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A THz Scanner to Detect Moisture on Wood Samples

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***Abstract* –Wood is a hygroscopic material that is subject to phenomena of water exchange with the external environment. These exchanges can cause dimensional variations and cracks to appear on a macroscopic level.**

In recent years, the use of terahertz technologies in the field of diagnostics applied to cultural heritage has increased considerably. One of the most important characteristics of terahertz radiation is its sensitivity to water content; this polar liquid strongly absorbs and reflects this radiation.

The subject of this study will be the detection of moisture in pine wood samples using a 97 GHz terahertz imaging system.

I. INTRODUCTION

In recent years, strong interest has developed in terahertz (THz) radiation, which is a powerful investigative tool in various fields of application, such as in the field of diagnostics applied to cultural heritage. At these frequencies, materials with a wide band gap, such as insulators (plastics, paper, wood, ceramics, etc.), are transparent, while metals totally reflect this radiation [1-5].

This type of radiation, due to its longer wavelength, has a greater penetration both than UV/VIS radiation, which is limited to the surface layer, and infrared radiation, whose penetration does not go beyond the preparatory layer. These characteristics can be used in the field of cultural heritage. Indeed, the high penetrating power gives us the possibility of observing the internal structures of an artwork, without using X-ray radiation, which has excellent penetration properties in materials, but due to the high energy of the photon it is ionizing and invasive and therefore difficult to use in practice, especially for field measurements. As mentioned before, since the energy of the THz photon is low, this type of radiation is non-invasive, non-destructive and above all safe for operators and objects [6].

Terahertz radiation can be used for Imaging and Spectroscopy applications, which allow us to analyse the sub-surface layers of pictorial surfaces and mosaics, detect hidden paintings, defects or structural detachments in artwork, as in the case of frescoes [7]. Another distinctive feature of THz radiation is its high sensitivity to the presence of water; at these frequencies the water absorbs and reflects this radiation and through this detail we are able to detect infiltration damage under mosaics and frescoes [8].

In addition, THz-TDS (THz-time domain spectroscopy) was applied to layers of papyrus sheets written with carbon black ink, with the aim of reading their contents [9]. Furthermore, THz techniques have been tested both on cases in which the writing was completely covered by stains [10], as well as for the characterization of iron gall inks [11].

Unlike wood panels, canvases are more transparent at THz frequencies; THz techniques have been applied to underdrawings detection, as demonstrated in [12]. With regard to paintings on canvas, terahertz techniques are able to map pigments on wall paintings [13] although the most important application on this type of art is to assess the extent of cracks in the plaster [14].

Another application of THz radiation concerns the study of tissue-wrapped objects such as mummies, which are usually examined by routine techniques such as X-ray radiography or computed tomography systems [15,16]. Obviously, THz radiation does not have the same depth of penetration as radiography, but at the same time it provides images of objects wrapped in bandages [17]. Indeed, it has been applied to mummies of small animals and parts of mummified human bodies to study the soft tissue attached to the surface of the bandages [18].

In this study, a THz imaging system was used to detect moisture on a pine wood sample.

II. THZ SCANNER AT 97 GHZ

This THz scanner, designed in the laboratories of the ENEA centre in Frascati, near to Rome, has already been successfully applied in the fields of aerospace and

precision agriculture [19-22]. For this study, this imaging system operating in reflection, although it can be modified to work in transmission, was used to detect moisture on a wood sample (Fig. 1).
This system for detecting information on the sample exploits the phase shift phenomenon, that occurs during the reflection process. A more in-depth description of this phenomenon is described in [8]. Moreover, this experimental system is designed to simultaneously move both the source and detector of the reflected radiation. The system has the possibility of moving the source/detector block along the third co-ordinate, i.e. along the z-axis, orthogonally to the surface of the work, bringing it closer to or further away from it, in order to exploit the phenomenon of phase shift in this way.

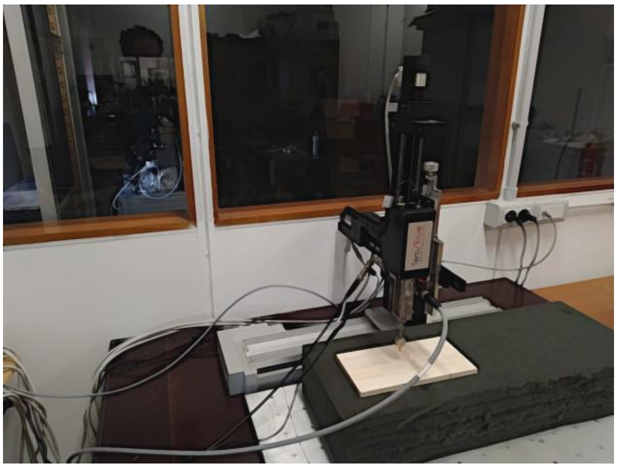

Fig. 1. THz scanner at 97 GHz.

