximation, utilizing n thermocouples increases the signal level by n times and multiplies the noise level by $\sqrt{n}$. Adding thermocouples also augments the overall impedance of the sensor, and the quantity of metal which must be taken into account for the best absorption. As a trade-off, a topology incorporating 6 thermocouples is placed on a circular membrane.

3. Measurements of the absorption of the grids

3.1. Grids with extension far larger than the wavelength

To validate the design of the absorber, measurements on grids are performed at 0.3 THz. Absorption is deduced from transmission and reflection measurements. To do so, titanium square grids of various geometries (cf. Table I) are deposited on glass wafers using a lift-off process. Their overall dimensions of 1.5 cm x 1.5 cm are far greater than the wavelength (1 mm in free space), which enables the use of plane waves approximation on semi-infinite layers needed for our model.

Table I: Dimensions of the grids for THz characterization

Metallic Grid	1	2	3	4	5	6	7	8	9
2a (µm)	1	1	2.5	4	10	2	2	4	20
g (µm)	20	100	50	200	200	200	200	200	400

Figure 2 presents the experimental set-up in the case of reflection measurements. The electronic source consists of two stages. The first one selects the sixth harmonic of a 16.667 GHz synthesizer thanks to a Schottky diode. That output is further amplified and fed into a second stage that selects the third harmonic with a final maximum power of 0 dBm. The mm-wave beam is focused on the device under test using two parabolic mirrors and a beam splitter. A commercial liquid-He bolometer is placed either behind the grid to measure the transmission or as presented in figure 2 to measure the reflection. The difference between the incoming, reflected and transmitted measured energies allows us to determinate the absorption of the grid [13].

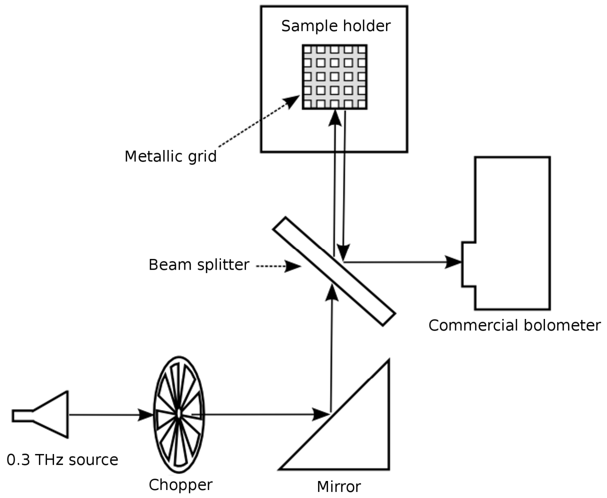

Fig. 2: Experimental THz set-up (reflection measurement)

Figure 3 shows consistency between theoretical and experimental values, with some differences. These differences are attributed to the lack of knowledge about the thin film resistivity, the thickness variation of the substrate and some defects in the grids. The defects come from an uncompleted lift-off that leaves some extra metal and therefore increases the reflection. This problem has been recently solved using wet etching instead of the lift-off process. Finally, the THz beam is not totally focused on the metallic sample, leading to uncertainties in the THz measurements.

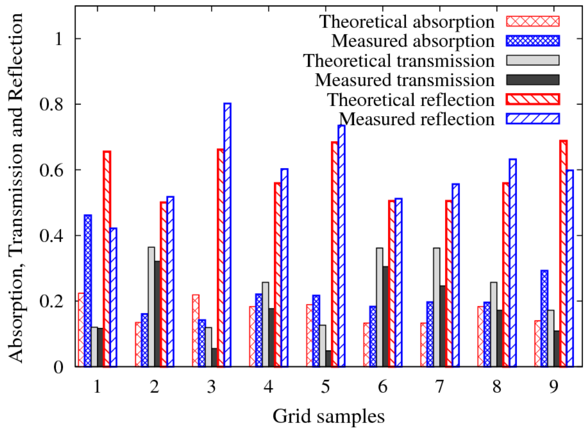

Fig. 3: Absorption, reflection and transmission, measured and predicted at 0.3 THz for different grid dimensions

3.2. Grids with extensions smaller than the wavelength

In order to improve the spatial resolution in near field applications, it is necessary to produce sub-wavelength sensors, thus preventing the resolution limit (Rayleigh criterion). With the aim of building sub-wavelength sensors, it is important to study the absorption of metallic grids with an overall dimension smaller than the wavelength. To avoid too small grids and since the EM behaviour is the same at RF frequencies, this experiment is performed at these frequencies. To generate the RF electrical field, we designed a TEM (Transverse Electro-Magnetic) guide, stripline type, with dimensions chosen to have a 50 Ω-impedance. The grid is placed in the TEM cell. Transmission and reflection are measured to deduce the absorption. Calibrations without a grid and with a "short circuit" (grids with 2a = g) are conducted to take into account losses, in particular the lateral radiation.

