TERAHERTZ TECHNOLOGY: CURRENT ADVANCES AND FUTURE PROSPECTS

by Jana Publication & Research

Submission date: 09-Dec-2025 12:21PM (UTC+0700)
Submission ID: 2814323157
File name: IJAR-55139.pdf (547.58K)
Word count: 5896
Character count: 31870

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ABSTRACT

In recent times, there has been considerable interest in Terahertz technology owing to its promising potential for diverse applications across multiple domains, including communication, imaging, spectroscopy, and sensing. Terahertz radiation occupies a region in the EM spectrum that is situated between the microwave and infrared regions. This area of the spectrum has distinctive properties that make it advantageous for various applications., such as high penetration depth, non-ionizing radiation, and sensitivity to molecular vibrations. This review article presents a summary of the latest developments and potential future applications of terahertz technology. It begins by examining the means of generating and detecting terahertz radiation, covering both conventional and innovative methods, such as quantum cascade lasers and terahertz metamaterials. Secondly, we review the applications of terahertz technology in different fields, such as communication, imaging, and sensing. We highlight the recent developments in terahertz communication, which has the potential to provide fast, wireless communication in the terahertz band. We also discuss the advances in terahertz imaging, including medical and security applications, and the potential of terahertz spectroscopy for identifying and characterizing materials. Finally, we discuss the future prospects and challenges in terahertz technology, including the need for more efficient and compact terahertz sources and detectors, as well as the need for standardized measurement techniques and safety guidelines. We also highlight some of the potential applications of terahertz technology, such as terahertz sensing for agriculture and food safety, and terahertz imaging for cultural heritage preservation. Overall, this review paper provides an up-to-date summary of the current state-of-the-art in terahertz technology and the exciting opportunities that lie ahead.

Keywords: Spectroscopy, laser-Plasma interaction, Optical-rectification.

INTRODUCTION

James Clerk Maxwell, a physicist, discovered the existence of terahertz radiation in the late 1800s as part of his theory of electromagnetism. However, it was not until modern technology that terahertz radiation could be generated and detected with accuracy. Terahertz radiation, also called submillimetre or THz radiation, refers to electromagnetic waves that have frequencies ranging in between 0.1 and 10 terahertz. This frequency range is significant for many scientific and technological applications, particularly in imaging and sensing, as it can penetrate various materials like paper, plastic, and clothing without ionizing radiation. This makes it a viable option for non-destructive imaging and testing in fields such as medicine, security, and materials science.

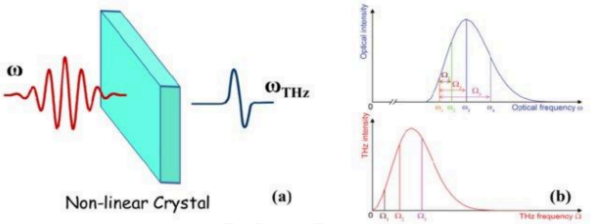
Terahertz radiation is also being studied for its potential in high-speed communication, as it has the potential to transmit huge amounts of data wirelessly at marginally very fast speeds. In addition, it is being explored for its potential in spectroscopy and chemical analysis, as the unique vibrational frequencies of molecules in the terahertz range can provide valuable information about their composition and structure[4]. Despite its many promising applications, terahertz radiation is still less extensively investigated in comparison to other regions of the EM spectrum, due in part to the technical challenges involved in generating, detecting, and manipulating these waves. However, with ongoing advancements in technology and increasing interest in its potential uses, the study of terahertz radiation is expected to continue to expand and advance in the future.

One of the challenges in working with terahertz radiation is generating it in the first place. Unlike lower frequency electromagnetic waves, which can be generated using conventional electronic circuits, terahertz radiation requires more specialized techniques, such as using femtosecond lasers or photoconductive antennas[5,11]. These techniques involve exciting electrons in a semiconductor material, which then emit terahertz radiation as they relax back to their ground state. Once generated, terahertz radiation can be detected using a variety of methods, including bolometers, pyroelectric detectors, and semiconductor devices such as Schottky diodes. These detectors are typically sensitive to changes in temperature or electric fields, which are induced by the terahertz radiation as it interacts with the material being studied. In these terahertz has attracted a growing interest due to its wide range of applications in wireless communication, security screening, and biological imaging. For example, terahertz imaging has been used to identify defects in composite materials, detect skin cancer, and screen for hidden weapons or explosives. In addition, terahertz communication has the potential to enable high-speed, high-bandwidth wireless data transfer, which could revolutionize fields such as virtual reality, autonomous vehicles, and the Internet of Things. Despite these promising applications, there are also potential risks associated with exposure to terahertz radiation, particularly at high intensities. As with any form of radiation, it is important to carefully evaluate the risks and benefits of using terahertz radiation for different applications, and to take appropriate safety precautions to minimize any potential harm.

