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FRP 복합재료의 T-Ray 비파괴특성 평가 및 적용

Evaluation and Application of T-Ray Nondestructive Characterization of FRP Composite Materials

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초 록 최근에는 T-ray(terahertz ray)를 이용한 비파괴기술이 새로운 분야로 주목을 받고 있다. 본 연구에서는 FRP 복합재료의 내재결함이나 레이업(lay-up) 특성을 검사 및 평가하기 위한 T-ray 시간영역 분광기(time-domain spectroscopy)를 활용하였으며 또한 이 T-ray 분광기의 일반적인 반사 및 투과모드를 이용하여 T-ray 이미지를 구현하였다. 특히, 2개의 톱날 인공결함이 내재한 GFRP 복합재의 평가방법을 제시하였다. CFRP 복합재료에 대해서는 T-ray 전파는 탄소섬유로 인해 진행 장애를 받는다. 이에 따라 T-ray의 전기장(E-field)의 방향과 탄소섬유 방향의 의존성을 분석하였다. 한편 인공결함인 알루미늄 테이프, 박리, 충격손상, 이물혼입 등을 T-ray를 이용하여 비파괴 검사 및 평가하였다. 이를 통해 FRP 복합재료의 T-ray비파괴평가의 적용 가능성 및 한계 등을 확인 할 수 있었다.

주요용어: T-Ray, FRP 복합재료, 비파괴평가, 반사모드, 투과모드, 전기장

Abstract Recently, T-ray (terahertz ray) applications have emerged as one of the most promising new powerful nondestructive evaluation (NDE) techniques. In this study, a new T-ray time-domain spectroscopy system was utilized for detecting and evaluating layup effect and flaw in FRP composite laminates. Extensive experimental measurements in reflection and thru-transmission modes were made to map out the T-ray images. Especially this was demonstrated in thick GFRP laminates containing double saw slots. In carbon composites the penetration of terahertz waves is limited to some degree and the detection of flaws is strongly affected by the angle between the electric field(E-field) vector of the terahertz waves and the intervening fiber directions. The artificial defects investigated by terahertz waves were bonded foreign material, simulated disbond and delamination and mechanical impact damage. The effectiveness and limitations of terahertz radiation for the NDE of composites are discussed.

Keywords: Terahertz-Ray, FRP Composite Materials, Nondestructive Evaluation, Reflection Mode, Through-Transmission Mode, Electric Field

1. Introduction

Recently, T-ray (terahertz ray) advances of technology and instrumentation has provided a probing field on the electromagnetic spectrum because the terahertz radiation has a shorter wavelength, relatively higher resolution than microwaves. The terahertz radiation is of critical importance in the spectroscopy evaluation of airport security screening, medical imaging, polar liquids, industrial systems and composites as well (Hu and Nuss, 1995). Also the terahertz time

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domain spectroscopy (THz-TDS) is leading noncontact accurate detection of flaws and impact damages in composites, in which the THz-TDS is based on photoconductive switches, which rely on the production of few-cycle terahertz pulses using a femtosecond laser to excite a photoconductive antenna (Huber et al., 2000). This can generate sub-picosecond bursts of THz radiation, and subsequently detect them with high signal-to-noise. With the emitted power distributed over several terahertz, they consequently span a very broad bandwidth. A transient change of the emitter occurs in the resistance of a photoconductive switch on a terahertz timescale (Rudd and Mittleman, 2002; Gregory et al., 2000). Also, another method is optical heterodyne conversion, or photomixing, which can be obtained using two continuous-wave(CW) lasers (Brown et al., 1993; Brown et al.; 1995). The mixing of two lasers could produce beating, which can modulate the conductance of a photoconductive switch by the terahertz difference frequency. So, the CW-terahertz(CW-THz) radiation is produced. In some cases, T-ray images can show chemical compositions of the object. these features of T-ray imaging have generated interest in commercial applications in diverse areas as moisture analysis, quality control of plastic parts and packaging inspection (monitoring) (Schueler et al., 2001).

Due to a wide range of applications and the simplicity of the technique, THz-TDS has the potential to be the first THz imaging system which is portable, compact, and reliable enough for practical application.

