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Thermoreflectance temperature measurement with millimeter wave

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GigaHertz (GHz) thermoreflectance technique is developed to measure the transient temperature of metal and semiconductor materials located behind an opaque surface. The principle is based on the synchronous detection, using a commercial THz pyrometer, of a modulated millimeter wave (at 110 GHz) reflected by the sample hidden behind a shield layer. Measurements were performed on aluminum, copper, and silicon bulks hidden by a 5 cm thick Teflon plate. We report the first measurement of the thermoreflectance coefficient which exhibits a value 100 times higher at 2.8 mm radiation than those measured at visible wavelengths for both metallic and semiconductor materials. This giant thermoreflectance coefficient κ , close to 10^{-3} K^{-1} versus 10^{-5} K^{-1} for the visible domain, is very promising for future thermoreflectance applications. © 2014 AIP Publishing LLC. [<http://dx.doi.org/10.1063/1.4884639>]

I. INTRODUCTION

For years, thermoreflectance^{1–7} techniques have been used to perform thermal imaging of heterogeneous materials. Working at visible wavelength allows a spatial resolution close to $1 \mu\text{m}$. Furthermore, the use of ultra-fast lasers allows a picosecond time resolution. Tessier *et al.*⁸ 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 $\kappa \text{ (K}^{-1}\text{)}$ varies from 10^{-4} to 10^{-6} K^{-1} .⁷ Mainly due to the short wavelength, it has also been shown^{8,9} 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.^{10–15} THz waves are defined as a very far IR wavelength covering a spectral range from $30 \mu\text{m}$ to 3 mm . A key point of THz electromagnetic waves is their non-ionizing properties: the low photon energy of this radiation ($\sim \text{meV}$) 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.¹⁴ 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,^{16,17} we have developed a very useful technique^{18,19} 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. A classical thermoreflectance scheme is applied using a millimetric probe instead of a visible one. Like pointed above, the transparency of such wave to materials classically opaque to visible or near infrared allows temperature measurements of reflective materials placed behind a shield of plastic, wood, or concrete. Our measurements were performed on materials hidden behind a 5 cm thick plate of Teflon. First, the experimental setup is described and the principle of the method is detailed. Then, the temperature measurements obtained on silicon, aluminum, and copper plates are presented. Finally, the thermoreflectance coefficient is given by comparing the temperature variation measured with a thermocouple and the reflected millimetric signal.

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 GHz 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.

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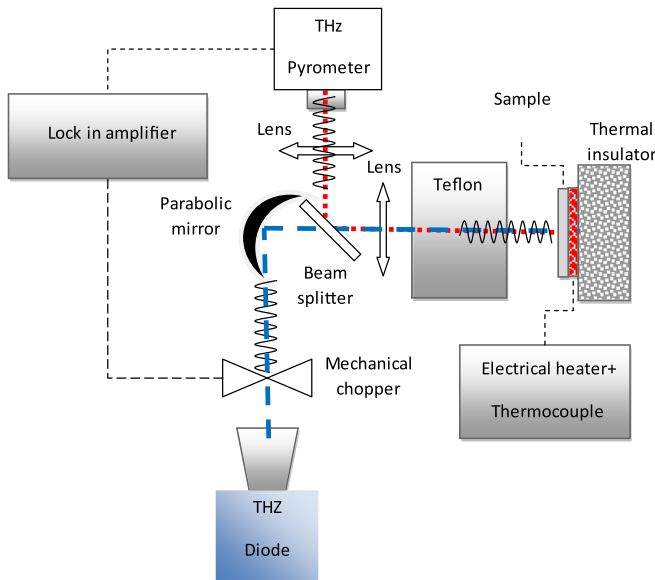


FIG. 1. GHz thermoreflectance setup using a 2.8 mm laser diode source. The sample is placed behind a 5 cm thick Teflon plate and is coupled to an electrical heater and a thermocouple to precisely control and measure its transient temperature.

