PROBLEMY MECHATRONIKI
UZBROJENIE, LOTNICTWO, INŻYNIERIA BEZPIECZEŃSTWA

PROBLEMS OF MECHATRONICS
ARMAMENT, AVIATION, SAFETY ENGINEERING

ISSN 2081-5891; E-ISSN 2720-5266 **https://promechjournal.pl/**

Research paper

Innovative Methods of Terahertz Diagnostics in Selected Key Military and Security Applications

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Received: July 15, 2022 / Revised: August 13, 2022 / Accepted: October 10, 2022 / Published: December 31, 2023.

2023, 14 (4), 83-90; https://doi.org/10.5604/01.3001.0054.1649

Cite: Chicago Style

Świderski, Waldemar, Krzysztof Dragan, Dariusz Mielnik, and Norbert Pałka. 2023. "Innovative Methods of Terahertz Diagnostics in Selected Key Military and Security Applications”. *Probl. Mechatronics. Armament Aviat. Saf. Eng.* 14 (4) : 83-90. https://doi.org/10.5604/01.3001.0054.1649

Abstract. The article presents the main research directions of the project implemented by the consortium under the National Defence and Security Program: "Development of modern, breakthrough technologies for state security and defence", codename "SZAFIR". During the implementation of the project, the possibilities of using terahertz radiation will be examined for diagnostic tests of components crucial for defence and security, such as solid rocket fuels, aramid fibre-based composites (bulletproof vests, helmets, pyrotechnic suits), and polymer composites reinforced with glass and carbon fibres (aircraft elements). As a result of research, the interaction of tetheric radiation with materials of these components will be analysed, followed by the development of a methodology for determining their defects. This will result in creating innovative dedicated stations for non-destructive testing of these components. Neural network-based advanced signal processing and artificial intelligence algorithms will be used for automatic diagnostics of key components, improve the process of their control and therefore increase the safety of people and military equipment.
Key words: automation and control systems, terahertz radiation, non-destructive testing, composites, infrared thermography

1. INTRODUCTION

The “Innovative methods for terahertz radiation in selected key military and security applications” (TeraDiag) project is being implemented under the National Defence and Security Program: “Development of modern, breakthrough technologies for state security and defence", codename "SZAFIR", financed by the Polish National Centre for Research and Development. The project is implemented by a consortium comprising the Military Institute of Armament Technology (Leader) in Zielonka, Poland, the Institute of Optoelectronics of the Military University of Technology (Warsaw, Poland), the Air Force Institute of Technology (Warsaw, Poland) and Transfer Technologii Sp. z o.o. (Warsaw, Poland).

The possibilities of using terahertz radiation will be examined in the project for diagnostic tests of components crucial for defence and security, such as solid rocket fuels, aramid fibre-based composites (bulletproof vests, helmets, pyrotechnic suits), and composites reinforced with glass and carbon fibres (aircraft elements). As a result of research, the interaction of tetheric radiation with materials of these components will be analysed, followed by the development of a methodology for determining their defects.

This will result in creating innovative dedicated stations for non-destructive testing of these components. Neural network-based advanced signal processing and artificial intelligence algorithms will be used for automatic diagnostics of key components, improving the process of their control and therefore increasing the safety of people and military equipment.

2. TERAHERTZ RADIATION

The spectral range of terahertz radiation is 0.1 to 3 THz (1 THz = 10^{12} Hz) and is part of the far infrared (FIR) – Fig. 1. In the wavelength domain, this corresponds to a range of 3 to 0.1 mm (or 100 μm). Other known names for terahertz radiation are tremendously high frequency (THF), introduced by the International Telecommunications Union, or submillimetre waves, most commonly used in astronomy. Sometimes they are referred by English abbreviations such as: T-rays or T-light. The Polish-speaking community uses the terms: THz waves or simply terahertz.

However, in the literature of the subject, there is also a slightly broader definition of the terahertz range, of 0.1 to 10 THz. This range therefore also includes the upper part of the MMW millimetre wave band (0.03-0.3 THz) and the lower part of the far infrared. This broader definition stems from the fact that some measuring devices and methods, including the TDS method described in the article, operate in a wider range than 0.1-3 THz and there is no reason to only be artificially limited to this section of the spectrum.

