Taking Hyperspectral Terahertz Imaging to the Industry (HYPERTERA)

Farid Ullah-Khan[1], Borja Jerez[2], Cristina de Dios[1,2], Ángel Rubén Criado[2], Pablo Acedo[1], Pedro Martín-Mateos[1,*]

[1] Electronics Technology Department, Universidad Carlos III de Madrid, C/Butarque 15, 28911 Leganés, Madrid, Spain
[2] Arquimea Centro de Investigaciones Avanzadas SL, Avda. Francisco La Roche 19 2, 38001 Santa Cruz De Tenerife
*Corresponding author: pmmateos@ing.uc3m.es

ABSTRACT

To this day the huge potential of terahertz systems remains largely unexploited by the industry; in order for this to change a leap in the performance of current terahertz hyperspectral systems is required. The HYPERTERA projects aims to develop a terahertz hyperspectral imaging technology, based on an advanced dual terahertz frequency comb source, capable of enabling true terahertz hyperspectral imaging with unprecedented measurement rates and spatial resolutions. We expect this gigantic boost in capabilities to be the last straw in pushing terahertz technology towards an intermediate-term adoption and widespread use in industry.

Keywords: Terahertz imaging; Hyperspectral imaging; Terahertz technology.

1. INTRODUCTION

Terahertz (THz) spectroscopy has already demonstrated a huge potential in different fields of industry and research. In particular, THz spectroscopy has demonstrated very promising advantages for the food and agricultural industries, with a variety of applications that range from the detection of harmful residues or microorganisms to quality assessment [1-2]. In addition, THz waves easily penetrate packaging materials such as cardboard or plastic, enabling the determination of the spectral characteristics of the objects inside. Furthermore, THz radiation is non-ionizing so no special personal protection equipment or policies are needed for its use. These features have triggered a strong interest in this frequency range, indeed the number of scientific papers published on THz technology and applications has grown at an average yearly rate of 17 percent during the last two decades. However, and even though it seems clearly contradictory, the actual impact of THz systems on industry has been, so far, minimal.

In order for the industrial sector to take full advantage of the above presented opportunities, a leap in performance, speed, and practicality is necessary. In addition, a rapid hyperspectral imager, instead of the common single-point analysers, is required; as this feature is vital for the sorting industries, where real-time product analysis/classification at large scale could lead to huge savings in processing cost and time. Nonetheless, whereas single-point time-domain and frequency-domain terahertz spectrometers have rapidly evolved in the last years, THz hyperspectral imaging systems have yet to be properly developed.

The main objective of this project is the design, implementation and experimental validation of the prototype of a THz hyperspectral imaging system for industrial applications. The system is based on the novel idea of using an advanced dual-comb THz illumination signal to make possible for any current off-the-shelf THz video-rate camera to read simultaneously both the spatial and the spectral information of the sample in short measurement times, thus enabling unprecedented performance.

2. STATE OF THE ART

Current THz hyperspectral imaging systems lack the level of performance that would be required for operation out of a well-equipped laboratory. Indeed, to the authors' knowledge, in every single prominent scientific paper published to date on terahertz hyperspectral imaging a single-point THz spectrometer operating in a pixel-by-pixel spatial scanning procedure has been employed [3-4] instead of a pure THz hyperspectral system. The result is a time-consuming imaging process in which several minutes are needed to acquire a single spectroscopic image. This, by all means, hinders the adoption of this technology by the industry. Besides this, in terms of technological development, very few innovative approaches have been proposed, and whereas some lack the ability to perform spectral interrogation [5], other, more advanced, systems still need to perform a mechanical 1D pixel-by-pixel scan [6] necessitating more than half a minute for 100 pixels. All in all, and in spite of many demonstrations proving the high suitability of THz spectroscopic imaging for industrial applications, the technology still lacks the level of maturity required for its widespread implantation.

3. BREAKTHROUGH CHARACTER OF THE PROJECT

The THz hyperspectral imager developed during the HYPERTERA project is based on a completely novel idea: a dual THz frequency comb imager. Optical frequency combs have pushed the limits of technology in many fields of knowledge, demonstrating unmatched performance and effectiveness. Luckily, dual-comb sources are also becoming readily available in the THz range [7-8], and a similar rise in spectroscopic performance and capabilities should be expected. The basic principle behind dual-comb spectroscopy is the use of two frequency combs with slightly different repetition rates that are used to interrogate the spectral response of the sample [9]. The subsequent detection of these signals produces (in the detector) the direct frequency-downconversion of the information engraved in the teeth of the combs to the radio frequency (RF) range, where robust acquisition and analysis tools are readily available.