2.Ways to generate/detect Terahertz experimentally:

There are several methods for generating and detecting terahertz (THz) radiation in a laboratory setting. Some of the most common methods include:

2.1 Optical Rectification



(Fig.1)

The basic principle of optical rectification is the generation of an electric field in a nonlinear crystal due to the interaction between the intense laser pulse and the nonlinear material. This electric field then drives the emission of terahertz radiation via a process known as difference frequency generation[1]. One of the main advantages of optical rectification is its ability to generate terahertz radiation with a broad range of frequencies. This makes it suitable for a variety of applications, including imaging and spectroscopy of materials, as well as communication[2]. Several research groups around the world have developed and optimized optical rectification techniques for generating terahertz radiation. For example, researchers at the University of Utah have demonstrated the effect of tilted pulse fronts to increase the efficiency of optical rectification, resulting in a significant increase in the generated terahertz radiation[3].

In summary, optical rectification is a powerful technique for generating terahertz radiation, with applications in imaging, spectroscopy, and communication. Ongoing research in this field is focused on improving the efficiency and frequency range of terahertz generation using optical rectification.

2.2 Photoconductive antennas

(PCAs) terahertz (THz) emitter that can generate THz radiation through ultrafast photoconductive switches. They are broadly used for THz time-domain spectroscopy, imaging, and communication because of their high efficiency, broad bandwidth, and tunable emission frequency.

PCAs consist of a semiconductor material that is illuminated by an ultrafast laser pulse, generating a photocurrent that is rapidly switched by the laser. This photocurrent then emits THz radiation, which can be detected and analysed for various applications[4]. Several research groups have investigated and optimized PCAs for THz emission. For example, researchers at the University of California, Los

Angeles have developed PCAs using low-temperature grown GaAs and demonstrated the generation of THz radiation with a peak power of over 1 W and a bandwidth of 1 THz[5]. Other researchers have focused on developing PCAs with tunable emission frequency for spectroscopy and communication applications. For instance, researchers at the University of Wuppertal in Germany have demonstrated a tunable PCA that can generate radiation with a terahertz frequency of order of 0.1 to 3 Terahertz[6]. Furthermore, researchers have also explored the use of novel materials for PCAs to further enhance their performance. For example, researchers at the University of Utah have developed PCAs using two-dimensional materials, such as graphene and transition metal dichalcogenides, demonstrating improved performance in terms of THz power and spectral bandwidth[7].

In summary, PCAs are a powerful and versatile technology for generating THz radiation with broad applications in spectroscopy, imaging, and communication. Ongoing research in this field is focused on strengthening the efficiency, tunability, and performance of PCAs for various uses.

2.3.Quantum-cascade

(QCLs) are semiconductor lasers that can emit terahertz (THz) radiation when electrically pumped. QCLs were first proposed and demonstrated in the mid-1990s and have since become an important tool for THz spectroscopy, imaging, and communication.

QCLs are based on the principle of intersubband transitions in quantum wells, where electrons can be excited from one subband to another within the same quantum well. This process can be used to generate THz radiation when the transition energy corresponds to a THz frequency. The design of the QCL structure allows for precise control over the subband energies and thus the emission frequency of the laser.Several research groups have investigated and optimized QCLs for THz generation. For example, researchers at the University of Leeds in the UK demonstrated a QCL having a peak power of 1.6 mW at 2.9 Terahertz, which was used for imaging of concealed objects[8].Other researchers have focused on developing QCLs with broad tunability and high output power for spectroscopy applications. For instance, researchers at the University of Neuchatel in Switzerland developed a QCL with a tuning range of 2.2 to 2.9 THz and an output of up to 3 mW, which was used for gas spectroscopy[9].

