

Piotr GARBACZ

Institute for Sustainable Technologies – National Research Institute, Radom
piotr.garbacz@itee.radom.pl

TERAHERTZ IMAGING – PRINCIPLES, TECHNIQUES, BENEFITS, AND LIMITATIONS

Key words

Terahertz imaging, non-destructive testing, hybrid imaging.

Abstract

This article reviews recent developments in the field of terahertz technology. A historical perspective and future trends along with unique features of THz systems are presented. Existing techniques for the generation and detection of terahertz radiation are briefly discussed and classified. Numerous examples that illustrate many exciting potential uses for this emerging technology are described, including biomedical imaging, security and defence, quality control, and technical diagnostic applications. Lastly, the physical limitations of terahertz imaging and the potential of use in hybrid imaging systems are discussed.

Introduction

Presently, Non-Destructive Testing (NDT) methods are commonly used in industry to evaluate the properties of materials, components, and systems. The increase in safety requirements and quality assurance demands in various industrial branches has led to the development of a number of various inspection

methods. A large part of existing techniques is based on the analysis of electromagnetic radiation interaction with matter. Different spectral bands of the electromagnetic spectrum, ranging from gamma rays to radio waves, are used for quantitative and qualitative analysis in NDT applications. However, one part of the electromagnetic spectrum, which is placed between infrared and microwaves regions (Fig.1), for many years had remained unexplored. Until the late 1980s this area was often called the Terahertz Gap, which was caused by the difficulties involved in developing suitable compact sources and detectors. The terahertz region ranges from frequencies of about 0.1 to 10 THz, which is an area of convergence between the electronics field and the photonics field in the electromagnetic spectrum.

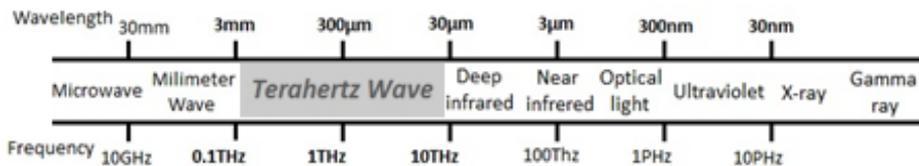


Fig. 1. Electromagnetic spectrum wavebands

THz radiation is characterized by the following unique features:

- It can penetrate through a wide variety of dielectric materials, such as fabric, paper, plastic, leather, and wood.
- It is non-ionizing and has minimal effects on the human body.
- It has very large absorption due to water.
- Metals highly reflect terahertz radiation.

These particular properties of THz waves make them suitable for a growing number of potential applications including biomedical imaging, security and defence, industrial quality assurance systems, and technical diagnostic systems. In 2004, MIT Technology Review selected THz as one of 10 emerging technologies that will change the world. According to recent forecasts, in near future, THz technology will reach a level of development that will enable implementation in on-line industrial inspection systems (Fig. 2). Furthermore, it is predicted that the terahertz technology market will grow from \$127 million in 2016 to \$570 million in 2021[2]. For these reasons, it is worth being aware of the potential advantages and limitations of terahertz technology that will be discussed later in this article.