In this paper , an investigation of terahertz radiation was made for the nondestructive evaluation of composite materials and structures. Terahertz radiation can readily penetrate considerable thickness of dielectric materials, so that non-conducting polymer composites reinforced with glass, quartz, or Kevlar fibers are well suited for terahertz inspection. Structures such as aircraft radomes, designed for passing radar signals, are good candidates for inspection by terahertz waves. Also, terahertz waves are investigated as an NDE tool for detecting and characterizing flaws and damage in non-conducting composites. Carbon fiber reinforced polymer composites, on the other hand, are generally too conducting for terahertz waves to penetrate. However, the degree of penetration in carbon composites by terahertz waves, especially as a function of fiber orientation, is measured quantitatively in this study. The modalities of the terahertz radiation used in this study were time domain spectroscopy(TDS) in the reflection and transmission modes and the continuous wave(CW) mode in transmission. The effectiveness and limitations of terahertz radiation for the NDE of composites are investigated.

2. T-Ray Instrument

The terahertz instrumentation systems used in this research were provided by TeraView Limited. The instrumentation includes a time domain spectroscopy(TDS) pulsed system and a frequency domain continuous wave(CW) system. The TDS techniques for generating, manipulating, and detecting terahertz pulses have been immerged. By obtaining images with THz-TDS, in which the entire terahertz waveform is measured at each pixel of the image, the data acquisition rate could be increased and unique aspects of the configuration of the terahertz optics used to collect and manipulate the radiation have had important implications in the imaging experiments. The TDS system has a frequency range of 50 GHz – 4 THz and a fast delay line up to 300 ps. The beam is focused to focal lengths of 50 mm and 150 mm and the full width at half maximum (FWHM) beam widths are respectively 0.8 mm and 2.5 mm. The TDS system can be configured for through-transmission or reflection (small angle pitch-catch) measurements. The frequency range of the CW system is 50 GHz - 1.5 THz,

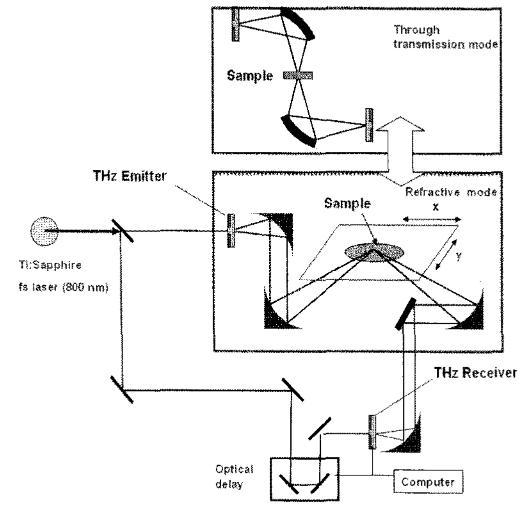


Fig. 1 Schematic diagram of a THz-TDS spectrometer

with the best resolution being 100 MHz. The focal lengths of the CW system are also 50 mm and 150 mm. Both the TDS and the CW systems are fully fiber optics connected. Fig. 1 shows a schematic diagram of a THz-TDS spectrometer, used for T-ray reflection, thru-transmission modes.

3. Application of GFRP and Kevlar Composites

Terahertz waves can readily penetrate non-conducting materials and can therefore be applied to the nondestructive testing(NDT) of glass, quartz, or Kevlar fiber reinforced polymer matrix composites. Solid laminates and sandwich structures with honeycomb or foam core can all be examined with terahertz waves. In this study, terahertz radiation was explored for the NDT of a variety of non-conducting composite materials and structures. Some results are summarized below.

3.1 Hidden Delaminations

The time domain waveforms of terahertz pulses in the TDS mode bear strong resemblance to ultrasonic signals. Wave propagation concepts

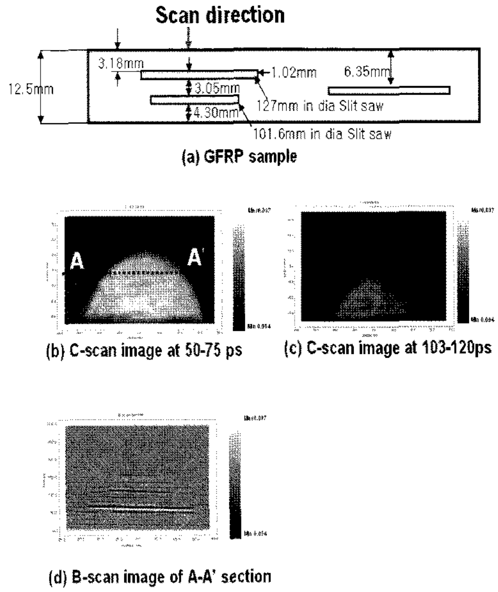


Fig. 2 Terahertz TDS through-transmission scan image of double and single saw slots in a glass composite solid laminate. The results demonstrated that terahertz waves do not suffer from "shadow effect."