Furthermore, researchers have also explored the use of novel materials for QCLs to further enhance their performance. For example, researchers at the University of Paris-Saclay in France have developed QCLs based on GaN/AlGaN heterostructures, demonstrating high-power and wide-tunability THz emission[10].

In summary, QCLs are a powerful and versatile technology for generating THz radiation with broad applications in spectroscopy, imaging, and communication.

2.4.Free-electron lasers

(FELs) are a type of laser that operates on the principle of stimulated emission of radiation by free electrons, which can be generated using a linear accelerator or a storage ring. FELs have been used widely in the terahertz range, due to their ability to generate intense, coherent radiation in this frequency range (fig 2).

FELs are powerful sources of coherent electromagnetic radiation that have been researched and developed extensively in recent years. They are especially useful for generating radiation of (THz) frequency range, which has significant applications in areas like material science, biology, and imaging. One of the primary benefits of FELs is their ability to produce narrowband, high-intensity radiation across a broad range of frequencies. This is accomplished by utilizing the interaction between a relativistic electron beam and a periodic magnetic field called an undulator. The electrons produce radiation as they travel through the undulator. This process creates a highly-intense, coherent beam of radiation that can be tuned across a wide range of frequencies.Recent advancements in FEL technology have enabled the development of compact, tabletop THz FELs, which have the potential to revolutionize fields such as imaging and spectroscopy.A recent study showed the use of a tabletop THz FEL for the non-destructive imaging of biological tissue, showing the potential of these sources for medical imaging applications[11].In addition to imaging, THz FELs have also been used for material science applications such as the study of high temperature superconductivity. For example, a recent study used a THz FEL to probe the collective excitations of a high-temperature superconductor, providing insight into the behavior of these materials at the atomic scale.

2.4.1.Operation of THz FELs

The operation of THz FELs can be divided into several stages: electron beam generation and acceleration, changing the properties of an electron beam, and then allowing it to interact with a resonant cavity in order to produce a type of radiation that is highly organized and consistent, known as coherent radiation.

The first stage involves the generation and acceleration of an electron beam, which is typically done using a linear accelerator (linac) or a storage ring. The electron beam is then passed through a series of undulators, which are arrays of alternating magnetic poles that induce a transverse oscillation of the electrons. As a result of this process, the electrons release energy in the form of synchrotron radiation, which spans a wide range of wavelengths including those from the infrared-x-ray part of the electromagnetic spectrum.

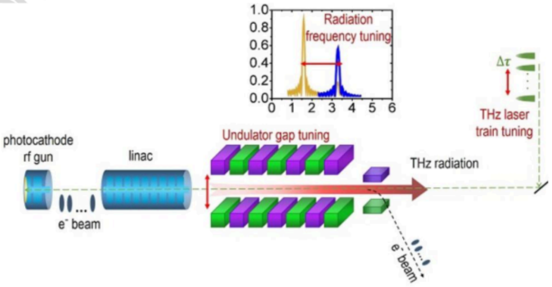
The second stage involves the modulation of the electron beam using a modulator, which can be a radio-frequency cavity or a magnetic field. This modulation process can introduce a periodic variation in the electron density, which can interact resonantly with the radiation emitted by the electrons in the undulator.

The third stage involves the interaction between the modulated electron beam and a resonant cavity, which can be a waveguide or a free-space cavity. This process can cause the radiation produced by the electrons in the undulator to become stronger, leading to the creation of synchronized radiation in the terahertz frequency range.

2.4.2.Applications of THz in FELs

THz FELs have a wide range of applications, including imaging, spectroscopy, and materials characterization.

Overall, FELs are a promising source of coherent radiation in the terahertz frequency band, with applications ranging from medical imaging to material science. Ongoing research in this field is expected to further improve the performance of these sources and expand their range of applications.



(fig.2)

2.5. Terahertz time-domain spectroscopy

THz-TDS is a potent method for analyzing materials at terahertz frequencies, offering valuable insights into their composition, structure, and dynamics. This technique is non-destructive and does not require labeling of samples, making it a highly useful analytical tool. In this response, I will explain THz-TDS and provide citations to support the information.