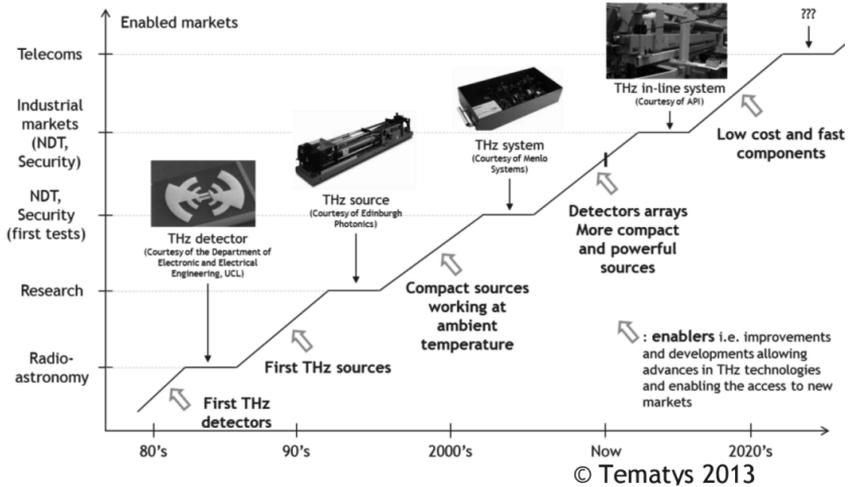


Fig. 2. THz technology and market trends [1]

1. Terahertz instrumentation and methods

The technology of generating and detecting THz radiation has been constantly evolving in recent decades. A number of approaches have been developed in parallel to fill the terahertz gap. Generally, THz methods can be divided into active and passive. Active solutions can be either pulsed or continuous-wave (CW). Table 1 shows a comparison of various detection schemes used in nondestructive analysis technology [3].

Table 1. Detection schemes of THz non-destructive analysis [3]

Mode	Imaging parameter	2D/3D	Main methods
Passive	Power	2D	THz camera
Active transmission	Power	2D	QCL with THz camera Mapping by QCL with detector
		3D	CT by QCL with detector
	Spectroscopy	2D	Mapping by TDS Mapping by FTIR Mapping by tuneable terahertz light source
		3D	CT by TDS
	Phase	2D	Mapping TDS
		3D	CT by TDS
Active reflection	Power	2D	QCL with THz camera Mapping by QCL with detector
	Spectroscopy	2D	Mapping by TDS Mapping by FTIR
		Differential time	1D (depth)
		3D	Mapping TOF

According to type of source used, THz systems can be divided into [4] vacuum electronic, solid-state electronic, lasers, and mechanical excitation. The choice of a terahertz source is determined by the type of required imaging technique. Low-power sources complicate detection, often necessitating the use of more demanding detection devices like cryogenically cooled sensors. From the practical point of view, it is important to be aware that, approaching the middle of the range of terahertz (1 THz), output power falls for most devices (Fig. 3). At present, a number of THz wave generation techniques are already commercially available including the following: optically pumped terahertz lasers, Quantum cascade lasers, time-domain system sources, THz IMPATT diodes, and Backward-wave oscillators.

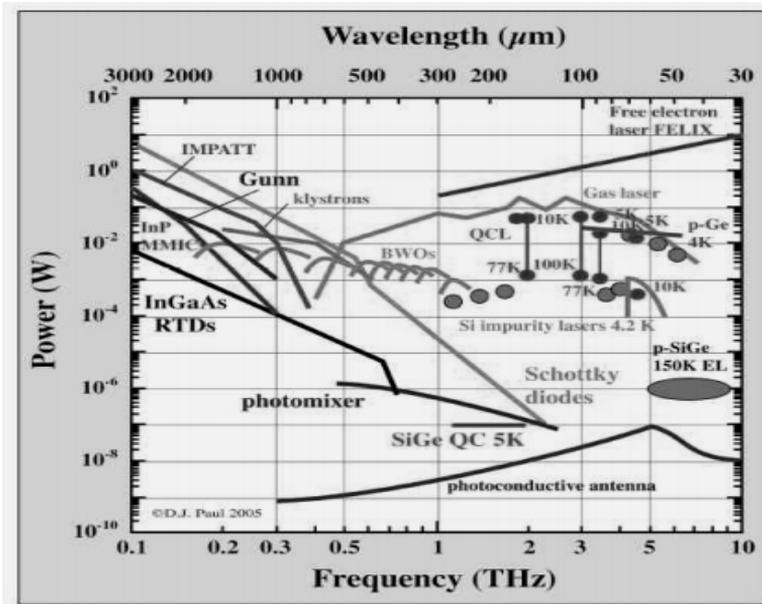


Fig. 3. Output power from THz sources [5]

