2022 International Symposium on Nonlinear Theory and Its Applications,
NOLTA2022, Virtual, December 12-15, 2022

Terahertz time-Domain Spectroscopy for Nondestructive Evaluation and Material Characterization

Alexandre Locquet†‡ , Min Zhai†‡, Haolian Shi†‡, Junliang Dong†‡, and David S. Citrin†‡

†International Research Lab 2958 Georgia Tech-CNRS, Georgia Tech Lorraine, France
2 Rue Marconi, 57070, Metz, France
‡School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, US
Email: alocquet@georgiatech-metz.fr

Abstract– We present applications of terahertz time-domain spectroscopy for the nondestructive evaluation of fiber-reinforced polymers, of coatings on metal substrates and in the field of cultural heritage. We focus on signal and image processing techniques that increase axial and lateral resolution and demonstrate their importance for applications.

Summary

Terahertz (THz) radiation penetrates a number of non-conducting materials and as a result can be useful for sub-surface nondestructive characterization, evaluation, and testing of materials and devices. Compared to optical techniques, THz waves suffer from lower resolution but usually benefit from better penetration. Compared to microwave techniques, THz penetration is limited but resolution is better. Depending on the material and source power, THz waves can penetrate from mms to tens of cms, and axial resolution can go from hundreds of microns to a few microns. In this review, we will present recent results obtained by our team on a variety of materials as well as signal processing techniques we have applied to increase axial and lateral resolution of measurements obtained with the THz time-domain spectroscopy (THz-TDS) method.

We will present in particular improvements in axial resolution resulting from the application of sparse deconvolution in multi-layer material assemblies [1,2] and from the extrapolation of spectral regions with low SNR levels based on the portion of the spectrum with high SNR [3].

In the field of composite fiber materials, we have demonstrated the ability to localize, in depth, inclusions in a multi-ply glass fiber reinforced polymer [4], fiber breakage and fiber/matrix delaminations resulting from impact damage in glass- and carbon fiber-based polymers [5,6], and the geometrical characteristics of the fiber weave [7].

We have also been able to characterize thin films such as the mill scale [8] appearing during the hot-rolling of steel, and the thickness of individual paint layers in multi-layer paint [9].

Material properties of glasses and plastics have been determined [10] and plastic weld joints have been characterized in particular through the analysis of birefringence [11].

Finally, in the field of cultural heritage conservation, THz imaging has proven successful in determining the stratigraphy of a XVIIth century oil painting on canvas [12] and in reading inscriptions, under the oxide layer, on a XVIth century lead cross [13].

ORCIDs

First Author: 0000-0002-6674-4956, Fourth Author: 0000-0003-3109-185X, Fifth Author: 0000-0002-3418-7745.

Acknowledgments

The authors would like to thank NOLTA2022 organizing committee members and the Conseil Régional Grand Est for its financial support.

References

[1] J. Dong, X. Wu, A. Locquet, and D.S. Citrin, "Terahertz super-resolution stratigraphic characterization of multi-layered structures using sparse deconvolution", *IEEE Trans. THz Sci. Technol.,* vol 3, pp. 260, 2017.

[2] M. Zhai, D.S. Citrin, and A. Locquet, "Terahertz Nondestructive Stratigraphic Analysis of Complex layered structures: reconstruction techniques", *J Infrared Milli Terahertz Waves,* vol. 42, pp. 929, 2021.

[3] J. Dong, A. Locquet, and D. S. Citrin, "Depth-resolution enhancement of terahertz deconvolution by autoregressive spectral extrapolation", Opt. Lett., vol. 42, pp. 1828, 2017.

[4] J. Dong, B. Kim, A. Locquet, P. McKeon, N. Declercq, D. Citrin, "Nondestructive evaluation of forced delamination in glass fiber-reinforced composites by terahertz and ultrasonic waves", *Compos. Part B,* vol. 79, pp. 667, 2015.

[5] J. Dong, A.Locquet. N. Declerq, and D.S. Citrin, "Polarization-resolved terahertz imaging of intra- and inter-laminar damages in hybrid fiber-reinforced composite laminate subject to low-velocity impact", *Compos. Part. B,* vol. 92, pp.167, 2016.

[6] J.Dong, P. Pomarède, L. Chemami, A. Locquet, F. Meraghni, N. Declercq, D.S. Citrin, "Visualization of subsurface damage in woven carbon fiber-reinforced

composites using polarization-sensitive terahertz imaging", *NDT&E Int.* vol. 99, pp. 72, 2018.
[7] J. Calvo de la Rosa, P. Pomarède, P. Antonik, F. Meraghni D.S. Citrin, D. Rontani, and A. Locquet, " Determination of the process-induced microstructure of a woven glass fabruc reinforced polyamide 6.6/6 composite using THz pulsed imaging", *NDT & E International* (under review).
[8] M. Zhai, A. Locquet, C. Roquelet, P. Alexandre, L. Daheron, and D.S. Citrin, "Nondestructive measurement of mill-scale thickness on steel by terahertz time-of-flight tomography", *Surf. Coat. Technol.*, vol. 393, pp. 125765, 2020.
[9] M. Zhai, A. Locquet, C. Roquelet, L.A. Ronqueti, D.S. Citrin, "Thickness Characterization of multi-layer coated steel by terahertz time-of-flight tomography", *NDT & E International,* vol. 116, pp. 102358, 2020.
[10] M. Zhai, A. Locquet, and D.S. Citrin, "Terahertz dielectric characterization of low-loss thermoplastics for 6G applications", *Int. J. Wirel. Inf***.** vol. 29, pp. 269, 2022.
[11] M. Zhai, E.T.A. Mohamed, A. Locquet, G. Schneider, R. Kalmar, M. Fendler, N.F. Declercq, and D.S. Citrin, "Diagnosis of injection-molded weld lines in ABS thermoplastic by polarized terahertz reflective imaging", *NDT & E International,* vol. 122, pp. 102497, 2021.
[12] J. Dong, A. Locquet, M. Melis, and D. S. Citrin, « Global mapping of stratigraphy of an old-master painting using sparsity-based terahertz reflectometry", *Sci. Rep.*, vol. 7, pp. 15098, 2017.
[13] J. Dong, A. Ribeiro, A. Vacheret, A. Locquet, and D.S. Citrin, "Revealing inscriptions obscured by time on an early-modern lead funerary cross using THz multispectral imaging", *Sci. Rep.,* vol. 12, pp. 3429, 2022.