As seen previously, when the overall dimension of the grid is large and the pitch small (so that there is no diffraction effect), a grid can be seen as a homogeneous metallic layer with an equivalent resistivity ρ_{eq} given by equation 1. This is no longer the case when the size G_s of the grid is smaller than the wavelength. Transmission and reflection of 1 cm and 2 cm grids at 900 MHz, 1.5 GHz, 1.8 GHz and 10 GHz are measured for several values of the parameter 2a (with g fixed at 1mm). For each couple (grid size G_s / frequency f), our theoretical model is used to fit the measurement results and to determine the equivalent resistivity. Figure 4 presents the case of the couple G_s = 1cm / f = 900MHz. The variation of the equivalent resistivity, as a function of the ratio between the grid size G_s and the wavelength λ, is shown in figure 5. This variation can be explained by the fact that the current density in a sub-wavelength metal grid cannot reach the value it would reach in long metallic tracks; consequently, the equivalent resistivity increases when the ratio G_s/λ decreases.

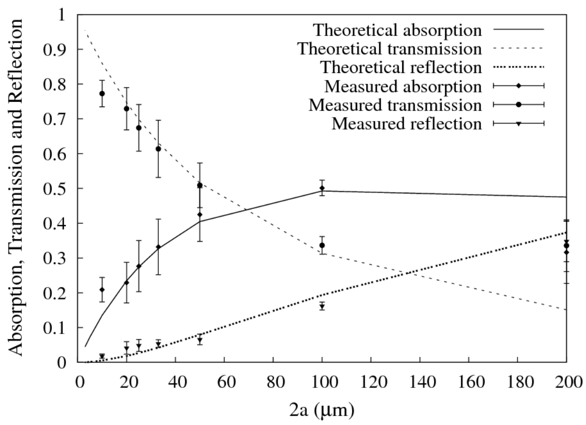

Fig. 4: Absorption measurements at 900 MHz on 1cm grids (dots)
Extraction of an equivalent resistivity (lines)

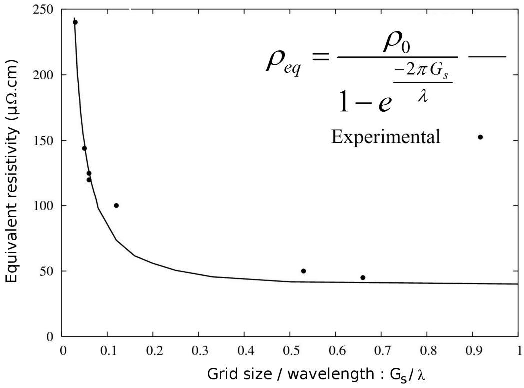

Fig. 5: Variation of the equivalent resistivity with the ratio between grid size (G_s) and wavelength (λ) at RF frequencies; ρ_0: measured resistivity of chrome film

4. Fabrication process of the THz sensor

Our THz sensor is initially designed to work at 3 THz with a spatial resolution of a few wavelengths. The size of the grids is chosen to be 3 mm that is to say 30 wavelengths. In order to increase the thermal isolation, the sensor is fabricated on a silicon dioxide (SiO_2) membrane. The process flowchart is shown in figure 6. The pattern of the membrane is defined by the deposition of an aluminium mask. The etching by DRIE (Deep Reaction Ion Etching) is stopped to leave about 15 µm of Si (cf. fig. 5a). A 1.4 µm thick SiO_2 layer is then grown by thermal oxidation and the backside oxide is removed in a bath of buffered HF (cf. fig. 6b). The metallic grid absorber and the first thermocouple track are made at the same time of titanium using evaporation deposition and conventional lift-off techniques (cf. fig. 6c). The design ensures that no short-circuit can take place with the second track of the thermocouples. The latter, made of aluminium, is also deposited by evaporation and patterned by lift-off techniques (cf. fig. 6d). Finally, a dielectric layer of SU-8 photoresist was coated and patterned to increase the absorption at 3 THz and to enhance the mechanical robustness. Its 15 µm thickness is a quarter of the wavelength with an estimated dielectric constant of 3. Because of inhomogeneity in the DRI etching of the membranes, the wafer is diced before individually finishing etching them (cf. fig 6e). Figure 7 shows a SEM (scanning electron microscope) image of the resultant THz sensor, viewed from the backside.