such as time of flight(TOF), transmission and reflection coefficients, refraction and diffraction are common to both waves. However, there are also fundamental differences when materials are probed with terahertz radiation, an electromagnetic wave, and with ultrasound, a mechanical wave. First and foremost, terahertz waves, unlike ultrasound, do not require a material medium to support it, and can therefore readily go through vacuum or air. In the ultrasonic inspection of flaws in a solid, the probing field suffers from the "shadow effect," where a smaller flaw behind a larger flaw could not be detected. In contrast, there is no such limitation with terahertz waves. To demonstrate this effect, two semi-circular saw slots were cut parallel to the surfaces into the side of a 12.5 mm thick glass composite laminate to serve as simulated delaminations, as shown in Fig. 2(a). Fig. 2(b) and (c) shows a C-scan image within the range of 50-75 ps and 103-120 ps, which mean time-window gates respectively. Fig.

2(d) show a C-scan image at the A-A' location. Here A-A' means an image of cross-sectional area as shown in Fig. 2(b). Fig. 2 The smaller slot (101.6mm diameter) was located below the larger slot (127mm diameter). Using the TDS terahertz system in the through transmission mode, a scan image was made of the sample containing the double saw slots. The image of the transmitted terahertz pulse amplitude, also shown in Fig. 2, clearly revealed both saw slots. The left side of the sample contained a single saw slot and some resin-starved region nearby, which appeared in the image above it. The sample was also scanned from the top surface with reflection mode TDS terahertz pulse, and the double saw slots were again imaged.

3.2 T-Ray Imaging of Impact Damages

Based on the capability described above, the multiple delaminations in solid composite laminates were imaged with reflection mode TDS terahertz waves. The specimen was a 24-ply woven glass epoxy solid laminate and the impact was made with a 51 mm diameter tup at an impact energy of 16 Joules. The reflection mode TDS scan was made on the back side of the sample so that the smaller delaminations were shadowed by the larger and shallower delaminations. Fig. 3 shows the time domain signal (terahertz A-scan trace), where the two prominent pulses were reflections from the top and bottom surfaces of the specimen. To produce the images of the impact-induced delaminations, a time gate was imposed on the A-scan signal and the peak amplitude within the time gate was used to generate the images. Fig. 3 shows time domain TDS waveform of glass composite laminate and three of such images with the time gates placed at 43-69 ps, 47-69 ps, and 56-69 ps, respectively. The series of images clearly showed the decreasing size of the delaminations toward the impact side.

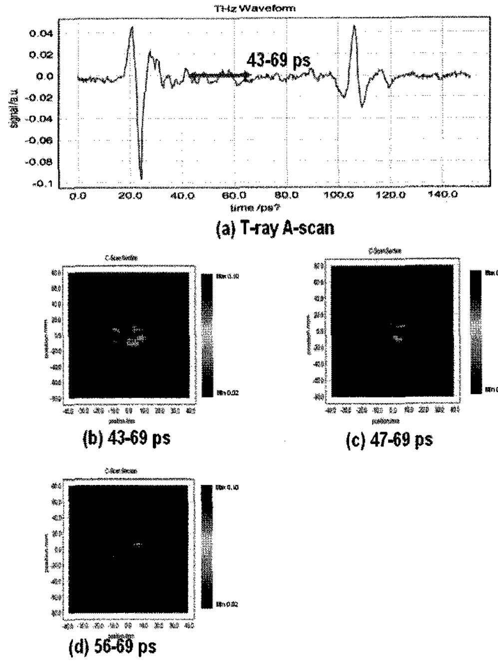


Fig. 3 Time domain TDS waveform of glass composite laminate

3.3 T-Ray Imaging of Embedded Flaws in Kevlar/Nomex Sandwich

Both the reflection mode (small angle pitch-catch) and the transmission mode TDS terahertz scans were found effective in mapping out defects embedded between the Kevlar composite facesheet and the Nomex honeycomb core of a sandwich panel. In addition to using the peak amplitude of the terahertz pulse reflected from or transmitted through the panel, images can also be generated using the frequency domain FFT signal. Fig. 4 shows embedded defects in Kevlar/Nomex honeycomb sandwich. Fig. 4(a) shows the whole scan of the reflected signal from the top facesheet of the Kevlar/Nomex panel, together with the image based on the peak amplitude of the FFT signal in the frequency window of 0.2 to 0.3 THz. The circle on the point A was a 25.4 mm diameter double Teflon film beneath the facesheet, and the circle on the left was a 25.4 mm diameter