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

The reflected millimeter wave is focused on a 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,

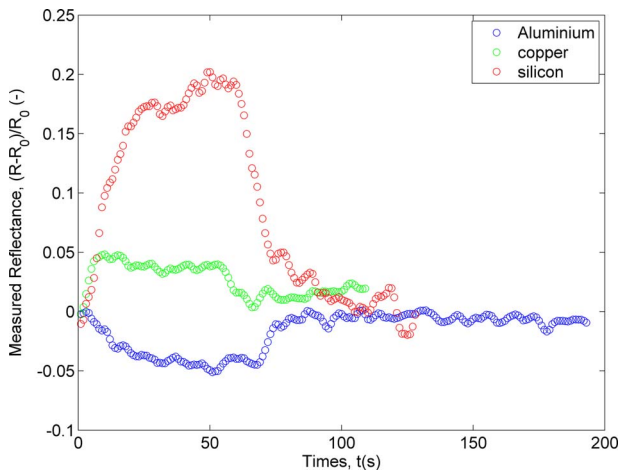


FIG. 2. Transient thermoreflectance response with millimetric wave (2.8 mm) for Cu, Al, and Si versus time.

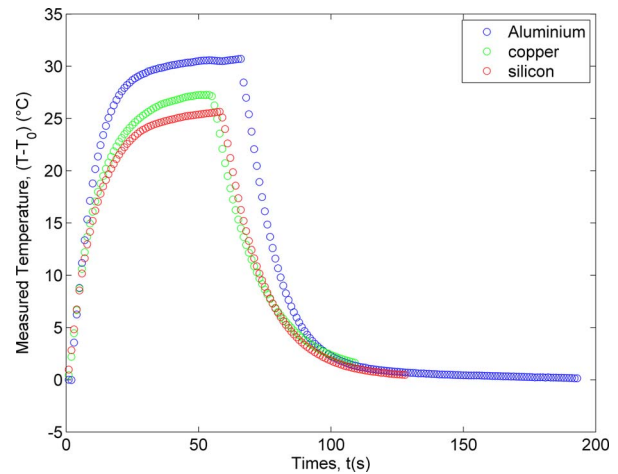


FIG. 3. Transient temperature monitored by the thermocouple for Cu, Al, and Si versus time.

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:

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

According to Eq. (1), an inverse method is used to estimate the thermoreflectance coefficient κ (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 τ (s) is a delay between the 2 signals given by the thermocouple and measured by thermoreflectance. A

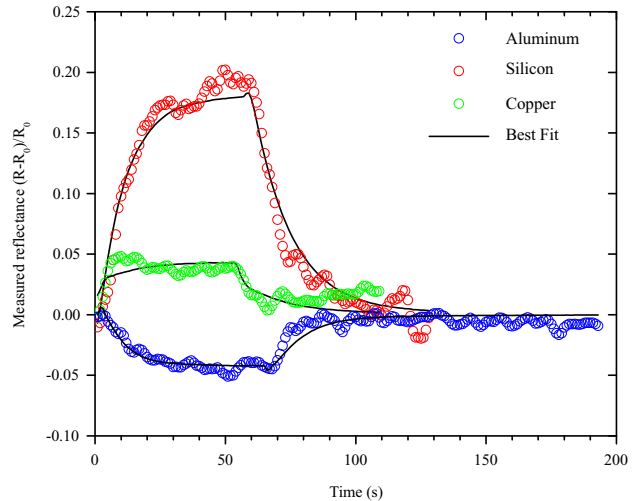


FIG. 4. Experimental (dots) and adjusted thermoreflectance signals (lines) for Al, Cu, and Si as a function of time.

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

	Al	Cu	Si
κ (K ⁻¹), at 2.8 mm	-1.4×10^{-3}	1.6×10^{-3}	7×10^{-3}
κ (K ⁻¹), average for visible wavelength	1×10^{-5} ²¹	...	4.5×10^{-5} ²³
κ (K ⁻¹), max for visible wavelength	1×10^{-4} ²¹	1.5×10^{-4} ²²	...
τ (s)	-2.4	5.5	-1

Gauss-Markov algorithm²⁰ is applied to fit the experimental data and identify the 2 unknown parameters κ and τ as shown in Figure 4.

The estimated values of κ and τ 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⁻¹²¹ for both metals and Si. Using a millimetric radiation, the measured coefficient κ is 7×10^{-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.

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