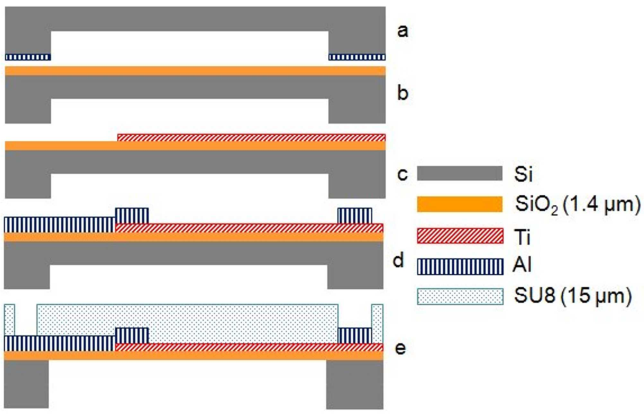

Fig. 6: THz sensor process flowchart

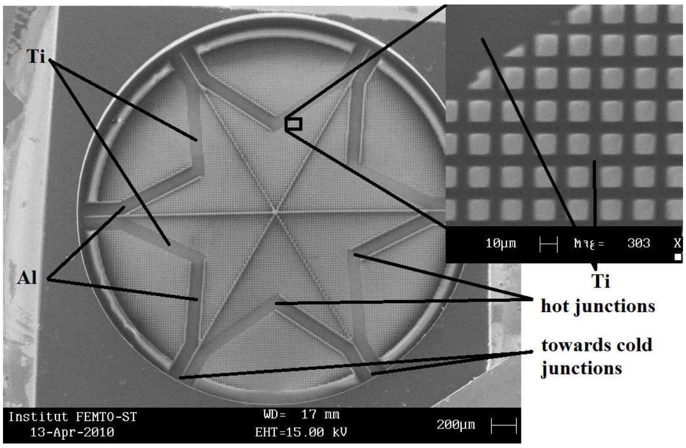

Fig. 7: Scanning Electron Microscope image of the backside of the THz sensor

5. Characterizations and discussions

5.1. Time constant

To characterize the THz sensor, the same THz source is used as for the absorption measurements of the grids. A mechanical chopper enables an amplitude modulation of the 0.3 THz wave with a frequency varying from 1 Hz to 21 Hz. The output of the sensor is connected to a lock-in amplifier. Dots in figure 8 show the evolution of the amplitude response according to the modulation frequency. The curve shows a slope of -20 dB per decade characteristic of a first order low pass, but the cut-off frequency f_c is lower than 1 Hz and cannot be obtained. It is measured by heating the sensor via a modulated laser. The cut-off frequency is approximated at 0.8 Hz, corresponding to a time constant of about 200 ms.

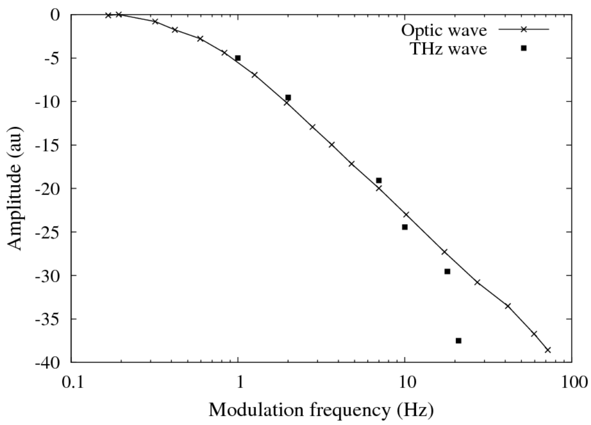

Fig. 8: Evolution of the sensor response according to the modulation frequency

Usually, a time response is calculated from the ratio between the thermal capacity and the thermal conductance of the support. However, estimating the overall thermal conductance of our sensor is difficult because the absorption is done over the whole membrane surface. Instead, we perform a 2D axisymmetric thermal modelling with the commercial software