The core of the system are the three motors that allow the source/detector to be positioned at the desired point and to do this, the engines are controlled via appropriate controllers, interfaced to a PC via a USB port. Therefore, these three controllers are responsible for adjusting all motor parameters along the axes (X, Y, Z).

A control software, based on the graphical programming language LabView was developed to perform both imaging and phase measurements.

The resolution of the motors is higher than required, especially for the X and Y axis motors. Therefore, a resolution of a few hundred microns is more than sufficient, considering that the lateral resolution of the system is physically limited by the diffraction limit for the wavelengths involved, on the order of a millimetre. For the vertical axis, a motor equipped with a gearing system was chosen, which allows it to move heavier loads, at the expense of speed.
Such a system is capable of moving the source/detector at a speed of 100 mm/s, so scanning a 30x50 cm area with a lateral resolution of 1 mm requires the scanning of 300 rows, each of which takes 5 seconds. Considering an additional second for moving from row to row, this results in a time of approximately 30 minutes. Actually, the real scanning speed is limited by the time it takes to acquire the data, which currently slows the system down by about 30%. It is possible to eliminate this slowdown through hardware/software optimisation of the acquisition system.

The device consists of an IMPATT-type source with a fixed frequency of 97 GHz, a directional coupler, a laser triangulation system and finally a Schottky diode used as a detector for reflected radiation.
The instrumentation with which the measurements were carried out uses an IMPATT-type source manufactured by the TeraSense company (see Figure 2).

Fig. 2. THz source.

This source, whose acronym is (Impact ionisation Avalanche Transit Time), has a frequency fixed at 97 GHz. It is a semiconductor diode used in microwave and THz applications. It has an output power of 70 mW and has a reverse polarisation, in fact it exploits the phenomenon of the avalanche effect.

A fraction of the reflected signal from the sample is collected by the directional coupler. A three-port directional coupler based on the WR-10 waveguide has been used in the imaging system, with 3 dB attenuation on the port used for reflected radiation.

In this study, the THz radiation generated by the IMPATT source is launched towards the sample via a truncated rectangular waveguide (TE mode, Electric transverse), (see Figure 3).

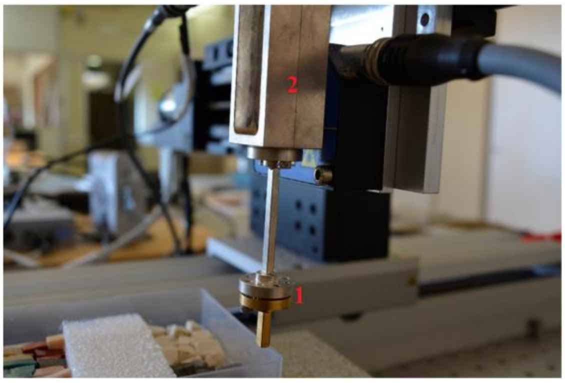

Fig. 3. Some components of the system; (1) truncated wave guide, (2) directional coupler.

Part of the radiation is reflected back at the exit of the truncated guide, because there is no adaptation to vacuum. A second component of the radiation is thrown towards the sample. Once it hits the sample, it is reflected and injected back into the same waveguide, overlapping with the first component reflected from the truncated guide. This generates constructive or destructive interference phenomena.

The reflected signal from the sample, interfering with the reflected component from the end part of the waveguide, allows us to obtain information on the phase, and consequently on the optical characteristics of the sample.

The Schottky diode is a particular type of metal-semiconductor junction diode which is characterised by having a low threshold voltage and high switching speed. The low threshold voltage allows very small signals to be detected, while the high switching speed means that the diode can follow the oscillations of the electric field up to frequencies of the order of hundreds of GHz.

Figure 4, shows the Schottky diode used in this study.

Fig. 4. Schottky diode.

It is desirable to be able to accurately measure the distance between the waveguide and the sample, both to be able to position it correctly and to exploit the system's ability to measure the phase of the reflected radiation. The phase value also depends on both the distance of the sample and the optical properties of the sample itself, and it is therefore crucial to be able to measure this distance accurately.

With the laser triangulation system (see Figure 5), it is possible to obtain information on the surface distance of each pixel in the image and, if the surface is not planar, the system is able to correct it.