THz-TDS is similar to Fourier-transform infrared (FTIR) spectroscopy in its underlying principles, but it operates at significantly higher frequencies. The technique involves generating a brief electromagnetic radiation pulse that passes through the material being studied. As the pulse interacts with the sample, a detector measures the resulting reflected or transmitted signal. By analyzing the time-domain signal, it is possible to obtain imortant information about the properties of the prototype. A key benifit of THz-TDS is its ability to analyze materials that are challenging to study using other methods.For example, THz-TDS has been used to study biological samples, such as proteins, DNA, and cells, because it can penetrate through water and other biological fluids without damaging the sample. THz-TDS has also been used to investagate thin films, semiconductors, and polymers, among other materials.THz-TDS has a number of important applications in areas such as materials science, biology, and medicine. In materials science, THz-TDS can be used to study the electronic properties of materials, such as their conductivity and permittivity. In biology, THz-TDS can be used to study the structure and dynamics of biomolecules, as well as to detect diseases such as cancer. In medicine, THz-TDS has potential applications in imaging and diagnosis, as well as in monitoring the progress of treatments.

Numerous research papers have been published on the use of THz-TDS in various applications. For example, a study by N. B. Terry et al. used THz-TDS to annalyse the dielectric properties of various polymers[11]. Another study by L. C. Chen et al.(2010) used THz-TDS to study the interaction of water molecules with biological molecules[12]. In the field of medicine, a study by M. Nagel et al. used THz-TDS to detect skin cancer[13].

In conclusion, THz-TDS is a powerful analytical technique that allows for the study of materials at terahertz frequencies. THz-TDS has numerous applications in areas such as materials science, biology, and medicine, and has been the subject of numerous research papers. The technique has the potential to make significant contributions to our understanding of the properties and behavior of materials, as well as to the diagnosis and treatment of diseases.

2.6 THz generation using Laser Plasma Interaction

One way to generate terahertz radiation is through laser-plasma interactions. This involves using a high-intensity laser pulse to obtain plasma, which is a state of matter where the electrons have been stripped from the atoms and molecules.whwn Plasma gets in interaction with laser, it creates a plasma wave, which is a coherent oscillation of the plasma density. Rajput et al. (2019) demonstrated the production of terahertz radiation in magnetized plasma using laser pulses that varied in frequency over time, a technique known as frequency-chirping[35].

There are several mechanisms by which the plasma wave can generate terahertz radiation. One of these mechanisms is known as optical rectification. In this process, the plasma wave travels through a non-linear crystal material, which is a material that can generate new frequencies of light when exposed to intense electromagnetic radiation. As the plasma wave travels through the crystal, it interacts with the crystal lattice and creates a second-order nonlinear polarization, which generates terahertz radiation through a process known as second-harmonic generation.

Another mechanism for generating terahertz radiation through laser-plasma interactions is through laser wakefield acceleration. In this process, a high-intensity laser pulse is focused onto a gas target, such as helium or nitrogen. The pulse of laser pump ionizes the gas and creates a plasma wave, which then accelerates electrons to high energies. As the electrons travel through the plasma wave, they emit radiation at a frequency that corresponds to their acceleration, which can include terahertz radiation.

The generation of terahertz radiation through laser-plasma interactions has many potential applications. One important application is in non-invasive medical imaging, where terahertz radiation can be used to detect abnormalities in tissue without damaging the tissue. Terahertz radiation can also be used in security screening, where it can penetrate many materials, such as clothing and packaging, to detect hidden objects. Additionally, terahertz radiation has potential applications in wireless communication, where it can provide high-bandwidth data transfer without the interference and safety concerns associated with higher frequency radiation.

Overall, the obtaining of terahertz radiation through laser-plasma interactions is an important area of research with many potential applications. As our understanding of these processes continues to improve, we may discover even more uses for terahertz radiation in a variety of fields.

3. Uses of Terahertz in various domains

Terahertz techonoplgy has influnced our modern life in vbarious senses and in various domains of our life, find some of the major applications in modern science under this heading:

3.1. Application in Spectroscopy

THz spectroscopy is a valuable technique that allows researchers to investigate the characteristics of substances and molecules within the terahertz frequency range, which typically spans from 0.1 to 10 THz (equivalent to 3 to 300 cm^-1).This frequency range is interesting because it occupies a position within the EM spectrum that is situated between the microwave and infrared regions., and it can probe a variety of fundamental excitations, including rotational, vibrational, and electronic transitions. In this response, I will explain the basics of THz spectroscopy and provide some relevant citations for further reading.

