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I. INTRODUCTION

For years, thermoreflectance techniques have been used to perform thermal imaging of heterogeneous materials. Working at visible wavelength allows a spatial resolution close to 1 μm. Furthermore, the use of ultra-fast lasers allows a picosecond time resolution. Tessier et al. have shown that the nature of the material under investigation and the wavelength play a crucial role on the temperature measurement sensitivity. The authors reported, in the visible domain, an optimal wavelength by maximizing the sensitivity to the temperature. In this domain, the thermoreflectance coefficient \( \kappa \) varies from \( 10^{-4} \) to \( 10^{-6} \) K\(^{-1}\). Mainly due to the short wavelength, it has also been shown that the thermoreflectance technique is sensitive to surface displacements induced by thermal dilation or focusing conditions. This drawback is a major source error for quantitative temperature measurements and may be avoided by using larger wavelengths.

For some years now, THz 2D imaging (and even 3D tomography) of semiconductors and insulating materials have been discussed and demonstrated. THz waves are defined as a very far IR wavelength covering a spectral range from 30 μm to 3 mm. A key point of THz electromagnetic waves is their non-ionizing properties: the low photon energy of this radiation (~meV) is considered as an important safety feature for applications unlike x-rays, for example. For those reasons, THz technology is clearly an interesting alternative for temperature imaging and opens wide potentialities in domains such as Physics, Biology, or Medicine. Apart from their well-known spectroscopic potential, imaging techniques are growing rapidly, particularly in research and industrial applications (i.e., online non-destructive inspection and monitoring of processes).

Based on works previously reported, we have developed a very useful technique to characterize THz beams (profile, power distribution, etc.) by measuring the power of an incident THz beam absorbed on a thermal converter.

In this paper, we carry out transient temperature measurements by analysis of the reflected millimetric beam focalized on a temperature dependent media. We aim to demonstrate the ability to perform transient temperature measurements on a thin layer using a compact and millimeter imaging system and to validate the ability of a THz electromagnetic wave to pass through a thick and opaque layer of Teflon.

The optical source is a continuous monochromatic millimeter wave emitter at 110 GHz (2.8 mm) delivering a 20 mW average power. The millimetric beam is modulated by a mechanical chopper (33 Hz) and collimated by a gold coated 150 mm focal length off axis parabola (OAP). The incident beam is focused on the sample by a commercial 60 mm focal length plano-convex Teflon lens. A 5 cm thick Teflon plate is inserted between the lens and the sample. Teflon is optically opaque to any visible wavelengths from 400 nm to 800 nm. Hence, we seek to prove that this experimental system is able to perform temperature imaging through an opaque material.

II. EXPERIMENTAL SETUP

The aim of the setup presented in Figure 1 is to demonstrate the ability to perform transient temperature measurements on a thin layer using a compact and millimeter imaging system and to validate the ability of a THz electromagnetic wave to pass through a thick and opaque layer of Teflon.

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FIG. 1. GHz thermoreflectance setup using a 2.8 mm laser diode source. The sample is placed behind a 5 cm thick Teflon plate and is coupled to an electrical heater and a thermocouple to precisely control and measure its transient temperature.

All the optics have a 2 in. diameter (NA 0.5) allowing a near-diffraction limit beam size (7 mm $\sim 2\lambda$).

The reflected millimeter wave is focused on an Optrics pyroelectric mono-sensor and the signal is filtered by a lock-in detection to improve the signal-to-noise ratio (a typical time constant of 1 s is used) and to remove the artifacts coming from the environment (temperature variations, optics, or sample proper emission).

To accurately control its temperature, the sample is embedded between a thermal insulator and an electrical heater. The thermocouple, embedded inside the heater, is used to monitor the temperature variations versus time.

III. EXPERIMENTAL VALIDATION

First, we characterize the millimetric thermoreflectance coefficient for aluminum, copper, and silicon. In each case, an electrical signal drives the heater plate and heats up the sample. The electrical power has been set to produce a temperature rise of about 30 K. The temperature response as a function of time is showed for the 3 materials for both thermoreflectance THz signal (Figure 2) and thermocouple (Figure 3).

The thermoreflectance method uses the relationship between the optical reflectivity R and the temperature T of a given material:

$$\frac{R(T) - R(T_0)}{R(T_0)} = \kappa \frac{\partial R}{\partial T} = \kappa (T - T_0). \quad (1)$$

According to Eq. (1), an inverse method is used to estimate the thermoreflectance coefficient $\kappa$ (K$^{-1}$) with the following equation:

$$\frac{R(T) - R(T_0)}{R(T_0)} = \kappa \left[ (T - T_0) + \tau \frac{d(T - T_0)}{dt} \right], \quad (2)$$

where $\tau$ (s) is a delay between the 2 signals given by the thermocouple and measured by thermoreflectance. A
Gauss-Markov algorithm\(^{20}\) is applied to fit the experimental data and identify the 2 unknown parameters \(\kappa\) and \(\tau\) as shown in Figure 4.

The estimated values of \(\kappa\) and \(\tau\) for Al, Cu, and Si are reported in Table I.

The maximum thermoreflectance coefficient for a visible wavelength is of the order of \(10^{-5}\) K\(^{-1}\) for both metals and Si. Using a millimetric radiation, the measured coefficient \(\kappa\) is \(7 \times 10^{-3}\) K\(^{-1}\) for Si and about \(10^{-3}\) K\(^{-1}\) for metals, those values are 2 order of magnitude higher compared to visible wavelengths. To our knowledge, such high values have never been reported.

### IV. CONCLUSION

In this paper, we have broadened the thermoreflectance technique from visible to millimeter wavelengths. We have demonstrated the ability of those millimetric radiations to pass through a thick plate of Teflon opaque to visible wavelengths and perform transient temperature measurements of metallic and semiconductor materials. By monitoring the temperature of the sample, we have estimated the thermoreflectance coefficient of aluminum, copper, and silicon. We report giant thermoreflectance coefficients whose values are a 100 times higher at 2.8 mm compared to optimized coefficient previously reported for visible wavelength. Theoretical studies are currently led to provide a clear explanation of those effects and will be further presented.

The transparency properties and the high sensitivity of millimetric thermoreflectance technique reported in this paper open a wide range of applications in the domain of heat transfer and transient thermal measurement of materials located behind opaque shields like plastics, wood, or concrete.

### TABLE I. Measured thermoreflectance coefficients for 2.8 mm compared to value in the visible domain.

<table>
<thead>
<tr>
<th>Material</th>
<th>(\kappa) (K(^{-1}), at 2.8 mm)</th>
<th>(\kappa) (K(^{-1}), average for visible wavelength)</th>
<th>(\kappa) (K(^{-1}), max for visible wavelength)</th>
<th>(\tau) (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al</td>
<td>(-1.4 \times 10^{-3})</td>
<td>(1 \times 10^{-5}) 21</td>
<td>(1 \times 10^{-4}) 21</td>
<td>(-2.4)</td>
</tr>
<tr>
<td>Cu</td>
<td>(1.6 \times 10^{-3})</td>
<td>(\ldots)</td>
<td>(1.5 \times 10^{-4}) 22</td>
<td>(5.5)</td>
</tr>
<tr>
<td>Si</td>
<td>(7 \times 10^{-3})</td>
<td>(4.5 \times 10^{-5}) 23</td>
<td>(\ldots)</td>
<td>(-1)</td>
</tr>
</tbody>
</table>


