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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 2. Section 3 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 5 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 5. 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.

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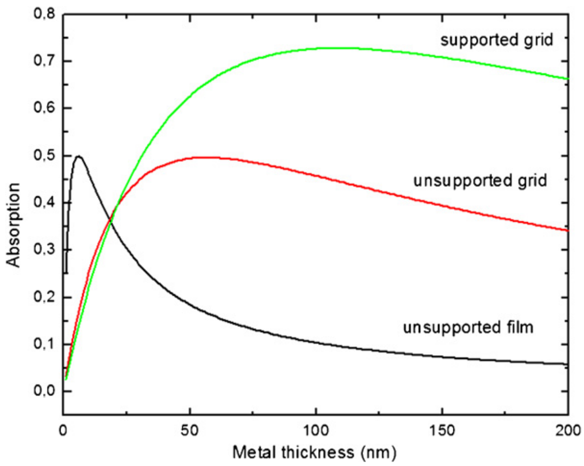

Fig. 1. Absorption of an unsupported metallic film, an unsupported metallic grid, and a grid with a $\lambda/(4n)$ thick dielectric placed before; $\rho_m = 5.4 \times 10^{-7}$ Ωm, $g = 20$ μm, $2a = 2$ μm, $n = 1.7$.

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

$$\rho_{eq} = \rho_m \cdot \left(\frac{g}{2a}\right) \quad (1)$$

with ρ_m the resistivity of the metal, g the pitch of the grid and $2a$ the width of the grid lines. Fig. 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 $\rho_m = 5.4 \times 10^{-7}$ 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. Fig. 1) a dielectric layer can be placed before the grid. With its thickness a quarter of the wavelength $\lambda/(4n)$ (refractive index n), the reflected waves are in-phase and increase the absorption.

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.

Table 1
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

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 1) are deposited on glass wafers using a lift-off process. Their overall dimensions of 1.5 cm × 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.

Fig. 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 Fig. 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. 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.

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