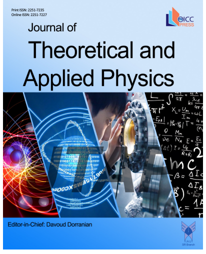

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Terahertz generation: a bibliometric study

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Abstract:

This study provides a comprehensive bibliometric analysis of global research trends in terahertz (THz) generation. Terahertz radiation, which has a frequency between microwaves and infrared regions of the electromagnetic spectrum, has drawn substantial scientific attention because of its unique properties and potential uses in telecommunications, security screening, medical imaging, and material characterization. In order to thoroughly examine the scholarly landscape, we utilized bibliometric analysis tools: VOSviewer and the Bibliometrix R-Package. The study analyzed over 3,600 publications from 2003 to 2023, providing insights into the annual publication trends, most prolific and cited journals, authors, countries, affiliations, keywords plus, and key articles. Findings reveal an average annual growth rate of 4.42 percent in THz generation-related publications. China, Japan, and the USA emerged as leading countries in publication counts, while key journals included "Applied Physics Letters" and "Optics Express". Osaka University (Japan), Tohoku University (Japan), and Tianjin University (China) are the leading affiliations. Xi-Cheng Zhang, affiliated with "The Institute of Optics, University of Rochester, USA," is the most productive and cited author. Keyword plus co-occurrence analysis yielded three primary research clusters and identified emerging trends, providing direction for future research. By offering a detailed map of global THz generation research, this paper serves as a valuable guide for new researchers, helping them identify key resources, potential collaborators, and emerging research trajectories.

Keywords: Terahertz; THz generation; Bibliometric analysis

1. Introduction

Terahertz (THz) radiation, occupying the frequency range (0.1 to 10 THz) between microwave and infrared regions of the electromagnetic spectrum, has emerged as a field of significant scientific and technological interest [1]. This unique spectrum portion is often called the "THz gap" because it has been largely unexplored compared to its neighbouring spectra. This is primarily due to the lack of efficient and tunable sources as well as detectors operating in this frequency range [2]. It is characterized by its non-ionizing radiation which makes it safe for human interaction, and its capability to penetrate a wide range of non-conducting materials [3]. The applications of THz technology are manifold and extend across various domains, such as telecommunications [4] and in the security and defence sectors [5]. In the medical field, THz imaging and spectroscopy can be used for non-invasive cancer detection and monitoring hydration levels [6]. Materials characterization at the THz frequency can provide unique insights into the properties of semiconductors, superconductors, and biological tissues [7]. The generation of THz radiation has been a major focus of research to harness these potential applications. Techniques for THz generation include but are not limited to: optical rectification, plasma and gas ionization, photoconductive devices and photodiodes, and metamaterials and other techniques [2]. Each method offers different advantages in terms of output power, tunability, and spectral coverage, and the choice of method depends on the specific application.

Terahertz waves can be generated from lasers by utilizing nonlinear optical (NLO) processes in specialized nonlinear crystals. These nonlinear crystals must have excellent growth characteristics, optical properties, and mechanical strength for efficient and high-powered terahertz generation. Key factors include high laser damage threshold, transparency to the interacting wavelengths, and phase-matching capabilities. Some of the options for these nonlinear materials are inorganic crystals like traditional infrared crystals (e.g., GaSe, $ZnGeP_2$), ferroelectric crystals (e.g., $LiNbO_3$, $LiTaO_3$), and zinc-blende crystals (e.g., GaAs, GaP, ZnTe). Other options include $KTiOPO_4$-type crystals and organic crystals such as salts (e.g., 4-N-methylstilbazolium tosylate (DAST), 4-N,N-dimethylamino-4′-N′4′-N′-methyl-stilbazolium 2,4,6-trimethylbenzenesulfonate (DSTMS)), and hydrogen-bonded crystals (e.g., 2-[3-(4-hydroxystyryl)-5,5-dimethylcyclohex-2-enylidene] malononitrile (OH1), BNA). Terahertz waves can be efficiently generated by utilizing the optimal nonlinear crystals with the desired properties.