In this project, a highly coherent electro-optic dual-comb THz source capable of generating RF beat notes with linewidths of a few milihertz has been implemented. This feature makes possible to squeeze the whole terahertz spectrum of the source into an electronic bandwidth of a few hertz. Hence, any regular THz camera would be more than capable of reading the dual-comb interferogram generated at each one of the pixels of the image. This solution represents a giant technological leap in comparison with current systems, as it does not contain any movable mechanical component, enables the analysis of all the pixels of the image simultaneously and speeds up the measurement process. It is also worthwhile noting that the spatial resolution of the resulting hyperspectral imager is equal to that of the camera, and with 0.1 megapixels terahertz cameras already available in the market, the system proposed would largely fulfil even the tightest industrial requirements.

Tab. 1. Comparison of performance between current technology and dual-comb THz hyperspectral imaging.

	Current technology	Dual-comb THz imaging
Parallel spatial and spectral interrogation	***No***	**Yes**
Mechanical/frequency sweeping required	***Yes***	**No**
Measurement time	***Medium to long***	**Short**
Frequency accuracy	***Depending on source***	**Very high**

4. PROJECT RESULTS

The main results of this project are the implementation and the experimental validation of the first demonstrator of a practical dual-comb THz hyperspectral characterization system for industrial applications. Firstly, the basics of the novel hyperspectral imaging method have been presented and first demonstrated in the near-IR region [10]; this paper was extremely well received by the scientific community, having also ample coverage by the international media. Besides this, and in parallel, the laboratory version of the dual-comb mm-wave and THz source was implemented, characterized and optimized. The results of some of the first experiments performed were documented in a paper that has already been accepted for publication [11] and in which several samples of interest for science and industry were analysed. Following this, the design of the first version of the laboratory demonstrator of the complete THz hyperspectral imaging system (including the dual-comb source and the camera) was completed; a brief description of the architecture (depicted in Fig. 1) and an overview of some preliminary results can also be found below.

The dual-comb THz source is based on an electro-optic signal generation arrangement consisting of a continuous wave laser together with a phase modulator to generate a set of coherent equally spaced optical teeth; an optical injection locking-based filtering stage that selects two teeth separated by a frequency equal to that of the THz signal to be generated, an electro-optic dual-comb generation system that creates a dual-comb out of one of the filtered teeth and a photo conductive antenna (more details of the arrangement can be found in Refs. [11] and [12]). The end result is a THz dual-comb signal with a freely adjustable centre frequency (only limited by the bandwidth of the photoconductive antenna), number of teeth and repetition frequency (separation between teeth); this offers the possibility of tailored THz dual-comb generation for any particular application. In addition, and as experimentally demonstrated during the HYPERTERA project, this type of dual-comb generator

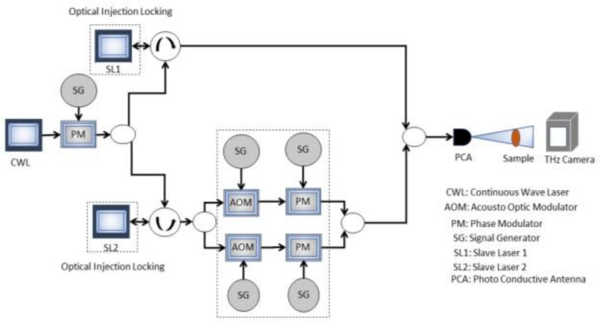

Fig. 1: Dual-comb THz imaging arrangement; the system is fully fiberized.

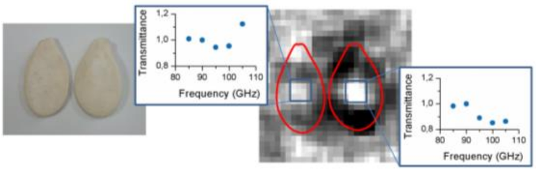

Fig. 2. Comparison of an empty seed to the left and a filled/viable seed to the right.

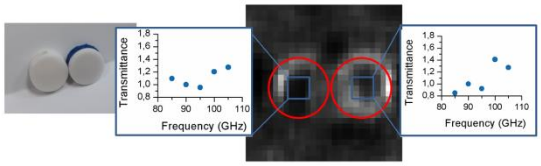

Fig. 3. Results of the analysis of two multi-layered plastic samples that have the same top layer but bottom layers with different densities.

offers such a high level of coherence between combs that allows for interferogram periods to be stretched up to several seconds. This ultra-low difference in repetition rates is a key feature of the system as it enables the direct detection of the dual-comb signal by a regular THz camera. The performance of the system has been validated, on a preliminary basis, using a THz imaging camera with a sensing area of 48 × 48 mm and 1024 pixels acquiring 7 frames per second for a total integration time of 10 s. The design of this equipment allows placing directly the samples on top of the camera to analyse the transmittance response (at the cost of a strong influence of scattering), which results in a very straightforward analysis process.