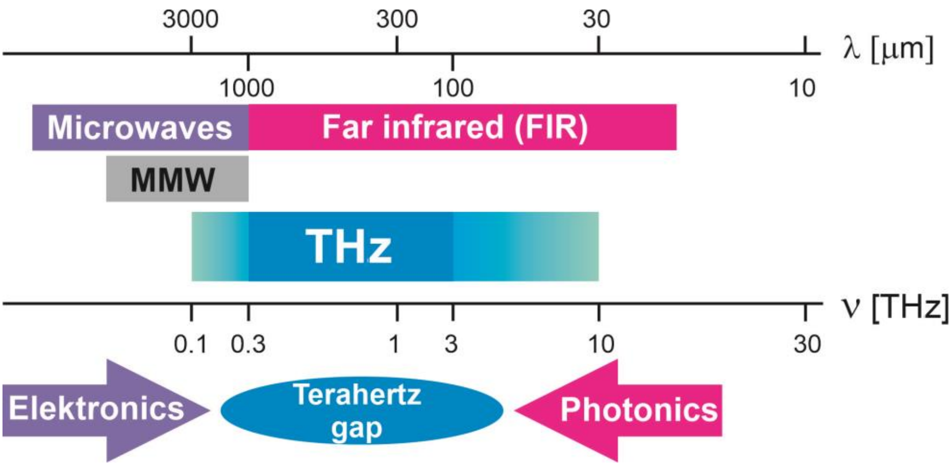

Fig. 1. THz radiation against spectrum of electromagnetic waves

Frequency units expressed in [THz] are most often used in the "terahertz" scientific community – Tab. 1. Wavelength expressed in [μm] or wave number *k* expressed in [cm^{-1}] is less common, while occasionally photon energy *E* is given in [meV].

The issue of project objectives is consistent with the objectives of "Priority research directions in the Ministry of National Defence for 2017-2026", especially with the "Area of defence techniques and technologies", whose main objective is to develop and implement “breakthrough technologies”, which include technologies and techniques related to terahertz radiation.

Table 1: Basic units found in the terahertz band

Frequency ν **[THz]**	**Wavelength** $\lambda = c/\nu$ **[μm]**	**Wave number** $k = 1/\lambda$ **[cm^{-1}]**	**Photon energy** $E = h\nu$ **[meV]**
0.1	3000	3.33	0.41
1	300	33.33	4.14
10	30	333.33	41.41

Due to the non-ionising nature of this radiation and, consequently, its lack of harmful effects on living organisms, it may replace X-ray devices in many applications. The lower penetration of terahertz radiation allows for the examination of materials with lower density, which X-rays could not do. After x-raying the sample, the resulting image shows structural defects that are not detected by ordinary optics. This can be used to detect points of damage to various elements, e.g., in composite structures or in semiconductor devices. With regard to laminates, THz radiation easily penetrates through most polymer materials, including those coloured and impenetrable for the visible and infrared range. The needs of the market related to the defence industry for non-destructive testing are very high, especially in the case of testing bulletproof vests and composite helmets after long-term use, where randomly selected samples are subjected only to destructive testing [1]. This means several to several thousand pieces to be tested every year. Non-destructive testing of solid rocket fuels [2], smoke and incendiary elements for grenades and artillery shells and composite parts and assemblies of aircraft have a direct impact particularly on the safety of the operators of these systems.

The civilian market also needs such diagnostic stations, which have a direct impact on the safety of use of objects containing composite parts and assemblies [3, 4].

3. TERAHERTZ NON-DESTRUCTIVE TESTING

The practical use of THz radiation for non-destructive testing involves imaging its structure in the two most common configurations – transmission and reflection. In the transmission configuration (Fig. 2), most often from a single source, radiation is shaped by the optical system so that it illuminates the entire sample area (or its main part). This radiation passes through the sample and is then detected by an array or lineup of detectors. The detected radiation provides comprehensive information about the sample attenuation distribution. Further image analysis can identify areas with different absorption properties for detecting anomalies. The advantage of this type of imaging is its high speed and thus it can be used for routine screening of various elements.