In nonlinear optical (NLO) methods, optical rectification (OR) is a widely used technique for terahertz (THz) generation, where a high-power laser beam is used to generate a terahertz pulse by exciting a nonlinear crystal. This technique has been demonstrated in various studies, including those by Tanabe et al. [8] who achieved tunable THz-wave generation from 3 to 7 THz in GaP crystals under small-angle, noncollinear phase-matching conditions. Hebling et al. , Fülöp et al. [9–11] also achieved tunable THz pulse generation, high-power THz pulses, and THz pulses with 0.4 mJ energy by OR of ultra-short laser pulses with tilted pulse fronts using $LiNbO_3$ crystals, respectively. Moreover, Hirori et al.; Huang et al. [12], [13] employed optical rectification (OR) within $LiNbO_3$ to produce single-cycle terahertz pulses, achieving amplitudes surpassing 1 MV/cm, and generated high-energy terahertz pulses using OR within cryogenically cooled $LiNbO_3$. In another work, Taniuchi et al.; Schneider et al.; Hauri et al. [14–16] produced widely tunable THz waves, THz pulses, and high-power single-cycle terahertz pulses with electric fields beyond 1 MV/cm in organic DAST crystal and discussed their spectroscopic application and theory, respectively. Additionally, Fülöp et al. [17] designed high-energy THz radiation and generated sub-mJ THz radiation pulses based on optical rectification. Further, Vicario et al. [18] achieved progress in enhancing the efficiency of terahertz (THz) generation through the illustration of elevated THz radiation generation efficiency in DAST, DSTMS, and OH1 organic and crystals, driven by a Cr: forsterite laser.

Another technique for terahertz generation is plasma and gas ionization. This method involves the creation of plasma through the interaction of a high-power laser with a gas target. The intense laser pulse ionizes the gas, forming a plasma with free electrons and ions. As these electrons are rapidly accelerated and decelerated in the electric field of the laser, they emit radiation in the terahertz frequency range. This plasma acts as a source of coherent terahertz waves, which can be harnessed for a variety of applications. This technique of terahertz pulse generation has been explored by several research teams over the past two decades. As early as 2003, Leemans et al. [19] observed terahertz pulses generation when bunches of laser-accelerated electrons crossed a plasma-vacuum boundary. In other pioneering research, Kress et al. [20] employed the same approach to generate THz pulses in air, utilizing laser pulses comprising both fundamental and second-harmonic waves. Additionally, Knap et al. [21] reported terahertz emission resulting from plasma waves in high electron mobility transistors with a 60 nm gate length. Furthermore, Kim et al. [22], [23] observed THz radiation emission originating from ultrafast ionization of air in symmetry-broken laser fields and also accomplished the coherent control of THz supercontinuum generation through interactions between ultrafast lasers and gases respectively. Moreover, D'Amico et al. [24] reported the observation of conical forward terahertz emission from femtosecond-laser-beam filamentation within the air medium. Similarly, Xie et al. [25] showcased the coherent control of THz wave generation in ambient air, providing a new approach to manipulate the THz waves. Polynkin et al. [26] showed how ultraintense Airy beams can lead to curved plasma channel generation, offering a novel mechanism that can be used for THz wave generation. Clerici et al. [27] showcased a successful mechanism for scaling the wavelength to achieve single-cycle THz field generation by gas ionization, providing insights into the potential of scaling the THz emission to longer wavelengths. More recently, through an examination of THz radiation characteristics, Andreeva et al. [28] resolved the long-standing problem surrounding the mechanism of THz generation within a two-color air filament. Their study showcased that both neutrals and plasma play pivotal roles in influencing the THz yield.

Photoconductive devices and photodiodes can also be utilized to generate terahertz waves through a process known as the photoconductive effect. In this process, a high-power laser pulse is incident upon a semiconductor material, which results in the excitation of carriers within the material. These excited carriers (electrons and holes) are then accelerated by an applied bias field. The ultrafast change in conductivity of the material due to the laser pulse, coupled with the acceleration of the carriers, results in the emission of a terahertz pulse. The photoconductive switch, the critical key component of these devices, acts as an efficient and tunable source of terahertz radiation. Building upon this fundamental understanding, several researchers have made significant strides in the practical application of these principles to generate terahertz radiation. For instance, Dreyhaupt et al. [29] exhibited the production of high-intensity terahertz radiation through a microstructured large-area photoconductor paving the way for efficient terahertz radiation sources. This development of photoconductive devices represents a significant stride in terahertz generation, a stride matched by Gregory et al. [30] who carried out optimization on photomixers and antennas to achieve continuous-wave terahertz emission. In the field of photodiodes, Ishibashi et al. [31] made significant advancements by developing and improving unitraveling-carrier photodiodes for THz radiation applications, offering promising prospects for THz radiation technology. A novel approach was taken by Yardimci et al. [32], who successfully produced high-power THz radiation generation through the utilization of large-area plasmonic photoconductive emitters.

