Experimental study of scattering effects of THz waves by clothes

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Abstract—Detection of dangerous or prohibited substances is one of the greatest applications expected in the THz domain. In this context, interaction between fabrics and THz waves is of prime importance. We propose in this paper an experimental method to characterize the radiometric response of fabrics, which is illustrated by the case of linen. In particular, by using a goniometer THz-TDS setup, we are able to measure the signal scattered by the sample. We then determine the absorption coefficient of linen. Our results strongly differ from those obtained by a classic THz-TDS setup for frequencies above 0.9THz.

One of the main applications of the technology of terahertz (THz) electromagnetic waves is certainly the security issue [1−2]. Thanks to the transparency, in the THz domain, of clothes and covering, wrapping and packaging materials (papers, plastic sheets, cardboards, …), a THz camera could help, at check points (borders, airport gates, …), verifying if people do not carry hidden dangerous or prohibited substances (explosives, drugs, …) or items (weapons), without body frisking or taking an X-ray image of people. Beside the development of smart THz matrix sensors and cameras [3−5], the interaction of THz waves and fabrics is of prime importance to determine the THz signals that are expected to be delivered by hidden materials and items. Fabrics have already been extensively studied in the THz range [6], mostly to determine their absorption coefficients versus different parameters, such as the type of fabrics, thickness, humidity, ….

Because most of the fabrics are manufactured by weaving or knitting, their structure is made of a network of interlaced yarns or threads, themselves often produced by interlocking fibres. Some of these threads and fibres exhibit a diameter or periodicity whose dimensions are of the order of a THz wavelength or smaller, resulting in diffraction and/or scattering when the THz wave is transmitted or reflected by fabrics. When using classical methods, like FTIR and THz time-domain spectroscopy (TDS) for measuring the coefficient of absorption of fabrics, scattering induces an additional loss of energy in the transmitted or reflected beams. This leads to overestimating the absorption in the material, and consequently to errors in the determination of the refractive index of fabrics.

In this paper, we report on the experimental study of the THz light scattered when a THz beam passes through fabrics. The measurements are performed using a THz-TDS set up, which delivers large bandwidth (0.1~5THz) THz signals and which has been fibered in order to easily measure the light scattered out of the incident plane.

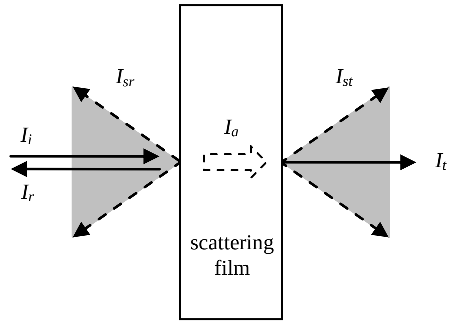

Fig. 1. Scheme showing different THz signals involved in the transmission/reflection process of a THz beam propagating through a scattering film.

Figure 1 shows a scheme of principle with different THz signals transmitted (indexed *t*), reflected (*r*) and scattered (*s*) when a scattering film (here linen) is illuminated by an incident (*i*) beam. Part of the beam intensity I is also absorbed (*a*) by the material itself, i.e. it is transformed into heat. We suppose the incident beam is a Gaussian one of limited waist. The conservation of energy implies [7]:

$$I_i = I_r + I_{sr} + I_a + I_t + I_{st} \tag{1}$$

In (1), I_r and I_t are the intensities of the reflected and transmitted beams that are not scattered, i.e. their Gaussian shape is preserved. Using classical THz-TDS, only E_r or E_t (or both) are measured (E is the electric field of the THz beam, $I \propto E^2$). E_{sr} and E_{st} are neglected, resulting in E_a overestimation and thus of the absorption coefficient α. Here, we make use of a goniometric TDS set up, which allows us to measure E_r, E_t and E_{st}, and then to deduce the corresponding intensities. In a second time, E_a, and thus α, can be obtained from the measured data and from (1).