All radiation detection systems in THz spectral ranges can be divided into two groups: incoherent detection systems (broadband), and coherent detection systems (narrowband). In broadband detection, direct detectors based on thermal absorption are commonly used. Most of these detectors require cooling to reduce thermal background. The most common systems are bolometers and pyroelectric infrared detectors [6]. In narrowband signal detection systems, methods based on photoconductive sampling and free-space electro-optic sampling are often used [7]. Difficulties in the development of high-power

radiation sources and the noise caused by the thermal background radiation require the use of highly sensitive methods of detection of terahertz radiation. Continuous developments have led to enormous progress in this area. In the case of bolometers, sensitivity has been doubled every 2 years in the past few decades. Simultaneously, the size of pixel arrays is constantly enlarged [8] from number of approximately one hundred pixels in year 2000 to QVGA size (320x240 pixel) in 2014 [9].

2. Applications of terahertz imaging

Advances of terahertz sources and detection techniques are opening up opportunities for a wide range of applications. In this section, selected THz applications from different research areas are presented.

The previously described properties of terahertz radiation, such as very low photon energy, sensitivity to water, and characteristic spectral signatures for many substances make THz imaging suitable for many biomedical applications. The non-ionizing character of THz radiation makes it less harmful to living tissue than X-ray. This unique feature is especially interesting for medical applications including cancer diagnosis [10]. It has been proved that terahertz imaging can be used as an alternative to other diagnostic technologies for imaging the structure of teeth and the identification of dental caries [11]. Another interesting application is wound assessment, which can range from the severity of burns to cuts. The advantage of terahertz radiation in this particular case is that it can image skin through wound dressings [12].

High water absorption of THz radiation makes it a very valuable tool for plant scientists for the inspection of the water content in vegetative tissues [13]. Several research groups are currently working on the development of innovative methods for continuous monitoring of irrigation in plants [14]. The interaction of THz radiation with molecules of water is also used in Time-Domain-Systems to determine the level of water in lubricant oils, which is one of the important factors for the wearing processes. [15] Many chemical substances have characteristic spectral fingerprints in the terahertz waveband, which can be used for the identification (Fig. 4) and detection of unwanted contamination during drug production in the pharmaceutical industry [16].

In the field of defence and security, terahertz technology is also a subject of much ongoing research. It has been shown that THz spectroscopy can be used for the detection of explosive materials, while terahertz imaging has great potential for the detection of concealed weapons [17] as an alternative to x-ray and non-imaging microwave and millimetre-wave systems [18].

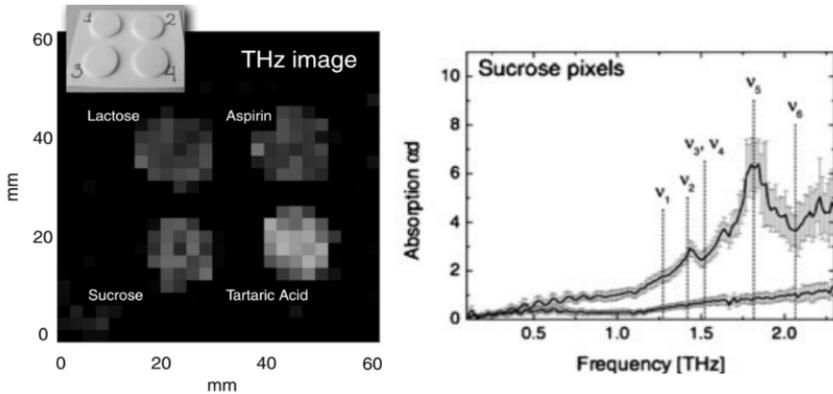


Fig. 4. Terahertz technology used for identification of chemical samples [16]

Non-destructive THz imaging is highly promising for meeting the current demands in the areas of quality control and technical diagnostic applications. Its core uses are seen in the plastic and paper industries. Most polymeric materials are transparent for THz radiation. Therefore, it is possible, for example, to examine the quality of welded joints in plastic [19]. Sorting and separation of the collected plastic is required to achieve high quality recycling. Black items cannot be effectively separated by classical optical sensors due to limited reflection. Terahertz technology can enhance current optical sorting equipment by identifying the different plastic resins effectively and sorting black plastic resins [20].