In order to illustrate the spectral interrogation features of the system an initial characterisation in the mm-wave range of different samples has been carried out. Fig. 2 shows the results of a comparison between an empty pumpkin seed and a filled/viable seed; whereas the spectral characterization of the empty seed yields a spectrum strongly characterized by diffraction at high frequencies, the filled seed presents a flatter spectrum featuring the typical water absorption profile from which the humidity level could be estimated. In Fig. 3, the contrast between two multi-layered plastic samples (with the same top layer but a different bottom layer) is shown. The effect of the lower density in the second layer of the sample located at the right can be identified by a well differentiated spectral response. It is worthwhile noting again that these are only preliminary results and that the performance and the resolution of the final THz imager will be far higher (as a matter of fact, in the first demonstration in the near-infrared the 327,680 pixels of the camera captured the spectral response of the sample in a single second [10]).

With the big majority of THz imagers operating at a single illumination frequency, imaging contrast comes exclusively from scattering and absorption mechanisms, rendering chemical identification unfeasible. To further complicate matters, scattering (and diffraction) are strongly dependent on the frequency of the THz signal and the shape, size and composition of the sample, further hindering any reliable information extraction possibility. <u>The hyperspectral imaging approach presented here offers for the first time the basis for accurate spectral recognition by providing simultaneously both the spatial and the spectral characterization of the sample.</u> Therefore this approach has the potential to differentiate between sample absorption and scattering/diffraction patterns, a capability will be fully explored in the near future as a tool to enhance the consistency of the analysis process. In the same way, in the months to come the THz hyperspectral imager will undergo a complete set of tests in which several cameras and measurement arrangements are to be evaluated at THz frequencies for the analysis of relevant agri-food products. On the final test of the HYPERTERA Phase 1 project, the optimized imager is to be evaluated at an industrial facility.

5. FUTURE PROJECT VISION

5.1. Technology Scaling

High performance and groundbreaking capabilities by themselves are insufficient to achieve the desired impact on the industry; cost-efficiency, easy deployability and adaptability to every potential application are also indispensable features. To this effect, the approach proposed and validated in this project has the potentiality to comply with all these requirements. In addition, an implementation based on off-the-shelf components (it should be noted that all of them can be purchased from European manufacturers) guarantees robustness, reliability and straightforward technology scaling. Indeed, not only TRL 4 has already being achieved during the Phase 1 HYPERTERA project, but the implementation of a prototype of the THz imager to be tested at an industrial facility has been also completed at 90%. A successful outcome of these tests, which will be carried out as soon as the present circumstances permit, would increase the TRL of this technology to 5. The basis of this prototype will be used for achieving TRL 6, as the main differences would lie in the control and data processing electronics and the selection of components. Furthermore, HYPERTERA Phase 2 will perform a thorough feasibility assessment on alternative technologies with the main target of identifying feasible future developments.

5.2. Project Synergies and Outreach

A technological breakthrough like the one envisioned by HYPERTERA Phase 2 could only be achieved by a committed and knowledgeable consortium. We plan to take advantage of the connections within groups of the intra-ATTRACT THz alliance (established in Pisa on December 17, 2019). The consortium will take advantage of the experience of the research groups of the T-CONVERSE and ROTOR projects for the optimization of the illumination arrangement and the selection of components. Researchers from the GRANT project will design and optimize the imaging architecture and the association with the TACTICS project will imply the supplementary application of the THz imager to plastics extrusion industry. Besides, our current industrial partner and two end-users will be responsible for designing the tests and evaluating the performance the systems in operational environments. An additional research group will perform feasibility assessments of alternative technologies. A rough budget estimation would be 1.6 million Euros.

5.3. Technology application and demonstration cases

Food safety has been identified as one of the research challenges that can have a highly beneficial impact on European citizens and, in this respect, THz spectroscopy has demonstrated several features that are unmatched by virtually any other technology. The main HYPERTERA Phase 2 system will be an inline THz product inspection tool for the agri-food industry (the optical sorter market is expected to exceed three billion dollars by 2024) demonstrating:

- Foreign body detection (metallic and non-metallic contamination) in packaged products.
- Identification of defects in packaging.
- Study of moisture content.
- Identification of cereal grain varieties and quality.

Additionally, five feasibility studies are to be performed:

- Monitoring of plastics extrusion.
- Analysis of waste.
- Quality control of pharmaceutical products.
- Quantification of plant water status in forestry.
- Process monitoring in the wood industry.