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Our THz-TDS setup [8] uses LTG-GaAs photoswitches as THz antennas excited by 100fs laser pulses at λ=800nm. The receiving antenna is triggered thanks to a delayed laser pulse delivered through an optical fibre whose dispersion is pre-compensated. It is placed on a rotating arm at 15cm from the rotation centre. This antenna is made of a classical Auston switch on which a 1.5 cm diameter high-resistivity silicon hyper-hemispherical dome is attached. The sample is placed at the centre of the goniometer and is illuminated under normal incidence. The angular resolution is 1°. To measure the signal reflected by samples, a 45° orientated beam splitter can be added. We chose to characterize a 35×35 mm^2 square of linen that is 500µm thick.

The first experimental stage consists in measuring the signal reflected by linen. The results are presented in Fig. 2. We can see that I_r remains weak, and is less than 1% above 0.4THz. Since the reflected intensity is negligible, and as the signal scattered in transmission I_{st} is much weaker than the one directly transmitted I_t (see below), we make the hypothesis that the signal I_{sr} scattered in reflection is as well smaller that the one reflected I_r, and thus it is insignificant.

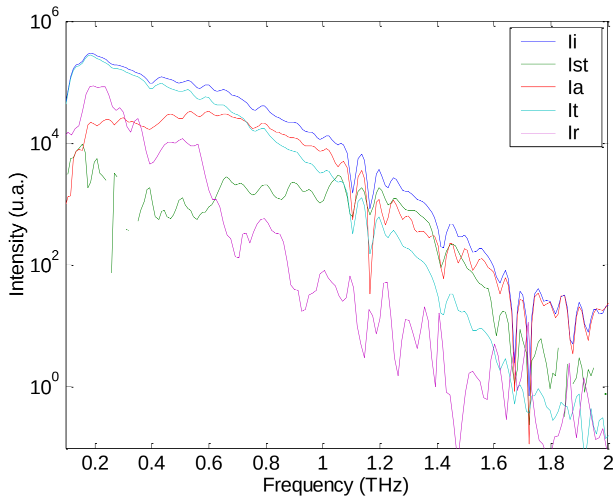

Fig. 2. Incident, scattered, absorbed, transmitted and reflected signal spectra.

The second step is to determine I_{st} and I_t. An angular study is then carried out. A first run of measurements, consisting in measuring the signal every two degrees of detection without any sample, is carried out to characterize the incident beam. This allowed us to confirm its Gaussian shape and to establish I_i. The second time, the piece of linen is placed at the goniometer centre and a second run of measurements is performed in the same experimental conditions. The plots obtained at 1THz are shown in Fig. 3.

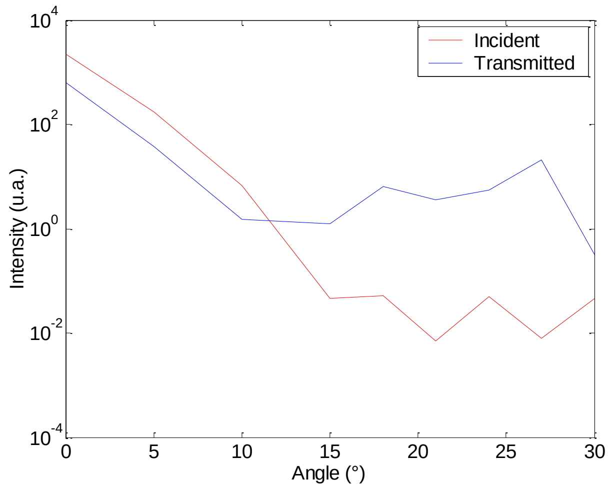

Fig. 3. Incident and transmitted beam intensities at 1THz measured with a goniometric THz-TDS setup.