Another application that has great potential is the inspection of composites. THz images can be used for identifying areas of different fibre filling content in polypropylene specimens [21] or the evaluation of the structural integrity of wind turbines [22]. Wood polymer composites, which are sensitive to water absorption, can be examined by THz spectroscopy to monitor the increase in water content within the material by measuring the decreasing THz transmission [21]. In a similar way, paper humidity and thickness can be determined [23].

Due to the transparent properties of cardboard and plastic in the THz waveband, the detection of foreign objects inside packaging meant to exclude human error or defective items inside the package can be performed. Terahertz systems can also be used to solve one of the most important problems in the food industry, which is the detection of potentially harmful contaminants such as pieces of plastic, wood, glass, stone, or metal. It has been showed that, by use of THz technology, metallic and non-metallic materials can be detected in chocolate bars with a spatial resolution of less than 1 mm (Fig. 5).

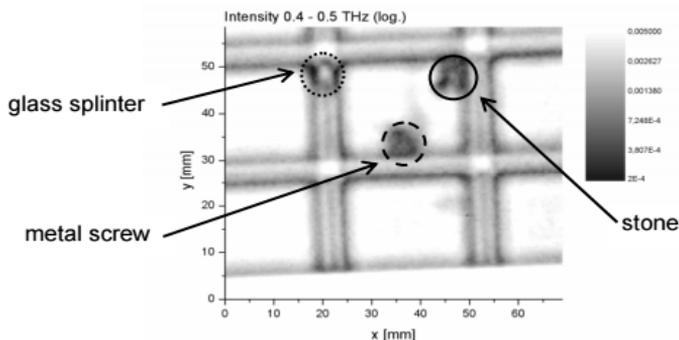


Fig. 5. THz image of chocolate bar with different contaminants [24]

Maintenance and inspection of aging infrastructures like oil and gas pipelines is an important issue. Conducted research has shown that, by the use of terahertz systems, it is possible to detect corrosion spots on the surface of pipelines beneath many insulation materials (mineral wool, urethane foam) [25]. It was also found that it is feasible to identify faults under corrosion protection coatings using THz Time-Domain-Spectroscopy [26]. Large area terahertz imaging was also used for the identification of flaws in the external tank of the space shuttle. It was determined that terahertz pulses (0.3 THz) can penetrate as much of 20 cm of foam and enable imaging with a lateral resolution of less than 2 mm and a depth resolution of <100 microns [27].

3. Limitations of terahertz imaging systems

Although there has been enormous progress in the construction of sources and detectors of terahertz radiation, there are many aspects to be taken into account when considering the possibility of implementing this technology in commercial applications. First of all, detecting terahertz signals is difficult, because blackbody radiation at room temperatures is strong at terahertz frequencies. To improve the signal to noise ratio, terahertz images can be created by mechanical scanning an object pixel by pixel with the use of a coherent source. However, this solution may be applied only for static objects. To overcome this issue, an imaging array can be used. This results in a trade-off between the signal-to-noise ratio and the size of the area being imaged, since the energy of the pulse is being spread over an array of detectors. The big concern for THz imaging is atmospheric transmission. The atmospheric attenuation of the THz domain is much more severe than in the other spectral regions, such as infrared and visible-light regions [28]. This requires that THz imaging should be short-range when compared to imaging in the other modalities. Another problem is the selection of appropriate optics in imaging systems. Generally, lenses are

not used so widely in the terahertz regime because of lack of convenient materials and anti-reflection coatings functioning over wide range of frequencies [29]. Difficulties in the construction of advanced lenses are associated with one of the most important limitations of THz systems, which is the measurement resolution.