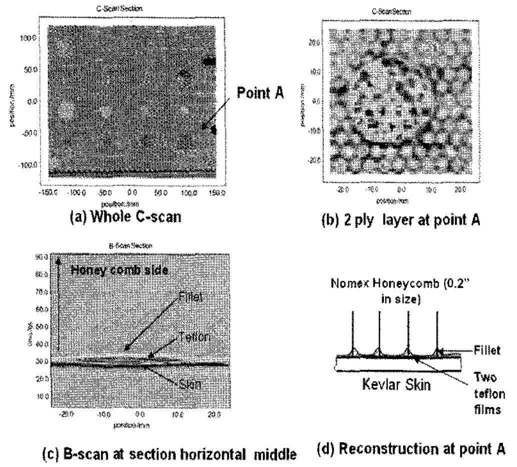


Fig. 4 Embedded defects in Kevlar/Nomex honeycomb sandwich

single Teflon film. And image (Fig. 4(b)) is based on amplitude in the 0.2-0.3 THz frequency window. Fig. 4(c) shows a B-scan image at point A and Fig. 4(d) shows a reconstructed image at point A.

4. Application of CFRP Composite Laminates

Terahertz waves can penetrate dielectric materials quite easily but not electrically conducting materials. The application of terahertz waves to the inspection of carbon composites is mentioned in the literature (Schueler et al., 2001) but there has not been in depth studies. Carbon fiber reinforced polymer composites(CFRP) are poor conductors for electricity and the conductivity is anisotropic, so it is worthwhile to quantify the penetration of terahertz waves in carbon composites. The carbon fibers used in the manufacturing of CFRP are highly anisotropic microscopically; the electrical conductivity along the fiber axis is about three orders of magnitude greater than that in the radial direction. In a unidirectional laminate of carbon fiber composite, the transverse electrical conductivity is further impeded by the lack of continuity. The conduction mechanism in the transverse direction (perpendicular to the fiber axis) is a percolation process that relies on the random contact between adjacent fibers. In the literature, the electrical conductivity data for carbon composites are somewhat sparse (Hsu, 1985). The reported values of longitudinal conductivity (σ_l) varied from 1x104 S/m to 6x104 S/m. The range of reported data on the transverse conductivity (σ_t) is particularly large; from 2 S/m to as high as 600 S/m. The value of transverse conductivity in a unidirectional laminate is highly dependent on the manufacturing process and the quality of the composite. In a unidirectional carbon composite, the in-plane conductivity with the electrical current flowing at an angle θ from the fiber axis is given by (Tse et al., 1981):

$$\sigma = \sigma_l \cos^2\theta + \sigma_t \sin^2\theta \quad (1)$$

Because of the highly anisotropic electrical conductivity ($\sigma_l >> \sigma_t$), the penetration of terahertz waves through a unidirectional carbon composite depends on the relative angle between the electrical field vector and the fiber axis. When the electric field of the terahertz wave is parallel to the axial direction of the carbon fibers, the conductivity is the highest and the penetration is the lowest. When the electric field vector is perpendicular to the fiber axis, the conductivity is the lowest and the penetration is the highest. Using a value of σ_t = 10 S/m, the skin depth of a unidirectional carbon composite for a terahertz wave, with the electric field oriented normal to the fiber axis, is approximately 0.2 mm at 1 THz and 0.5 mm at 0.1 THz. Experimentally, we have measured the angular dependence of the power transmission through a 22-ply unidirectional carbon composite laminate using the CW terahertz system. Near the low end of the frequency spectrum (f ~ 0.1 THz), the transmitted power is more than 30 dB above the noise floor. The angular dependence of the transmitted power at 0.1 THz is shown in Fig. 5.