Efforts to develop innovative techniques and metamaterials for terahertz generation have been progressive. For instance, the development of metamaterials specifically for terahertz applications has been a key focus. Chen et al. and Iorsh et al. [33], [34] have made significant strides in this area, with the development of active terahertz metamaterial devices and hyperbolic metamaterials based on multilayer graphene structures, respectively. In another work, the use of femtosecond laser pulses to observe coherent THz radiation emission from ferromagnetic films was done by Beaurepaire et al. [35]. Graphene has also been explored as a medium for terahertz generation. Hafez et al. [36] achieved highly efficient THz high-harmonic generation in graphene through the involvement of hot Dirac fermions. Similarly, Vijayraghavan et al. [37], achieved broadly tunable terahertz generation using mid-infrared quantum cascade lasers. These diverse efforts underscore the extensive range of approaches being investigated within this field.

To assist researchers in comprehending and mastering the evolution of the terahertz generation field and identifying its most important applications, many review papers [2], [38–41] were prepared by carefully summarizing the available literature. Generally, review articles often summarize published work, emphasizing the researcher's familiar field, resulting in a need for more accuracy and objectivity. To address these issues, it is crucial to employ information extraction techniques for more accurate, unbiased, and comprehensive research summaries [42].

Bibliometrics is a branch of scientometrics that deals especially with the quantitative evaluation of publications [43], usually with an emphasis on academic and scientific literature [44]. It involves the use of statistical and mathematical methods to examine patterns and trends within published works, such as journal articles, conference papers, books, and patents [45]. Bibliometric analysis has become an established and rigorous approach for systematically investigating and making sense of vast amounts of academic literature. This method allows us to closely examine the intricate developmental patterns and trends within a particular area of research. In addition, it reveals the nascent topics and directions emerging in that field [46]. Bibliometrics scrutinizes science as a system of generating knowledge [47] and offers a viewpoint that can effortlessly be scaled from a micro to a macro level [48]. This approach offers a unique perspective to comprehensively understand the trajectory, current status, and potential future directions of Terahertz generation research.

Numerous other authors have recently explored bibliometric studies related to this field and its associated fields. For instance, Chen et al. [46] conducted a bibliometric analysis of laser processing research using the Web of Science (WoS), examining 3,958 articles and reviews from 1990 to 2019. This research aimed to shed light on the global status of laser processing research by highlighting global contributions, leading nations or regions, significant research fields, journals, top institutions and authors, highly cited publications, and prominent author keywords. Over the recent past studies on bibliometric analysis in the domain of terahertz [42] reported in areas such as the terahertz metamaterial [49], and laser-plasma interaction [50]. Li et al. [42] analyzed 11,585 articles on global terahertz research using WoS. This comprehensive scientometric study provided insights into annual outputs, active journals, leading authors, contributing countries. Additionally, they analyzed the literature across several research directions using co-word and co-cited reference networks, with the aim of aiding researchers in understanding the development and key applications in the terahertz field. In another investigation, Chouhan [49] reviewed 1,186 articles and scientific literature on terahertz metamaterials. The analysis identified Optics Express and Nature Nanotechnology as the most prolific journals in this area, with China, Greece, and the United States being the most active countries. This study offered valuable insights to guide future terahertz metamaterials research. Furthermore, Abedi-Varaki [50] conducted a bibliometric analysis on laser-plasma interaction, reviewing 2,650 documents from 1990 to 2022. The study revealed the USA as the leading country in publishing volume, research institutes, and related journals, followed by China, France, and the UK, providing a clear picture of current and future research directions.

With a growing interest in research related to THz generation, we intend to conduct this bibliometric analysis to investigate the subsequent research questions (RQ's):

RQ1: What are the publication trends (number of publications per year) and mean total citations (TC) per year in THz generation research over the past two decades?