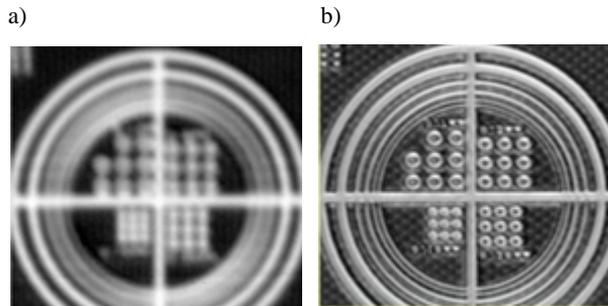


Fig. 6. THz image a) at 0.3 THz b) at 1THz [25]

Despite the increasing number of pixels in cameras, THz solutions are as limited by diffraction phenomenon as are any other imaging systems. An absolute upper performance limit controlled by the laws of physics is controlled by the sensor size working f-number of the lens and the wavelength of light that passes through the lens [30]. In the diffraction-limited case, frequency determines resolution (Fig. 6).

4. Concept of use of THz imaging in hybrid vision systems

Hybrid imaging is an emerging direction in Non-Destructive Evaluation and Structure Health Monitoring [31]. There are many examples showing that a combination of an simultaneous image analysis of two or more spectral bands allows the efficiency of vision inspection to be increased [32, 33]. However, due to early stage of the development of terahertz methods, there are not many hybrid systems in which this technology is applied. Nevertheless, considering the fact that even THz images with low pixel resolution still provide valuable information, there are attempts to combine them with the high-resolution images from a visible spectral band for concealed-object detection in security systems [34]. On similar principles, measuring systems can be developed for gauging elements placed in a material that is transparent for THz radiation and opaque for VIS (visible-light) radiation. In many industrial applications, there is a need for measuring the correctness of the relative position of objects embedded in another material. In the presented simulated scenario, two elements (A and B) with high absorption to THz radiation (Fig. 7a) are placed in a transparent

material for this spectral band (e.g., plastic). Using only the terahertz camera image would result in a low accuracy of external dimension measurements of the inspected object due to limited resolution and a low signal to noise ratio. The use of an additional high-resolution VIS camera and backlighting setups facilitates high accuracy external edge detection. For many cases, the proposed method could replace hybrid systems that employ X-ray radiation for the screening of materials. Nevertheless, such techniques would require the development of special algorithms for image fusion and sophisticated calibration methods.

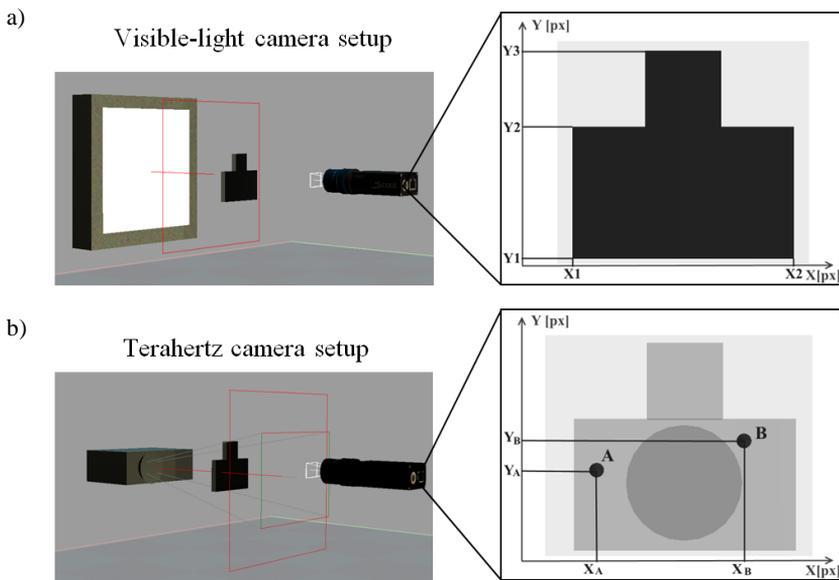


Fig. 7. The concept of hybrid vision system consisting of (a) Terahertz camera and (b) Visible-light camera