THz radiation is typically generated by either optical rectification or photoconductive switching of a femtosecond laser pulse in a nonlinear crystal or semiconductor device. The resulting THz pulse can be focused onto a sample and the transmitted or reflected signal can be measured as a function of frequency using a THz spectrometer. THz spectroscopy is a versatile tool that can be applied to investigate various types of substances, such as solids, liquids, and gases. This technique finds application in a wide range of fields, including materials science and biology.One of the key advantages of THz spectroscopy is its ability to probe molecular vibrations, which are typically in the range of 0.1 to 10 THz For example, THz spectroscopy has been used to study the vibrational modes of proteins and DNA because these molecules have characteristic vibrations in the THz frequency range. These vibrations are due to the movement of atoms within the molecule, and are sensitive to changes in the molecular structure or environment, which can provide insight into their structure and function[14,15]. THz spectroscopy has also been used to study the dynamics of hydrogen bonds in water and other liquids, which is important for understanding the properties of these materials[16,17].THz spectroscopy can also be used to study the electronic properties [illegible] materials, particularly those that have narrow band gaps or low carrier densities. For example, THz spectroscopy has been used to study the electronic properties of semiconductor nanowires and graphene, which have potential applications in electronic and optoelectronic devices

Finally, THz spectroscopy is useful for analysing the properties of materials under extreme conditions, such as high pressure or low temperature. For example, THz spectroscopy has been used to understand the phase transitions of materials under high pressure, which can provide insight into their crystal structures and properties

In conclusion, THz spectroscopy is [illegible] strong tool for studying the properties of materials and molecules in the terahertz frequency range. It has applications in a wide range of fields, and it can provide insight into the vibrational, electronic, and structural properties of materials.

3.2.Application in medical dignostics

Terahertz (THz) imaging has the potential to revolutionize medical diagnostics due to its ability to differentiate between different types of tissues and identify diseases at an early stage. THz imaging has been shown to be effective in detecting and distinguishing cancerous tissue from normal tissue in breast cancer patients, with high sensitivity and specificity. THz imaging can also be used to identify early-stage skin cancer and distinguish it from healthy skin tissue[18]. Moreover, THz imaging has the potential to detect dental caries in t 13 early stages of development, before they become visible to the naked eye or even X-ray imaging[19]. THz imaging has also been investigated as a potential tool for non-invasive glucose monitoring for diabetes patients[20]. In summary, due to its distinct characteristics such as high sensitivity to water content and ability to penetrate certain materials, THz radiation is a promising technology for early detection and diagnosis of several diseases.Rajput et al.(2020) explain that terahertz radiation has important applications in the area of biomedical imaging[34].

6 3. Appliaction of THz in the field of security

One of the most important applications of THz radiation in security is in the development of THz imaging systems, which can be used to scan individuals and objects for hidden weapons or explosives. THz imaging works by emitting a beam of radiation, which is then reflected back by the object being scanned. The reflected radiation is then analyzed to produce an image of the object, revealing any concealed items. Several research studies have demonstrated the effectiveness of THz radiation in security applications. For example, a study by Nishizawa et al. (2019) showed that THz imaging was able to detect hidden knives and guns on human subjects with a high level of accuracy[21]. Similarly, a study by Ferguson et al. (2002) demonstrated the use of THz spectroscopy to detect trace amounts of explosives on surfaces[22].

In conclusion, THz radiation has great potential in security applications due to its ability to penetrate through various materials and its unique spectral properties. THz imaging and spectroscopy systems have been shown to be effective in detecting hidden weapons and explosives, and further research in this area is expected to lead to the development of even more advanced security screening technologies.

3.4 Uses of THz in Material chracterization

Terahertz (THz) technology has emerged as a promising tool for material characterization due to its unique properties. THz waves can penetrate many materials that 15 opaque to visible light, making it an ideal tool for non-destructive testing and imaging. Moreover, THz radiation is sensitive to changes in the dielectric properties of materials, such as refractive index, absorption coefficient, and conductivity, which can provide valuable information about the sample's chemical and physical properties.

3.4.1. THz material characterization in pharmaceuticals.

One of the main applications of THz in material characterization is in the field of pharmaceuticals. THz spectroscopy has been used to analyze the chemical composition and structure of drugs and their excipients. For example, THz radiation can detect the presence of water molecules in pharmaceutical samples, which can affect the stability and efficacy of the drug. THz imaging has also been used to study the distribution and homogeneity of active pharmaceutical ingredients in tablets and capsules, which can impact drug release and bioavailability[23].