COMSOL Multiphysics. The sensor is modelled as 1.4 µm thick SiO_2 layer on a 380 µm thick Si ring (1.5 mm for the inner radius and 3 mm for the outer one) with a SU8 toping. The finite elements simulation is governed by the following equation:

$$\rho C_p \frac{\partial T}{\partial t} + \vec{\nabla}\left(-k\vec{\nabla}T\right) = Q + qsT \qquad (2)$$

with ρ the volume density, C_p the specific heat, T the temperature, k the thermal conductivity and the second term represents the volume density power input that is null in our case. Convection law fixes the boundary conditions as:

$$-\vec{n}\left(-k\vec{\nabla}T\right) = Q_0 + h\left(T_c - T\right) \qquad (3)$$

with $\vec{n}$ the normal to the structure, Q_0 the incident surface power, h the convection coefficient and T_c the high temperature. Simulations show that the convection plays a key role in the heat transfer. By varying the input power in a sinusoidal manner and making calculations at different frequencies, we obtain a frequency response that looks like a first order low-pass filter. For several convection coefficients h, the time constant is calculated as the time needed for the temperature to reach 63% of the threshold value after an incident power step. For a typical convection coefficient h of 100 $WK^{-1}m^{-2}$ [14] a cut-off frequency of about 1 Hz is obtained, which agrees very well with the measurement results.

5.2. Sensitivity and limit of detection

The THz sensor is positioned 5 mm behind the horn antenna of the THz source. Using 0.3 THz instead of 3 THz does not change the operating principle of the THz sensor, only the absorption of the wave. The properties of the metal layer at these two frequencies are the same. The only difference is that there is no longer a quarter wavelength thick dielectric layer. The maximum absorption therefore decreases from 73% to 50% (cf. fig. 1). The maximal power of the electronic source is 1 mW and was amplitude-modulated at 1 Hz. The sensor output voltage, measured with a lock-in amplifier, is 550 nV.

From the geometry of the source and simulation with the commercial software CST microwave, we deduced that the incident power on the 1.5 mm-radius absorber is 118 µW. Since the frequency of the THz wave is 0.3 THz and not 3 THz, the estimated theoretical absorption is 50%. Simulations with COMSOL Multiphysics, assuming a uniform power density, show an increase in temperature at the hot junction of 41 mK for a constant power input. For a modulated power input at 1 Hz, the increment of temperature ΔT_{1Hz} is therefore 25 mK (cut-off frequency of 0.8 Hz). The measured impedance of the sensor is 5.7 kΩ, which is small compared to the input impedance of the lock-in amplifier. Since there are 6 Al-Ti thermocouples in series (with Seebeck coefficient S of 7.4 μVK^{-1}), a first approximation of the theoretical output voltage is:

$$V = 6 \times S \times \Delta T_{1Hz} = 1 \mu V \qquad (4)$$

This is the double of what has been experimentally found. The difference may come from a lower power density incoming to the absorber or a too simple thermal simulation (the temperature of the cold junction has been supposed constant).

The responsivity of this sensor, defined as the ratio between the output voltage and the power density, is then estimated to be 35 nV/(W/m^2) at 1 Hz.

The noise threshold of the output voltage is about 50 nV, with the time constant of the lock-in amplifier fixed at 10 s. The limit of detection (power density leading to the noise threshold) is therefore about 1.4 W/m^2, which corresponds to an electrical field of 23 V/m. The NEP (noise equivalent power), defined as the power incident on the detector required to produce a signal to noise ratio (SNR) of 1, is about 8 10^{-5} $WHz^{-1/2}$. This value is several orders of magnitude higher than what can be usually found for far infrared devices [15]. This comes from both a large amount of noise and a small responsivity.

The THz sensor is used to map the H-plane of the horn antenna. The sensor is mounted on a XY micrometric table. The set-up is fully automated with National Instruments commercial software LabVIEW. The distance between the antenna and the sensor varies between 2 and 12 cm (with a step of 10 µm), with lateral steps of 100 µm. Figure 9 displays the corresponding mapping. The maximum colour scale (white) corresponds to 300 nV. As predicted from the value of the NEP, we can note the presence of a significant level of noise. To reduce this problem, we decide to improve the responsivity by using doped Si-metal thermocouples. As mentioned before, the measurement of the Seebeck coefficient of the thin film couple (Ti / doped Si) was 25 times greater than that of the Seebeck coefficient of the thin film couple (Ti/Al). The gain in the responsivity should be of the same order of magnitude.

