Nondestructive Evaluation of Aircraft Composites Using Terahertz Time Domain Spectroscopy

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***Abstract*—Terahertz time domain spectroscopy was used for nondestructive evaluation of aircraft glass fiber composites stressed with bending and heating damage. Refractive index and absorption coefficients were measured for both damaged and undamaged composites. The two dimensional extent of the heat damage could be shown with either a simple phase or amplitude terahertz imaging technique.**

I. Introduction And Background

Composite materials such as fiberglass, Kevlar, and carbon fiber are increasingly being used as structural components in high performance military aircraft, because of their high strength to weight ratios, improved aerodynamic performance, increased safety, and reduced corrosion compared with other structural materials. However, composites can be weakened by various defects and stress during the lifecycle of an aircraft, and routine maintenance of composite materials requires rather complicated inspection and repair techniques. Terahertz (THz) radiation could have the unique ability to penetrate composites and identify defects such as delaminations, air bubbles, or heat damage [2,3]. THz offers a non-invasive, non-contact, non-ionizing method of assessing composite part condition and could overcome some of the short-comings of other non-destructive techniques such as x-rays, ultrasound, video inspection, eddy currents, and thermographic techniques [1]. An aircraft glass fiber composite with various forms of damage was examined. Localized heat damage was applied to some of the samples, while another sample was etched to various thicknesses and then shallow cylindrical defects were etched from their center.

The THz time domain spectroscopy (TDS) transmission setup shown in Fig. 1 was used to collect data in transmission. A photoconductive switch was used as an emitter and an electro-optic technique (ZnTe crystal) was used as a detector.

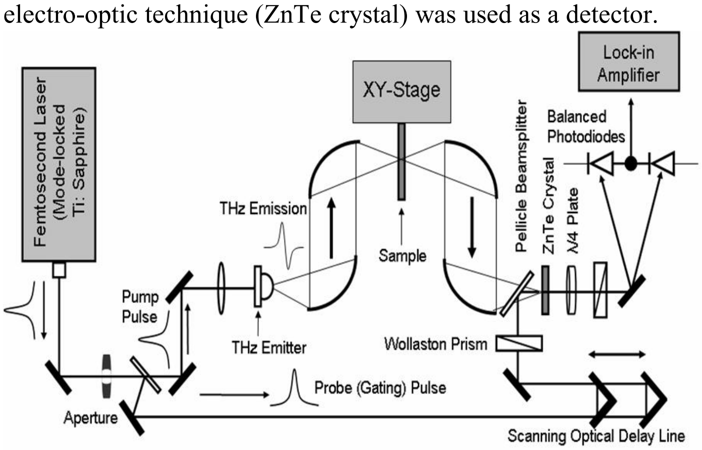

Figure 1. Experimental THz TDS transmissive setup.

The THz beam was focused on to the sample using a series of four off-axis parabolic mirrors. Measurements were made on the index of refraction and the absorption coefficient of the glass fiber samples with and without burn damage. The index of refraction, n, as a function of frequency and the absorption coefficient, α, spectrum were determined by the following equations:

$$n(\omega) = 1 + \frac{c\left[\phi_{sam}(\omega) - \phi_{ref}(\omega)\right]}{\omega d_{sam}} \quad (1)$$

$$\alpha(\omega) = -\frac{2}{d_{sam}} \ln\left[\frac{E_{sam}(\omega)}{T(\omega)E_{ref}(\omega)}\right] \quad (2)$$

where ω is the frequency, d_{sam} is the sample thickness, c is the speed of light in a vacuum, ϕ is the electric field phase of sample or reference, E is the electric field transmitted through the sample or reference, and $T(\omega)$, calculated from $n(\omega)$, is the fraction of power transmitted through the air-composite interface. Then a THz image was made by raster scanning the portion of the sample that was heat damaged [4].

II. Results

The glass fiber composite was composed of a glass fiber weave and a polyimide resin. Measurements were taken of the glass fiber at various thicknesses with and without heat damage. The index of refraction measurements are shown in Fig. 2, while the absorption coefficient results from a THz TDS scan are shown in Fig. 3. The index of refraction of the unaltered composite with a coating remained fairly constant around 2.05 ± 0.01 and the absorption coefficient was

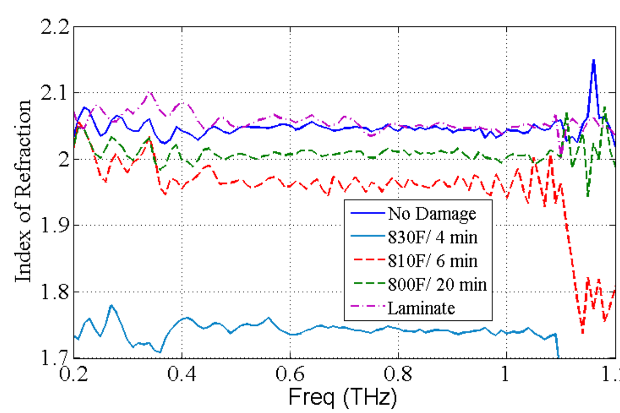

Fig. 2. Index of refraction vs. frequency for glass fiber samples with localized heat damage.