RQ2: Which journals, countries, institutions and authors are the most productive and influential in THz generation research based on publication and citation metrics?

RQ3: What are the most cited papers and references and frequently occurring KeyWords Plus in the field of THz generation research?

RQ4: What research gaps exist in optimizing terahertz generation efficiency?

This study aims to execute a comprehensive bibliometric evaluation of terahertz generation research on a global scale, encompassing past, current, and future trends. The analysis of annual publications' trends and the identification of significant contributors—including the most active and often referenced journals, nations, affiliations, and authors—are the main objectives. We also want to draw attention to the KeyWord Plus terms that are used the most, the articles and references that are the most pertinent, and the geographic distribution of this research.

In aligning these questions with our objectives, we aim to offer an extensive picture of the bibliometric landscape of the field, outlining thematic focus and contribution trends. The subsequent segments of the paper are structured into four main sections. Section 2 elaborates on the methodology and the bibliographic study conducted. The comprehensive results and discussion are presented in Section 3, while the final conclusions drawn from the study are outlined in Section 4.

2. Methodology and bibliographic study

2.1 Data acquisition

We gathered the data for this study by exploring the core collection of the esteemed Web of Science (WoS) platform, where we collected information through to August 1, 2023. WoS is widely recognized among the scientific community, offering access to diverse databases encompassing high-impact journals across various disciplines, including

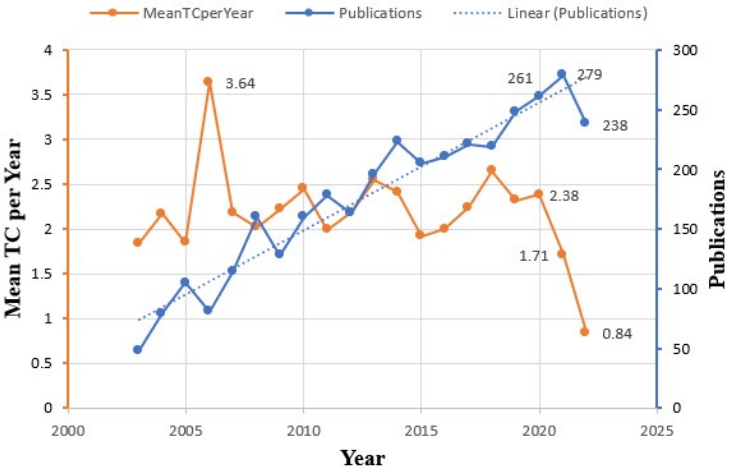

Figure 1. The publications and mean TC per year trend in THz generation (2003-2022).

engineering, social sciences, arts, humanities, natural science, and biomedicine [51] Our search query utilized a combination of relevant terms to obtain a large data set, such as (TS = "terahertz* generation*" OR "thz* generation*" OR "thz* radiation* generation*" OR "terahertz* radiation* generation*" OR "terahertz* pulse* generation*" OR "thz* pulse* generation*" OR "terahertz* wave* generation*" OR "thz* wave* generation*" OR "generation* of terahertz*" OR "generation* of thz*" OR "terahertz* emission*" OR "thz* emission*" OR "emission* of terahertz*" OR "emission* of thz*" OR "thz* production*" OR "terahertz* production*"). TS, which stands for "topic search," encompasses the process of identifying all relevant documents based on information extracted from article titles, abstracts, author keywords, and Keywords Plus. "*" operator was utilized to determine all possible keyword derivatives. Further, we applied filters such as document types ("Articles") and languages ("English") to refine our dataset. Through this approach, a comprehensive set of 3,632 documents was retrieved.