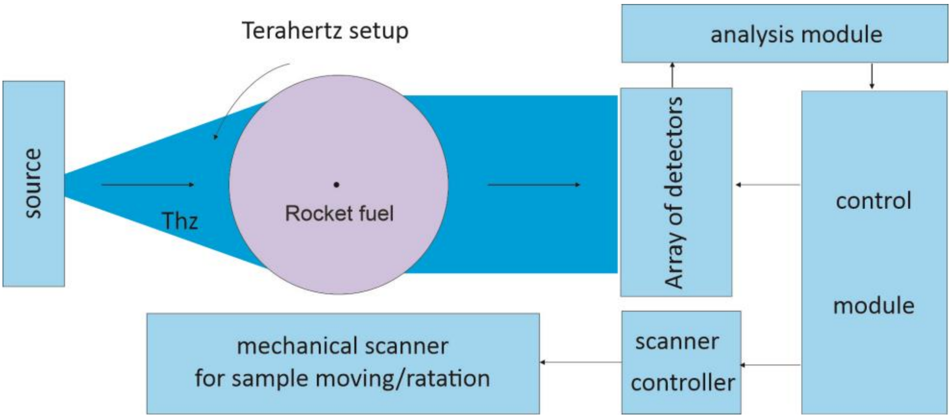

Fig. 2. Diagram of a terahertz station for testing rocket fuels in the transmission version

Its limitation is due to the fact that the sample must be transmissive, so this method cannot be used to test thicker elements or those covered with a metal layer impenetrable to THz radiation on one side. Two techniques are used in the reflection configuration – TDS (*Time Domain Spectroscopy*) [5] and FMCW (*Frequency Modulated Continuous Wave*) [6]. In both techniques, radiation from the source illuminates the points of the sample, partially penetrating it and partially reflecting from it and reaching the receiver. Imaging in this case involves point-by-point raster scanning of the sample. Compared to transmission techniques, both reflection methods can determine the boundaries of media in the sample material. Such boundaries of media may include, for example, delamination (sample – air boundary) or inclusions (sample – other material). The TDS has a large axial resolution (into the sample) and allows the detection of delamination of up to 50-100 μm; its limitation is a relatively small range of sample thickness, up to several cm. On the other hand, the FMCW method can be used for testing thicker samples, but with lower axial resolutions. It is first proposed to carry out a thorough analysis of key military elements that can be subjected to terahertz diagnostics. The non-destructive testing techniques described above will be used for such selected elements to ensure the optimal detection of hidden defects, taking into account material and technical requirements. In the first stage of the project, it is planned to build two or three types of terahertz models of diagnostic stations that will meet the PGT6 readiness level. These models will then be refined in subsequent stages to finally meet the requirements of the PGT9 readiness level.

The following description shows an example of how the diagnostic station operates in the reflection configuration (Fig. 3), which was considered during preliminary pre-design work. Solid rocket fuel has the form of a cylinder with a diameter of several dozen centimetres and a length of several dozen centimetres.

Due to the shape of the sample, it should be rotated and moved during the test, which can be done by a mechanical scanner controlled by the scanner controller. As the sample moves, the reflection system measures the reflected radiation, which is then analysed by the signal and image analysis module. The entire operation of the station is controlled by the control module.

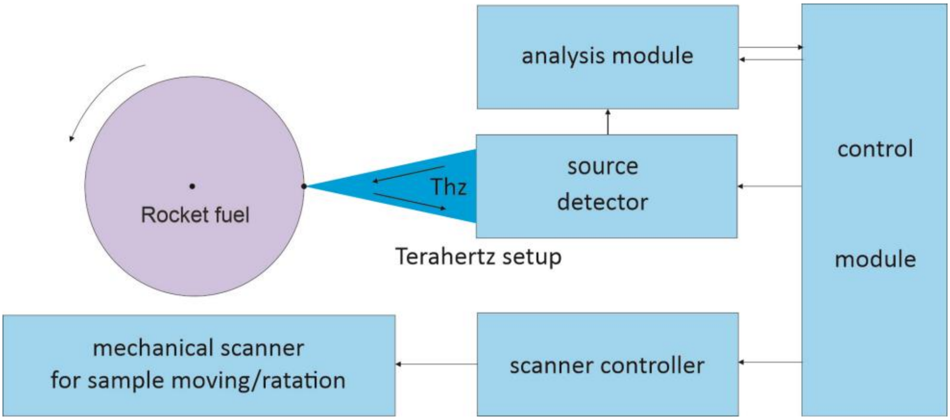

Fig. 3. Diagram of a terahertz station for testing rocket fuels in the reflection version