5.4. Technology commercialization

The first steps towards the commercialization of the active THz hyperspectral imager have already been taken. We have already signed a contract to develop a modified version of the prototype for real-time waste classification and a second contract is currently under negotiation (wood industry). We envision nonetheless that the potential of THz hyperspectral imagers might go much further and together with our current industry partner, which is integrated into an international technology group that develops innovative products for a wide variety of sectors, we are evaluating new collaboration possibilities.

5.5. Envisioned risks

Poor system performance (low probability): Previous findings and the available literature indicate that most certainly the imager will provide accurate results. If the system underperforms may be mainly due to component integration issues, the arrangement would be reviewed and different components employed.

System failure (low probability): The system will be protected using appropriate IP ratings, which should guarantee the successful development of the imager. Appropriate laboratory tests would be performed to ensure compliance.

Final price exceeding target (low probability): The price estimations that will be made to ensure an adequate market penetration will be pessimistic; the final system will be profitable for most end-users even if the price exceeds calculations. Several modifications on the final design might be introduced.

Underperforming partner (medium probability): The Consortium Agreement will include the measures to be taken to prevent this situation.

5.6. Liaison with Student Teams and Socio-Economic Study

The intra-ATTRACT THz alliance already organized a session within the 9th International THz-Bio Workshop (postponed) with the main aim of engaging with students in our research. This type of annual meeting would be organized throughout the ATTRACT Phase 2. The university partners in the consortium will create international student teams that will work, under the supervision of several partners, on the development of new ideas and designs that will be presented on a yearly basis on the previously mentioned workshop.

The three industrial partners in the consortium will elaborate independent socio-economic studies that would be consolidated on a final document. Whereas the end-users will analyse their own sectors, our current industrial partner will perform a broader study, analysing the impact on new potential application scenarios through meetings with experience personnel.

6. ACKNOWLEDGEMENT

This project has received funding from the ATTRACT project funded by the EC under Grant Agreement 777222.

7. REFERENCES

[1] H. Ge, Y. Jiang, F. Lian, Y. Zhang, and S. Xia, 2016, Quantitative determination of aflatoxin B1 concentration in acetonitrile by chemometric methods using terahertz spectroscopy, Food Chem. 209: pp. 286-292.

[2] A. A. Gowen, C. O'Sullivan, and C. P. O'Donnell, 2012, Terahertz time domain spectroscopy and imaging: Emerging techniques for food process monitoring and quality control, Trends Food Sci. Technol. 25(1): pp. 40-46.

[3] G. Ok, H. J. Kim, H. S. Chun, and S.-W. Choi, 2014, Foreign-body detection in dry food using continuous sub-terahertz wave imaging, Food Control 42: pp. 284.

[4] Y. Jiang, H. Ge, F. Lian, Y. Zhang, and S. Xia, 2016, Early detection of germinated wheat grains using terahertz image and chemometrics, Sci. Rep. 6, p. 21299.

[5] B. N. Behnken, G. Karunasiri, D. R. Chamberlin, P. R. Robrish, and J. Faist, 2008, Real-time imaging using a 2.8 THz quantum cascade laser and uncooled infrared microbolometer camera, Opt. Lett. 33(5): pp. 440-442.

[6] N. Kanda, K. Konishi, N. Nemoto, K. Midorikawa, and M. Kuwata-Gonokami, 2017, Real-time broadband terahertz spectroscopic imaging by using a high-sensitivity terahertz camera, Sci. Rep. 7, p. 42540.

[7] D. Burghoff, T.-Y. Kao, N. Han, C. W. I. Chan, X. Cai, Y. Yang, D. J. Hayton, J.-R. Gao, and Q. Hu, 2014, Terahertz laser frequency combs, Nat. Photonics 8(462).

[8] G. Hu, T. Mizuguchi, R. Oe, K. Nitta, X. Zhao, T. Minamikawa, T. Li, Z. Zheng, and T. Yasui, 2018, Dual terahertz comb spectroscopy with a single free-running fibre laser, Sci. Rep. 8, p. 11155.

[9] I. Coddington, N. Newbury, and W. Swann, 2016, Dual-comb spectroscopy, Optica 3(4): pp. 414-426.

[10] P. Martín-Mateos, F. Ullah Khan, and O. Elías Bonilla-Manrique, 2020, Direct hyperspectral dual-comb imaging, Optica 7(3): pp. 199-202.

[11] P. Martín-Mateos, D. Čibiraitė-Lukenskienė, R. Barreiro, C. de Dios, A. Lisauskas, V. Krozer and P. Acedo, 2020, Hyperspectral terahertz imaging with electro-optic dual combs and a FET-based detector, Paper accepted for publication.

[12] B. Jerez, F. Walla, A. Betancur, P. Martín-Mateos, C. de Dios, and P. Acedo, 2019, Electro-optic THz dual-comb architecture for high-resolution, absolute spectroscopy, Opt. Lett. 44(2): pp. 415-418.