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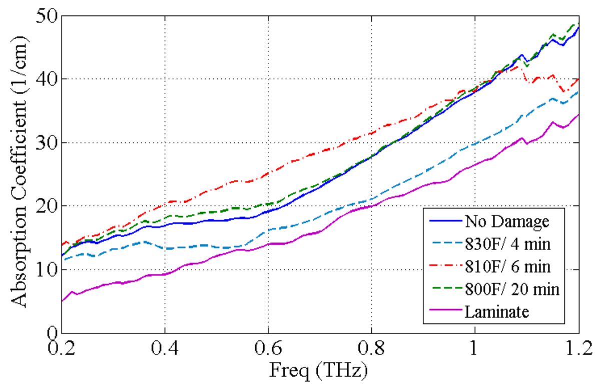

Fig. 3. Absorption coefficient vs. frequency for glass fiber samples with localized heat damage.

measured at 17.5 ± 0.8 cm^{-1} (0.5 THz), 27.5 ± 1.1 cm^{-1} (0.8 THz) and 38 ± 1.6 cm^{-1} (1 THz). This is comparable to another measurement made on glass fiber samples, where the index of refraction was 2.05-2.1 and the absorption coefficient was 12 cm^{-1} (0.5 THz) and 26-32 cm^{-1} (0.8 THz) [2]. For comparison, the burn mark material parameter measurements were calculated with the undamaged sample thickness, such that the optical path length through each damage spot was constant. Two of the damaged areas had the same optical path length as the undamaged area, but the third area (810°F/ 6 minutes) did not. This third burn spot may have been different due to a small area where either the coating was removed or a residue was deposited. The laminated piece of glass fiber did not have a coating like the others, which could have resulted in the lower absorption coefficient. These measurements suggest that burning the samples at these high temperatures does not alter the dielectric constants, but merely introduces a blistering of the glass fiber and/or coating.

The next task was to image the burn samples in order to locate the damage with THz radiation. This was accomplished using the THz TDS setup in Fig. 1 with a raster scanner to move the image through the THz beam. Initially, a glass fiber sample with a 1 cm diameter etched spot was imaged with THz TDS for callibration. Fig. 4 was formed using the arrival time (psec) of the peak of the THz waveform. A similar image was formed using the peak amplitude of the THz pulses. Next, the burn dots were imaged using the peak amplitude of the THz pulses. The first localized burn spot,

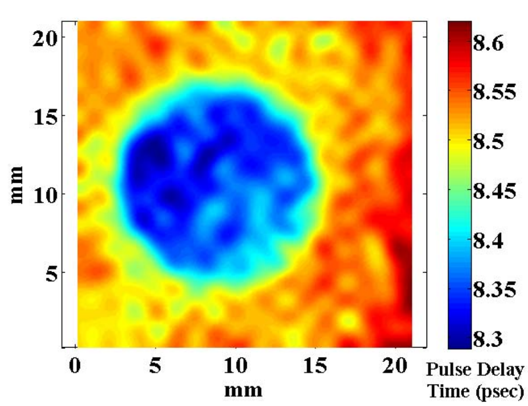

Fig. 4. THz TDS image of shallow cylinder (10 mm diameter) etched into glass fiber sample using relative pulse transit time (psec).

heated at 830°F for 4 minutes, is shown in the THz image of Fig. 5 where the visibly burned area (~ 1.5 cm X 2 cm) is shown by the blue shading.

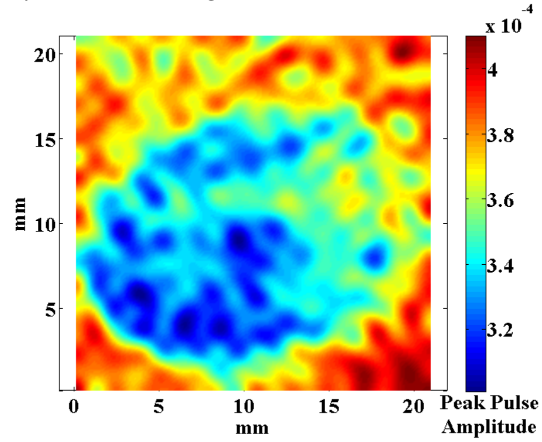

Fig. 5. THz TDS image of localized heat damage (830°F for 4 minutes).

Images were also made of the other two burn areas in which the blistering of the material was much less noticeable and the burn area had to be outlined with marker dots. In Fig. 6, the sample that was heated at 810°F for 6 minutes is shown with a circle drawn around the burn area. The dark blue area in the center of the circle roughly corresponds with the area of residue. The third burn area, heated at 800°F for 20 minutes, showed minimal difference with the rest of the sample. Similar amplitude and phase imaging techniques could be used to show areas with cracks, air gaps, and fiber fractures resulting from damage caused by bending cycles.

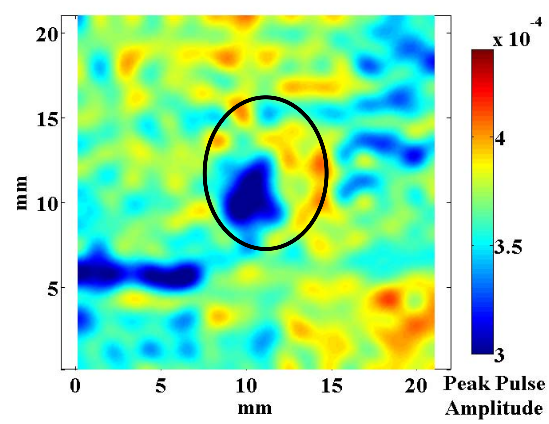

Fig. 6. THz image of localized heat damage (810°F for 6 minutes).

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