When compared to the theory prediction based on the angular dependent conductivity, the

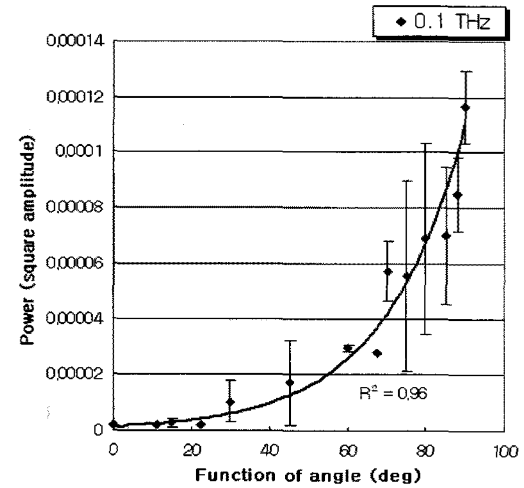
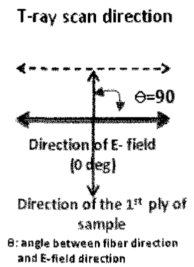


Fig. 5 Angular dependence of transmitted power of 0.1 THz terahertz waves through a 22-ply unidirectional carbon composite laminate. At 90 degree the electric field vector is normal to the fibers

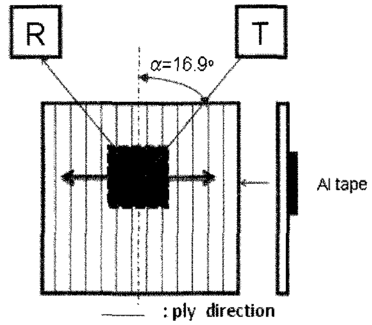
measured power transmission at angles away from 90 degree much higher the predicted. The value would have the unidirectional carbon composites behaving like a polarizer with a sharp cut-off under the assumptions that the incident terahertz ray is linearly polarized and that the fiber axes in the laminate are all parallel. It seems that the discrepancy contributes to the above involved things.

Based on the electrical conductivity in carbon composites, we tried to understand the detectability of bonded Al-tape at the back side in a carbon composite laminate. The Al-tape, 0.05mm thick and measuring 20 mm and 20 mm squares, were bonded under one ply carbon composite laminate as shown in Fig. 6. Note that the E-field (electric field) direction is horizontal, the fiber direction is vertical and the difference angle is called θ. Here by using TDS terahertz waves in the reflection mode, the flaws were scanned and imaged.

We then correlated the S/N of the flaw images to the conductivity of the first two plies. Since $\sigma_l >> \sigma_t$, Eq. (1) may be written as $\sigma \approx \sigma_l \cos^2\theta$. To interpret the T-ray scan images of the



(a) Direction between E-field and fiber



(b) Reflection mode of T-ray scan

Fig. 6 Schematics for T-ray reflection mode and one ply CFRP laminates with boned with Al tape (20 x 20 mm) at the back side

flaws under one ply, one must consider E-field (electric field) direction of the T-ray and the lay-up direction of CFRP composite laminates. First, the penetration through the one ply depends on the relative angle between the E-field and the fiber direction in the one ply. Secondly, one should consider the fact that the radiation is focused on the surface of the sample.

A simple argument is just needed as one resistor so that the resistance R is given by $(1/R)=(1/R_l)$. For this equation, we get the conductivity:σl and correlate its conductivity noise ratio of the flaws in the T-ray scan image. By using $\sigma \approx \sigma_t \cos^2\theta$, the conductivity has lowest value ($\approx 0.0\sigma_t$) when the E-field makes 90 deg. On one ply to the E-field direction. The S/N of the flaw image is therefore expected to be the highest when the sample is at this angle.