The stations proposed in this design require many dedicated subsystems, including: specialised terahertz systems and advanced signal and image analysis modules for extracting the most important useful information from the test results, or neural networks for automatic diagnosis of selected components. The use other non-destructive techniques with terahertz radiation has also been considered in order to improve the detection of defects thanks to the synergy effect. The operator of such a station will be tasked with placing the tested piece in a dedicated holder. The system will allow the operator to get easy interpretable information – the piece either meets or does not meet the relevant requirements.

4. CONCLUSIONS

Implementation of the project results applies to the use of non-destructive tests using terahertz methods of objects related to the safety of soldiers and reliability of equipment and ammunition. The first key parameter is the versatility of the terahertz methods used in diagnostic stations, allowing the non-destructive testing of objects ranging from solid rocket fuels to composites used in aircraft structures. Another parameter is the evaluation of reliability to increase the probability that the tested objects meet technical requirements. The project will also increase the safety of soldiers and crews of military equipment.

So far, bulletproof vests and composite helmets have not been comprehensively tested non-destructively, either upon the receipt of production batches or after many years of use.

Their non-destructive testing will eliminate products that do not meet the technical parameters, the use of which may endanger the health and life of soldiers and other uniformed services. So far, pyrotechnic suits have not been non-destructively tested after the warranty period and it is unknown whether they still meet the technical requirements. Terahertz radiation used in diagnostic stations is safe for operators, which is important when examining solid rocket fuels and smoke and incendiary charges, compared to the current X-ray method. In addition, there are no restrictions on the dimensions of the tested objects, unlike in the X-ray method, in which the length of the tested object is limited by the dimensions of the chamber.

Another parameter is the automatic detection of defects through the use of neural networks to analyse terahertz images.

FUNDING

The work has been financed by the Polish National Centre for Research and Development (Project No. DOB-SZAFIR/02/A/001/01/2020).

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Nowatorskie metody diagnostyki terahercowej w wybranych kluczowych zastosowaniach w wojsku i bezpieczeństwie

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Streszczenie. W artykule przedstawiono główne kierunki badawcze projektu TeraDiag realizowanego przez konsorcjum (WITU, IOE WAT, ITWL oraz LTT) w ramach programu NCBR na rzecz obronności i bezpieczeństwa państwa pn. "Rozwój nowoczesnych, przełomowych technologii służących bezpieczeństwu i obronności państwa" pk. "SZAFIR". W trakcie realizacji projektu zostaną zbadane możliwości zastosowania promieniowania terahercowego do badań diagnostycznych kluczowych dla obronności i bezpieczeństwa komponentów, takich jak stałe paliwa rakietowe, kompozyty na bazie włókien aramidowych (kamizelki kuloodporne, hełmy, kombinezony pirotechniczne), kompozyty polimerowe wzmacniane włóknami szklanymi i węglowymi (elementy statków powietrznych).W wyniku prac badawczych przeprowadzona będzie analiza oddziaływania promieniowania terahercowego anetz materiałami tych komponentów a następnie opracowana metodyka wyznaczania ich defektów. W rezultacie powstaną nowatorskie dedykowane co najmniej dwa stanowiska do badań nieniszczących tych komponentów. Zaawansowane algorytmy przetwarzania sygnałów i sztucznej inteligencji bazujące na sieciach neuronowych pozwolą na automatyczną diagnostykę kluczowych komponentów, przyczynią się do polepszenia procesu ich kontroli, a przez to poprawią bezpieczeństwo ludzi i sprzętu wojskowego.
Słowa kluczowe: kompozyty, badania nieniszczące, promieniowanie terahercowe, systemy automatyzacji i kontroli, termografia w podczerwieni