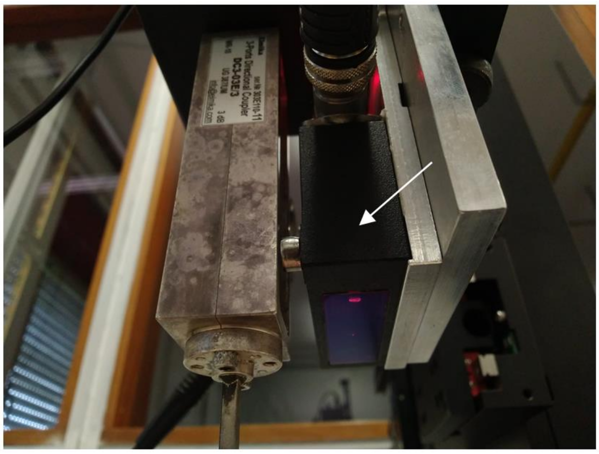

Fig. 5. The white arrow indicates the laser triangulation system.

Laser triangulation sensors emit a narrow beam that is projected onto an object or sample, and light reflected from the object's surface is focused by a high-quality optical lens onto a charge-coupled device (CCD) or complementary metal-oxide semiconductor (CMOS) image sensor.

Precisely, in this work, a laser sensor, having a wavelength of 670 nm (visible/red), with an optical power of $\leqslant$ 1 mW was used. The chosen model, ILD-1402-50 is capable of measuring distances between 50 and 100 mm with a resolution of 5 µm.

III. THE IMAGING SYSTEM MANAGEMENT SOFTWARE

LabView was used as control software of the terahertz imaging system. LabVIEW is a programming language developed by National Instruments for the creation of automatic measurement and/or control systems. Since this software mimics the appearance and operation of physical tools, LabView programmes are called virtual tools (VI).

They are characterised by a front panel and a block diagram. Figure 6A-B show the front panel and part of the block diagram of the THz imaging system.

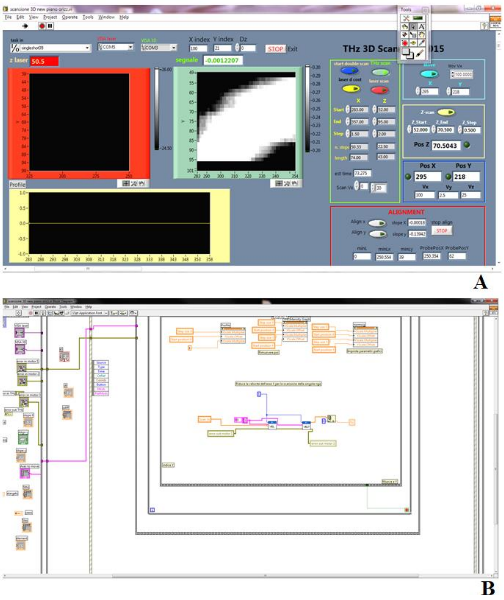

Fig.6. (A) Front panel and part of the block diagram of the THz imaging system (B).

IV. SAMPLE

As it is well known, pine and spruce, have a negative reputation because of the pitch they contain, but when well-seasoned and cleared of all traces of resin, they are perfectly suited for the production of wooden panels for icons [23].

For simulating the moisture below the wood pine (Pinus Pinae) sample, Figure 7, one millilitre of water was depositing, using a syringe, into the area marked by the red rectangle. The scanned area has the dimensions of 7.5 cm x 3 cm while the entire wood pine sample has a thickness of 1 cm (see Figure 8A, B, C, D).

For testing the capabilities of the THz imaging system, measurements were performed on the non-wetted surface of the sample. THz measurements were carried out placing the waveguide close to the surface of the sample.

Regarding the lateral resolution of the system, it is half a wavelength.

Fig.7. (A) Specimen of wood pine belonging to the species Pinus Pinae.