At higher detection angles (above 15°), incident signal reaches noise level. The entire signal detected behind the sample at these angles comes then from the scattering effect occurring in the fabrics. Since at each frequency this signal is roughly constant between 15° and 30°, we consider it to be constant at all angles (Lambertian-type scattering). This allows the transmitted signal I_t to be discriminated from the scattered one at each angle and for each frequency. I_{st} is then computed by integrating the scattered signal from 0° to 90°. I_a is finally deduced from (1). All the spectra can be seen in Fig. 2.

The transmitted signal slowly decreases from almost 100% below 0.2THz to less than 10% above 1.2THz. This loss in transmission at low frequencies is mainly due to absorption in the linen. However, between 0.9THz and 1.6THz, scattering must be considered as the scattered signal reaches up to 60% of the incident signal. This can be explained by the diameter of the yarns composing the fabrics (330µm). Below 0.9THz, the signal wavelength is less than the size of the scattering elements (yarns, fibres) and thus is not or very little affected. Above 1.6THz, scattered signal is weak again, representing less than 10% of the incident signal. The few peaks observed are artefacts due to water absorption.

The linen absorption coefficient α can be connected to I_a through Beer-Lambert law:

$$I_a = I_i\left(1-e^{-\alpha d}\right) \tag{2}$$

where d is the sample thickness, here 500µm. The plot presented in Fig. 4 is obtained from our measurements and (2). To facilitate the comparison, we also plot the absorption coefficient that can be deduced from classical

THz-TDS experiment (i.e. neglecting scattering).

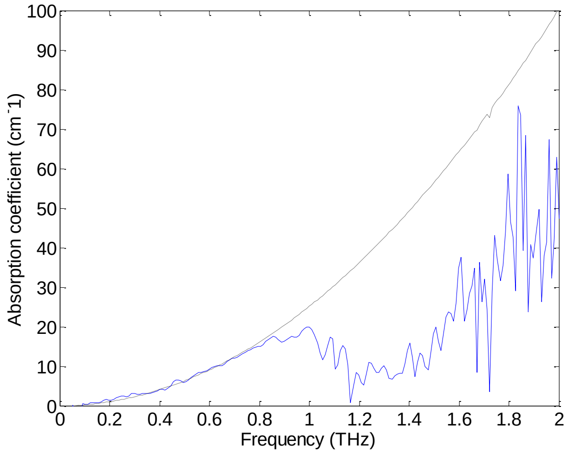

Fig. 4. Linen absorption coefficient deduced from classical THz-TDS experiment (dotted line) and from scattering measurements (plain line).

The absorption coefficient determination is directly influenced by our previous observations. At low frequencies, the two curves overlap since the scattering effect is very weak. From 0.9THz, half of the signal loss is due to the scattering properties of linen fabrics. With a classical THz-TDS experiment, the results obtained do not represent an absorption coefficient, but rather a coefficient including all the loss occurring in the sample (absorption + scattering). Our method is therefore more precise. Let us however notice that the absolute value of α given in Fig. 4 is not precise, as the thickness of the linen cloth is not measured with high precision (using for example a dial calliper can compress the sample). But, even if the vertical axis scale is imprecise, the shape of the curves in Fig.4 is well established. To derive the absorption of the linen yarn itself, a proportion of yarn volume in the fabrics should be included in the calculation. This parameter is, however, difficult to evaluate.

In conclusion, this paper presents the radiometric response of a piece of linen cloth. The sample is characterized thanks to a THz-TDS goniometer setup. For the first time, we are able to evaluate all the signals transmitted and reflected, as well as scattered and absorbed by the sample. We determine that the reflexion on linen is very weak. At lower frequencies below 0.9 THz, i.e. when the THz wavelength is larger than the smaller dimensions of the scattering structures (yarn, fibre), the loss in transmission is mainly due to absorption, but over 0.9THz a scattering effect adds up. The absorption coefficient computed from these measurements is compared to the one obtained with a classic THz-TDS setup. The classic method is accurate enough for low frequencies below 0.9THz but overestimates absorption for higher frequencies when scattering occurs.

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