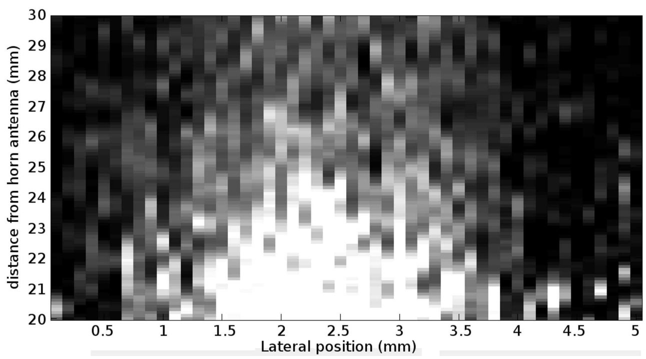

Fig. 9: H-plane mapping of the horn antenna using the THz sensor
(White colour corresponds to 300 nV)

6. Conclusion

The conception, realization and characterization of a room temperature THz sensor using a thermopile are presented. The absorber is designed as a metallic grid in order to have a thicker layer, easier to deposit. As a trade-off between sensitivity and spatial resolution, its radius is 1.5 mm. Six Ti/Al thermocouples are chosen to measure the variation of temperature. This topology brings an amplified thermal to electrical conversion efficiency while keeping a relative simplicity of the fabrication process within our clean room facilities. The metal grid is deposited on a 3 mm-diameter silicon dioxide membrane. A SU8 dielectric layer is added to improve absorption at 3 THz that however brought no advantage for the absorption because the characterizations are performed at 0.3 THz. The measured time constant of the overall sensor is 200 ms which is consistent with thermal simulations. Corresponding responsivity is estimated at 35 nV/(W/m^2) and its limit of E-field detection at 23 V/m. The NEP is 8 10^{-5} WHz$^{-1/2}$, which is very high. A study to reduce the noise has to be undertaken. The mapping of the H-plane of a horn antenna operating at the output of a 0.3 THz source by our THz sensor confirms the presence of a large amount of noise. Improved sensors will be made with doped Si/metal thermocouples and without the dielectric layer whose usefulness shown here was only to increase the mechanical robustness. Both responsivity and SNR are expected to increase. With a better sensivity we could reduce the dimension of the sensor, thereby allowing better spatial resolution. Thanks to the measurements of the equivalent resistivity as a function of grid size that were presented here, we are able to determine the optimum metal thickness for these future sub-wavelength sensors.

Acknowledgments

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Vitae

Sofiane Ben Mbarek was born in Tunisia (Kebili) in 1980. He received his B.S. degree in Electronic Engineering from the University of Toulon, France in 2005 and his M.S. in Telecommunications Radio Frequency and Microelectronic from the University of Nice Sophia Antipolis, France in 2007. He received his PhD. degree in 2011 in Engineering Sciences from the University of Franche-Comté, Besançon, France. His research involves sensors and instrumentation.

Sébastien Euphrasie was born in Bayeux, France, in 1976. He graduated from Ecole Centrale de Lille in 1999 and received his Ph.D. degree in electronics from the University of Valenciennes, France, in 2002. He was then working on active materials for Microsystems. He joined the FEMTO-ST Institute, Besançon, France, in 2004 as an Associate Professor. His current research focuses on Instrumentation, especially in Electromagnetics.

Thomas Baron obtained a PhD in Nano and Micro Electronics from the University Joseph Fourier in Grenoble in 2008. His Ph.D. was focused on the integration of NEMS with industrial CMOS process based on the SOI technology. He has been a researcher at the FEMTO-ST Institute in Besançon since 2008. His research was first focused on electromagnetic absorption for bolometer applications in the Micro Nano Sciences and Systems (MN2S) Department. His current research is focused on the micro fabrication processes for filters or resonators applications based on monocrystal material.

Laurent Thiery was born in France in 1965. He is graduated from Franche-Comte University. After a Ph.D. of Engineering Science obtained in 1994, he received the Habilitation degree in 2009. Since 1995 he has been assistant professor in thermal science. His research activities are mainly focused on the development of thermal probes for near-field imaging techniques.

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