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THz QCL - based active imaging applied to composite materials diagnostic

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***Abstract*—This paper presents a CW raster-scanning THz imaging setup used to perform Non-Destructive Testing of Kevlar^{TM}and carbon fibre samples. The setup uses a 2.5 THz Quantum Cascade Laser as a source. Delamination defect in a Kevlar sample was detected showing a sensitivity to laser polarization orientation. Detection of a break in a carbon/epoxy sample was also performed.**

I. Introduction

Composite materials such as glass fibre epoxy, carbon fibre and Kevlar have experienced a rapid development during the last decade. Their use in aeronautical engineering is now very important. For example, in the Airbus A380, fibrous composite materials have been deployed extensively in primary loadcarrying structure to achieve a 17% lower fuel use per passenger than comparable aircraft.

Non-Destructive Testing (NDT) is useful for initial inspection of test samples and analysis of reasons for failure. Several methods are currently used: ultrasonic testing with single element transducers and linear phased array probes in pulse echo and through transmission mode, resonance methods, shearography and thermography for example.NDT using THz waves can be an alternative when "traditional" methods have poor efficiency (composite made from soft epoxy resin, for instance) or to improve spatial resolution.

During the five past years, some works have been conducted about characterization or imaging, in the THz range, of various composite materials. Most of these works used pulsed THz-Time Domain Spectroscopy (THz-TDS). Rutz and coworkers [1], [2] studied low density polyethylene (LDPE) containing titanium dioxyde nanospheres and glass-fibre reinforced polymers to measure the concentration of glass fibres. The orientation of glass fibres in reinforced plastics can also be determined [3], sand inclusion or metal in HDPE weld joints can be detected [4].

Test of fire damages on carbon fibre using reflectivity dependence to polarization was reported [5], [6]. Stoik et al. [7] also used THz-TDS to detect burn damages and delamination on glass fiber.

Only a few of these works have also performed CW THz imaging: at 1.63 THz with a gas laser [5] or with Gunn diodes at 0.2 and 0.38 THz [5] or 0.6 THz [6].

Composite materials diagnostic using CW THz waves produced by Quantum Cascade Laser have not yet been investigated. Considering the QCLs capability to emit a few tens of mW in the [1-4] THz frequency range, with beam qualities in constant improvement, this approch seems to be very promising.

In this paper, transmission properties of Kevlar and carbon fibre samples are investigated with a QCL based imaging setup. Measurements have been made on various samples, known to present a defect, for two orthogonal electric field orientations relative to sample structure.

II. Experimental setup

The source used in the raster-scanning imaging experimental setup is a Quantum Cascade Laser (QCL)emitting at 2.5 THz. The QCL is driven by a pulsed current source. A ten of milliwatts at 2.5 THz are available at the output of the cryostat. The emitted beam is then collected by a set of four off-axis parabolic mirrors that allow us to focus it on the sample to be imaged. The object is moved in X and Y by two motorized translation stages. Two types of detector can be used: either a cooled NTD-Ge bolometer or a Golay cell. The signal is acquired via a lock-in amplifier.

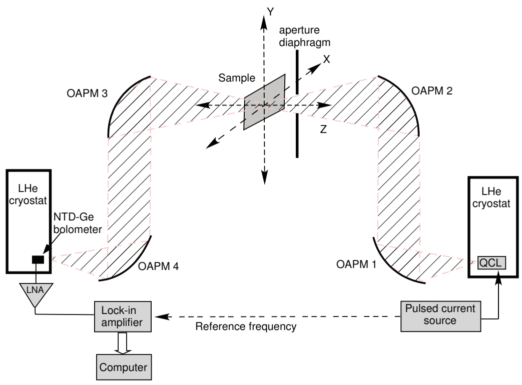

Fig. 1. Experimental setup

The setup was completely characterized:

- spot size is 1.09 mm along vertical axis and 1 mm along the horizontal one.
- spatial resolution is 0.7 mm (imaging a metallic resolution target with a 1 mm step and datas processing)
- the CW THz power is 0.5 mW, mainly due to atmospheric transmission losses.