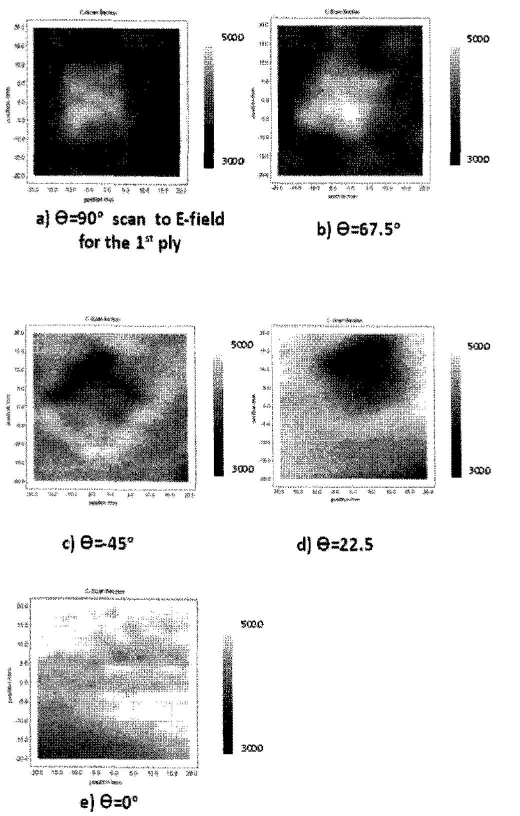


Fig. 7 TDS reflection mode terahertz scan images of embedded flaws in a quasi-isotropic carbon composite laminate. Θ is the angle between the electric field vector and fiber axis in the one ply, and ψ is the angle between the electric field vector and fiber axis in the second ply. (a) Θ=90° (b) Θ=67.5° (c) Θ=45.0° (d) Θ=22.5°, and (e) Θ=0.0°

In contrast, sample direction that gave a high value conductivity, such as θ = 0 degree (σ = 1.0 σ_t) had poor signal-to-noise ratio. A trend of flaw detectability shows that the prediction of S/N based on the conductivity is in qualitative agreement with the testing. So, it is found that the detectability of the flaw depends on the relation between the E-field and the fiber direction. So, Fig. 7 shows the reflection mode images under the different angle between the E-field and the fiber direction. So, especially, Fig. 7(a) shows the highest S/N T-ray image; however, Fig. 7(e) shows the lowest S/N T-ray image.

Finally, it was found that the application of terahertz waves to the inspection of carbon composites is available to one ply on the Carbon fiber reinforced polymer composites(CFRP). They are poor conductors for electricity and the conductivity is anisotropic, so it is needed to quantify the penetration of terahertz waves in carbon composites. Much more THz applications can be expected when this technique is applied in practical field.

5. Conclusion

Initial results were obtained in an exploration of terahertz wave applications for the NDT of composites. First of all, in non-conducting composites of glass, and Kevlar fibers, terahertz can complement ultrasonic NDT, especially with its penetration ability and immunity to shadow effect. The conductivity of carbon fibers will substantially limit the utility of terahertz waves even in one-ply CFRP laminate; therefore it is found that the detectability of the flaw depends on the relation between the E-field and the fiber direction. It is thought that a application of terahertz applications for composite NDT could be very useful.

Acknowledgements

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References

Brown, E. R., Smith, F. W. and McIntosh, K. A. (1993) Coherent Millimeterwave Generation by Heterodyne Conversion in Low-Temperature-Grown GaAs Photoconductors, *J. Appl. Phys.*, Vol. 73, No. 3, pp. 1480-1484

Brown, E. R., McIntosh, K. A., Nichols K. B. and Dennis, C. L. (1995) Photomixing up to 3.8 THz in Low-Temperature-Grown GaAs, *Appl. Phys. Lett.*, Vol. 66, No. 3, pp. 285-287

Gregory, I. S., Baker, C., Tribe, W., Bradley, I. V., Evans, M. J. and Linfield, E. H. (2000), Optimization of Photomixers and Antennas for Continuous-Wave Terahertz Emission, *IEEE Journal of Quantum Electronics*, Vol. 41, NO. 5, pp. 717- 728

Hsu, D. K. (1985) Characterization of a Graphite/Epoxy Laminate by Electrical Resistivity Measurements, *Prog. Rev. Quantitative NDE*, Vol. 4, Plenum Press, pp. 1219-1228

Hu, B. B. and Nuss, M. C. (1995) Imaging with Terahertz Waves, *Opt. Lett.*, Vol. 20, pp. 1716-1718

Huber, R., Brodschelm, A., Tauser, A. and Leitenstorfer, A. (2000) Generation and Field-Resolved Detection of Femtosecond Electromagnetic Pulses Tunable up to 41 THz, *Appl. Phys. Lett.*, Vol. 76, pp. 3191-3199

Rudd, J. V. and Mittleman, D. M. (2002) Influence of Substrate-Lens Design in Terahertz Time-Domain Spectroscopy, *J. Opt. Soc. Amer. B*, Vol. 19, No. 2, pp. 319–329

Schueler, R., Joshi, S. P. and Schulte, K. (2001) Damage Detection in CFRP by Electrical Conductivity Mapping, *Composite Science and Technology*, Vol. 61, 6, pp. 921-930

Tse, K. W., Moyer, C. A. and Arajs, S. (1981) Electrical Conductivity of Graphite Fiber-Epoxy Resin Composites, *Materials Science and Engineering*, Vol. 49, pp. 41-46