2.2 Data processing and bibliometric analysis tools

The resulting dataset, exported as plain text files, underwent further processing using the R Studio software (version 2023.03.1+446). Duplicate documents were removed, resulting in a final corpus of 3,630 unique documents. To gain deeper insights and visualize the scholarly landscape, we utilized two robust bibliometric tools: VOSviewer (version 1.6.19) developed by van Eck and Waltman [52] and the Bibliometrix R-Package (version 4.1.3) by Aria and Cuccurullo [53]. VOSviewer is an open-source software coded in Java, explicitly designed for the creation of maps and visual representations derived from network data. It allows for exploring and visualizing bibliometric networks involving journals, affiliations, countries, authors, and documents. Various types of analyses, such as co-authorship, co-occurrence, co-citation, and bibliographic coupling, can be performed using VOSviewer [54]. In addition to VOSviewer, we utilized the Bibliometrix R-Package, a package specifically designed for quantitative research in scientometrics and bibliometrics using the R statistical programming language [55]. The Bibliometrix package offers a range of functions designed to import bibliographic data from diverse sources, including Clarivate Analytics' (WoS) Web of Science, SCOPUS, and PubMed databases. It also enables bibliometric analysis and the creation of data matrices for various analyses, including co-citation, coupling, scientific collaboration, and co-word analysis.

3. Results and discussion

3.1 Key findings

The bibliometric analysis of "Terahertz Generation Research" includes 3,630 documents from 341 sources from 2003 to 2023. The study shows an average document age of 8.22 years and an average annual growth rate of 4.42 percent. The dataset's documents have each acquired an average of 20.46 citations, highlighting the significance of the research. The research offers insights into the interconnection and categorization of the literature with 45,859 references and 2,763 Keywords Plus. With 82 single-authored publications and an average of 5.93 co-authors per document, the research has 7,481 authors. Co-authorships with foreign authors make up 31.43 percent of all co-authorships. These results form the basis for further comprehensive analysis of prolific journals, productive countries and institutions, key authors, influential papers, research trends, and collaborations in the field of THz generation.

3.2 Publication trends and impact

Figure 1 shows that from 2003 to 2022, there has been an overall increasing trend in the number of publications per year, from just 48 in 2003 to 238 in 2022, with a peak in 2021 (279 publications), indicating the growing interest and research activity in the field. The mean total citations (TC) per year, which reflects the average impact of publications in terms of citations, fluctuated between 1.71 to 3.64 over the years, with an average of 2.08. 2006 received the highest mean TC per year (3.64) and mean TC per article (65.51), suggesting greater recognition and impact of the research conducted during those periods. In the earlier years, the

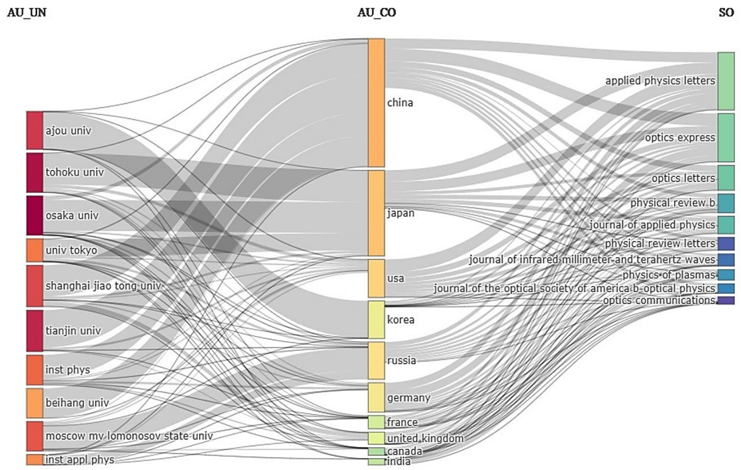

Figure 2. Plot of three fields from left to right displaying the affiliation of the author, their country, and their source (2003-2023).

mean total citations per year ranged from 1.84 to 3.64, indicating a relatively higher citation impact. However, there has been a decline in the mean total citations per year recently, with the lowest value recorded in 2022 (0.84). The decline in citation impact could be due to the novelty of the publications, which have not had enough time to accumulate citations.

3.3 Sankey diagram: a three-field plot on THz generation research

Based on the Sankey diagram first published by Stasko et al. [56], Figure 2 shows a visual depiction known as a “three-field plot”. This visualization method illustrates interrelationships among author universities (AU-UN), author countries (AU-CO), and sources (SO) in a three-field plot. Traditionally, Sankey diagrams portray the flow of energy or materials across diverse networks and processes. They effectively illustrate the movement, associations, and shifts with accompanying quantitative insights, as noted by Kumar et al. [57]. The width of the rectangular nodes signifies the frequency of occurrence of a specific institution, country, or source within the collaborative network. Correspondingly, the thickness of the lines connecting the nodes mirrors the count of connections, as highlighted by Koo [58]. The diagram reveals that China (AU-CO) had the substantial number of connections (1.78 k), trailed by Japan (1.19 k) and the United States of America (527). Within China, (AU-UN), Tianjin University emerged as the top contributing institution, while Osaka and Tohoku University were the leading institutions in Japan. In terms of journals (SO), the main contributors to “Applied Physics Letters” (799) were the United States of America (179) and China (159). Similarly, “Optics Express” (672) had significant contributions from China (173) and Canada (135).