- QCL is linearly polarized, oriented in the horizontal plane.

III. Composite Materials Diagnostic

Two samples, one Kevlar fibres and the second carbon fibres, both with resin epoxy, with known defects have been used. For all experiments, we performed two acquisitions for each sample. As the QCL is linearly polarized in the horizontal plane, the first image is made for a given position of the sample, taken as a reference. For the second image, the sample is rotated by 90°. So, we obtain two images for two perpendicular orientations of the electric field, relative to the sample.

The first sample is made of two Kevlar sheets (thickness = 0.5 mm, mesh size $\approx$ 2 mm), assembled with epoxy. A thin film, 5 mm wide, is inserted between two sheets to avoid resin polymerization. By this way, a region of weakness is produced where, applying a stress, we can create delamination. Figure 2 shows processed images (84x84 pixels, each pixel 0.25 mm x 0.25 mm). As explained before, the two images are obtained for two orthogonal positions of the sample relative to laser polarization, arrows showing electric field orientation.

The delamination appears as a dark region corresponding to low transmission. This can be explained by scattering from Kevlar fibres. In fact, the stress was applied in a zone where epoxy is not present and, as Kevlar fibres are not teared due to their elasticity, fibres perpendicular to the delamination direction connect the opposite sides of the break whereas fibres parallel to the break are retracted on each side This fibres arrangement can behave as a subwavelength grating. Actually, its step $\Lambda \approx 10\mu m$ is well below the working wavelength ($\lambda = 125\mu m$): such structures are known to be polarization dependent.

On THz images, defect is more visible when electric field is perpendicular to the delamination main direction ie parallel to fibres main orientation (fig.2 *right*).

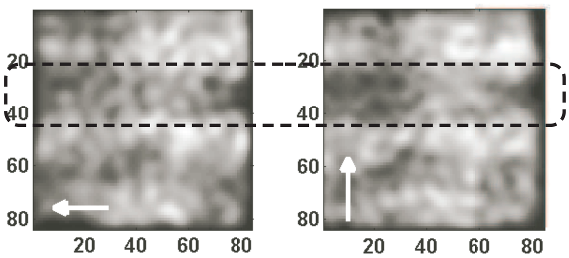

Fig. 2. Processed images *(84 x 84 pixels or 21 mm^2)*

We also tested a 0.5 mm thick sample of carbon fibre epoxy. An adhesive film is also sandwiched between two sheets of fibre to create a weak region where a stress has been applied to break the fibres. Figure 3 presents the 120 x 100 pixels processed images, white arrow indicating electrical filed orientation.

We can clearly identify the region where fibres are broken, corresponding to a maximum in transmission. This surprising behavior, compared to the one observed for Kevlar, can be explained from the fact that, in this case, fibres are totally broken and an open failure is created. This failure dimensions are about a few wavelengths, allowing transmission of the THz wave with some diffraction and a low sensitivity to polarization.

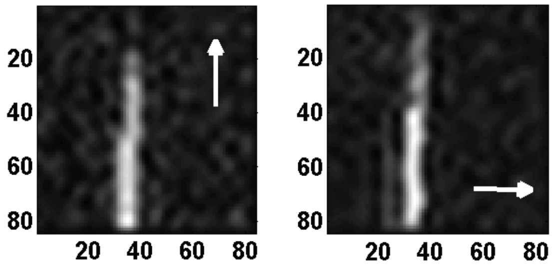

Fig. 3. Processed THz images *(84 x 84 pixels or 21 x 21 mm^2)*

IV. Conclusion and Prospects

Non-Destructive Testing of Kevlar and carbon fibre samples was realized by THz transmission mode imaging using a 2.5 THz Quantum Cascade Laser. A delamination defect in a Kevlar sample was detected showing a sensitivity to laser polarization orientation. A break in carbon/epoxy was also detected.

As a perspective, it will be interesting to test these samples in transmission at other frequencies and in reflection mode imaging, this evolution of the setup being essential to envisage in-situ evaluation of materials. Obviously, samples tested in this paper are not real cases as they are thin and very damaged. However, these results seems to be promising.

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