Summary

The technological race has caused enormous progress in both the generation and detection techniques of terahertz waves. THz systems are beginning to slowly move from research laboratories into industrial applications. Presently, complete integrated systems are available to non-expert THz users. Nevertheless, effective implementation of terahertz systems requires a full understanding of the inspection process, physical properties of the object being tested, and imaging techniques. The unique characteristics of terahertz radiation, such as high absorption by water and the reflectivity metals may be unacceptable limitation in some cases and an advantage in other cases. It is also

important to consider whether the THz system will be used for measurement or for interpretation of the specific features of inspected objects. At the stage of development, it is crucial to take into account the physical limitations of terahertz imaging systems. The measuring resolution of the detection system and output power of the selected source can vary significantly, depending on the applied THz frequency range. However, for minimizing the impact of the resolution limitation of terahertz images, in some cases, a hybrid vision system with a visible-light camera can be applied.

Scientific work executed within the Strategic Programme “*Innovative Systems of Technical Support for Sustainable Development of the Country’s Economy*” within Innovative Economy Operational Programme.

References

1. Robin T., Bouyé C., Cochard J., d’Humières B.: Terahertz Components & Systems: Technology and Market Trends, www.photonics21.org.
2. PreScouter Inc.: Report 9 Disruptive Technologies Changing The World, 2015.
3. Song H., Nagatsuma T.: Handbook of Terahertz Technologies: Devices and Applications, 2015, pp. 565.
4. Lewis R.A.: A review of terahertz sources, *Journal of Physics D: Applied Physics*, 2014.
5. Cooke M.: Filling the THz gap with new applications, *Semiconductor TODAY, Compounds&Advanced Silicon*, Vol. 2 2007.
6. Lee C.H.: *Microwave Photonics*, Second Edition, 2013, pp. 441.
7. Chan W.L., Deibel J., Mittleman D.M.: Imaging with terahertz radiation, *Reports on Progress in Physics*, 2007, vol. 70, pp. 1325.
8. Rogalski A., Sizov F.: Terahertz detectors and focal plane arrays, *Opto-Electronics Review*, 2011, pp. 346–404.
9. NEC company, NEC develops ultra-sensitive terahertz camera, http://www.nec.com/en/press/201411/global_20141111_01.html
10. Yu C., Fan S., Sun Y., & Pickwell-MacPherson E.: The potential of terahertz imaging for cancer diagnosis: A review of investigations to date. *Quantitative Imaging in Medicine and Surgery*, 2012.
11. Leiss-Holzinger E., Wiesauer K., Stephani H., Heise B., Stifter D., Kriechbaumer B., Spachinger S.J., Gusenbauer C., Withalm G.: Imaging of the inner structure of cave bear teeth by novel non-destructive techniques, *Palaeontologia electronic*, 2015, vol. 18.
12. Pogson E.M.: Thesis, Terahertz Applications in Medicine, the Environment and Optics, University of Wollongong, Australia, 2012.