3.4.2.THz material characterization in polymers

Another application of THz in material characterization is in the field of polymers. THz spectroscopy can provide information on the molecular structure and dynamics of polymers, as well as their thermal and mechanical properties. THz imaging can also be used to study the morphology and defects in polymer films and coatings. For example, THz spectroscopy has been used to annalyse the glass transition temperature of polymers, which can affect their processing and performance[24].

3.4.2.THz material chracterization in food science

THz technology has also been used in the field of food science. THz spectroscopy can detect and quantify the moisture content and quality of food products, such as fruits, vegetables, and grains. THz imaging can also be used to study the internal structure and defects in food products, which can affect their texture and shelf life[25].

In conclusion, THz technology has emerged as a promising tool for material characterization, with applications in the fields of pharmaceuticals, polymers, and food science. THz spectroscopy and imaging can provide valuable information about the chemical and physical properties of materials, making it an ideal tool for non-destructive testing and quality control.

4. Challenges in achiving/detecting Terahertz

Achieving terahertz (THz) frequencies presents several challenges, including:

4.1. Sources:

Traditional electronics, such as transistors and diodes, are not efficient at generating THz radiation. This is because the frequency of THz radiation is much higher than the frequency of the signals that these devices are designed to handle. Researchers are exploring new materials and technologies, such as quantum-cascade lasers, that can produce THz radiation. Quantum-cascade lasers are semiconductor devices that use a series of quantum wells to generate THz radiation through a process known as intersubband transitions[26]. Other materials that are being explored for THz generation include graphene[27] and carbon nanotubes[28].

4.2.Detection:

THz radiation is difficult to detect using traditional methods. Many materials are opaque to THz radiation, making it difficult to measure. Researchers are developing new detection methods, such as using ultrafast lasers or specialized sensors, to detect THz radiation. For example, (THz-TDS) is a method that uses ultrafast lasers to generate and detect THz radiation[29]. Other detection methods include using microbolometers[30] and quantum-well infrared photodetectors (QWIPs)[31].

4.3.Transmission:

THz radiation is easily absorbed by many materials, including air and water. This makes it difficult to transmit THz radiation over long distances. Researchers are exploring new materials and waveguides that can be used to transmit THz radiation more efficiently. One approach is to use metamaterials, which are artificial materials designed to have specific properties not found in nature[32]. Metamaterials can be used to create waveguides that can transmit THz radiation over long distances with low loss.

4.4.Interference:

THz radiation is sensitive to interference from other sources of radiation, such as radio waves and microwaves. This can make it difficult to isolate and measure THz radiation accurately. Researchers are developing new shielding and filtering methods to reduce interference. For example, bandpass filters can be used to selectively pass THz radiation while blocking other frequencies[33]. Shielding can also be used to reduce interference from external sources.

4.5.Cost:

THz technology is still relatively new and expensive. Specialized equipment is required to generate, detect, and transmit THz radiation. As the technology becomes more widespread, the cost is expected to decrease. However, the high cost of THz technology can limit its availability and use in certain applications.

CONCLUSION

In conclusion, terahertz technology has witnessed significant advances in recent years, and its future prospects look promising. The development of terahertz sources, detectors, and imaging systems has opened up new opportunities in various fields such as security, biomedical imaging, and communication. With ongoing research and development, terahertz technology is expected to continue to revolutionize these areas and provide new insights into materials and biological systems. However, there are still challenges to overcome, such as the limited range of terahertz waves and the need for more efficient and reliable sources and detectors. Although there are still challenges to overcome, terahertz technology offers significant potential benefits and is expected to have a growing impact on our daily lives in the near future.

ACKNOWLEDGEMENT

I would like to express my sincere gratitude for the opportunity to conduct this research independently. I am grateful for the chance to work on this project without assistance, as it has allowed me to develop and refine my skills and knowledge in this area. I would also like to thank the resources and materials that I consulted throughout this process, which helped me to gain a deeper understanding of the subject matter.

CONFLICT OF INTERESTS

The authors declare that there is no conflict of interests.

CONTRIBUTION OF AUTHORS

All the authors contributed significantly to this manuscript, participated in reviewing/editing and approved the final draft for publication. The research profile of the authors can be verified from their ORCID ids, given below:

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