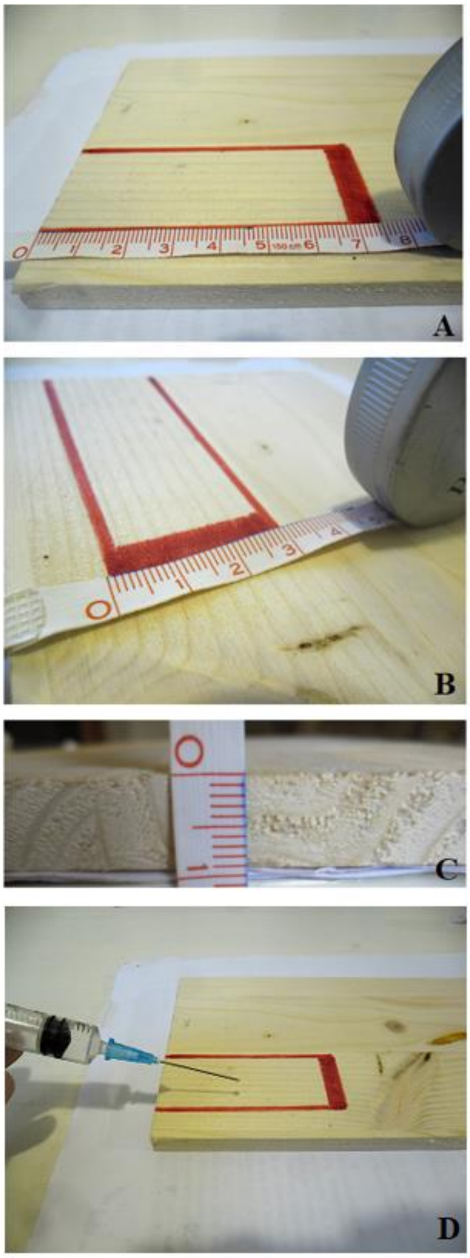

Fig.8.Pine wood sample. The length and the width of the scanned area are shown in (A) (B);(C) shows the thickness of the pine sample while (D) shows the water injected in the red marked area.

V. RESULTS

In this study, measurements were aimed at revealing the presence of water below the wood pine specimen. For this purpose, imaging measurements were performed by comparing the image of the dry sample with that of the sample after depositing a controlled amount of water into the area marked by the red rectangle.

A first scan was carried out on the dry wood, while on the wet sample, measurements were taken at time intervals of 7, 15 and 19 minutes, thus favouring both the diffusion of water and the evaporation process (see Figure 9).

The THz images, shown in figure 8, were acquired with the scanning software developed in LabView, and subsequently processed with the matlab software.

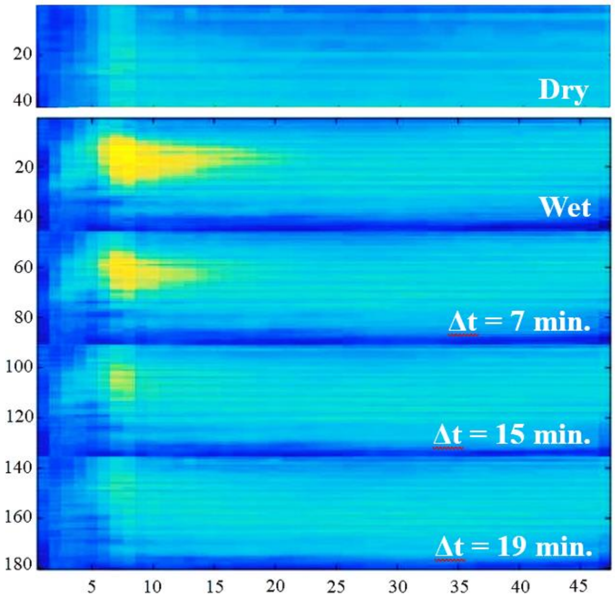

Fig. 9. Sample image processing using matlab software. This image shows the difference between the wet sample after 7, 15 and 41 minutes and the dry sample.

Observing carefully at Figure 8 on the wet sample, a gradual diffusion of water into the subsurface layers is evident. As reported in the introduction, at these frequencies the water strongly absorbs and reflects this radiation, whereby the amount of water depositing under the sample can be detected and therefore observed in particular on wet sample and after a $\Delta t = 7$ minutes. After 8 minutes, the water begins to evaporate, as we can see from the image, while the sample returns to its initial situation after $\Delta t = 41$ minutes.

VI. CONCLUSIONS

The THz imaging system was tested to monitor the diffusion of water at pre-determined time intervals, allowing its evolution to be followed. Imaging measurements performed on the pine sample have detected the presence of water, highlighting the potential of this system for assessing any moisture damage.

One of the main limitations of the 97 GHz imaging system is the scan time, which is long (about 3 minutes) when compared to the water diffusion time. This obviously prevents monitoring what happens in the first moments when the water is injected, thus losing important information.

To significantly reduce the scanning time, the next step will be the implementation of a detector array on the THz imaging system that will allow a complete scan to be performed in a few seconds. Further studies should be done in order to optimise the experimental setup.

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