13. Freebody M.: Challenges Not Insurmountable for Terahertz Spectroscopy, <http://www.photonics.com>.
14. Gente R., Koch M.: Monitoring leaf water content with THz and sub-THz waves, *Plant Methods*, 2015.
15. Gorenflo S., Tauer U., Hinkov I., Lambrecht., Buchner R., Helm H.: Dielectric properties of oil–water complexes using terahertz transmission spectroscopy, *Chemical Physics Letters*, 2006, vol. 421, pp. 494–498.
16. Walther M., Fischer B. M., Ortner A., Bitzer A., Thoman A., Helm H., Chemical sensing and imaging with pulsed terahertz radiation, *Analytical and Bioanalytical Chemistry*, 2010, vol. 397.
17. Liu H., Zhong H., Karpowicz N., Chen Y., Zhang X.: Terahertz Spectroscopy and Imaging for Defense and Security Applications, *Proceedings of the IEEE*, 2007, vol. 95, pp. 1514–1527.
18. Kapilevich B.Y., Harmer S.W., Bowring N.J.: Non-Imaging Microwave and Millimetre-Wave Sensors for Concealed Object Detection, Taylor & Francis Group, 2015.
19. Koch M., Krok P.: Quality Control of Plastic Joints with THz-Imaging Technique, Application notes, <http://www.menlosystems.com>.
20. TeTechS, Identifying and Sorting Black Plastic Polymers, <http://tetechs.com>.
21. Menlo, Discover the World of THz, <http://www.menlosystems.com>.
22. Hsu1 D., Lee K., Park J., Woo Y., Im K.: NDE inspection of terahertz waves in wind turbine composites, *International Journal Of Precision Engineering and Manufacturing*, 2012, vol.13, pp. 1183–1189.
23. TOPTICA Photonics AG Terahertz Applications – Paper Quality Control, <http://www.toptica.com>.
24. Jordens C., Rutz F., Koch M.: Quality Assurance of Chocolate Products with Terahertz Imaging, *European Conference on Non-Destructive Testing*, 2006.
25. Zomega Terahertz Corporation, The Terahertz Wave eBook June 2012 Edition, <http://dl.z-thz.com>.
26. Moriguchi A., Tanaka T., Sakagami T., Hangyo M.: Nondestructive Evaluation of Steel Plate Coated with Corrosion, 13th International Symposium on Nondestructive Characterization of Materials, 20–24, France, 2013.
27. Zimdars D., White J.S., Stuk G., Chernovsky A., Fichter G., Williamson S.: Large Area Terahertz Imaging and Non-Destructive Evaluation Applications, The 4th International Workshop on Ultrasonic and Advanced Methods for Nondestructive Testing and Material Characterization, USA, 2006.
28. Nguyen D.T.: PhD Thesis: Design, modeling, and characterization of innovative THz detectors, Université de Grenoble, 2012.

29. Lewis R.A.: Terahertz Physics, Cambridge University Press, 2012.
30. Lizarraga J., Del-Rio C.: Resolution Capabilities of Future THz Cameras, Radioengineering, 2011, vol. 20, pp. 373–379.
31. Cheng Y., Den Y., Cao J., Xiong X., Bai L., Li Z.: Multi-Wave and Hybrid Imaging Techniques: A New Direction for Nondestructive Testing and Structural Health Monitoring, Sensors, 2013, vol. 13.
32. Czajka P., Garbacz P.: Use Of Hybrid Vision Methods For Diagnostics Of Technical Processes, Maintenance Problems, 2014, pp. 73–85.
33. Garbacz P., Giesko T., Mazurkiewicz A.: Inspection method of aluminium extrusion process, Archives of Civil and Mechanical Engineering, Vol. 15(3), pp. 631–638.
34. Kowalski M., Kastek M., Piszczek M., Życzkowski M., Szustakowski M.: Harmless screening of humans for the detection of concealed objects, Safety and Security Engineering VI, 2015, pp. 215–226.

Zasady, techniki oraz zalety i ograniczenia obrazowania terahercowego

Słowa kluczowe

Obrazowanie terahercowe, badanie nieniszczące, obrazowanie hybrydowe.

Streszczenie

W artykule przedstawiony został postęp w dziedzinie technologii terahercowej. Zaprezentowano rys historyczny, przewidywane trendy w rozwoju oraz unikalne cechy systemów terahercowych. Omówione zostały i sklasyfikowane aktualnie istniejące techniki generowania i detekcji promieniowania terahercowego. Zaprezentowano liczne przykłady zastosowań, które ilustrują duży zakres możliwych aplikacji tej szybko rozwijającej się technologii, zarówno w aplikacjach biomedycznych, bezpieczeństwa i obrony, kontroli jakości oraz diagnostyki technicznej. W ostatniej części artykułu przedstawione zostały fizyczne ograniczenia obrazowania terahercowego oraz potencjalne zastosowania w hybrydowych systemach wizyjnych.