3.4 Most relevant sources

Figure 3 displays the top 15 sources in terahertz generation research, along with their No. of Documents from 2003 to 2023. “Applied Physics Letters” and “Optics Express” are the most prolific publishers, with 328 and 296 articles, respectively. Notable contributions come from “Optics Letters” (162 articles), “Journal of Applied Physics” (129 articles), and “Physical Review B” (106 articles). Approximately 28.12% of the total articles (3,630) on terahertz

Table 1. Local impact of sources based on h-index, g-index, and Impact Factor 2022.

Rank	Source	h-index	g-index	IF 2022
1.	Applied Physics Letters	53	82	3.971
2.	Optics Express	45	72	3.833
3.	Physical Review Letters	39	62	9.185
4.	Optics Letters	37	58	3.560
5.	Physical Review B	32	52	3.908
6.	Journal of Applied Physics	25	42	2.877
7.	Journal of the Optical Society of America B-Optical Physics	21	42	2.058
8.	Scientific Reports	21	39	4.997
9.	IEEE Journal of Selected Topics in Quantum Electronics	21	35	4.653
10.	Physics of Plasmas	20	30	2.357

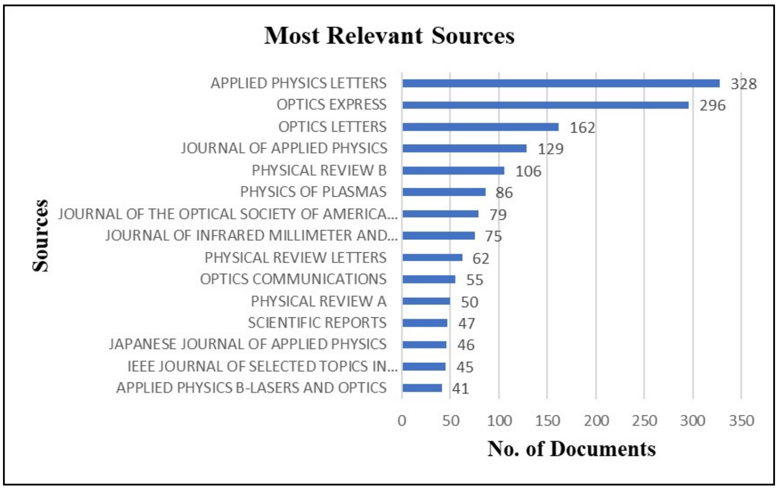

Figure 3. The top 15 most relevant Sources in terahertz generation (2003-2022).

generation research were published by the top five sources. Comparing the most relevant sources from the past five years (2018-2022) with the 2003-2023 period, Figure 4 depicts that "Optics Express" (107 articles) remains prominent, while "Optics Letters" (60 articles) and "Applied Physics Letters" (56 articles) exhibit fewer recent articles, suggesting shifting research focus. New influential sources include "Physical Review Applied" (26), "Advanced Optical Materials" (25), "ACS Photonics" (22), "Applied Physics Express" (19), and "Optik" (19) articles, respectively. These findings highlight dynamic research trends and increased activity in global terahertz generation research.

3.4.1 Most locally cited sources

Some noteworthy findings are drawn from the analysis of the most locally cited sources. Local citations show how often an article (or author) from this collection has been referenced by other writers who are also present in this collection of 3,630 papers. Figure 5 shows that with an impressive total of 13,227 local citations, "Applied Physics Letters" is the most locally cited source, highlighting its sig-

Table 2. List many countries based on Times Cited (TC) and Average Article Citations.

Country	Times Cited	Average Article Citations
USA	**16519**	41.7
JAPAN	**11160**	22.5
CHINA	**9099**	12.1
GERMANY	**7181**	26.2
RUSSIA	**4469**	11.3
FRANCE	**3959**	32.5
Uk	**3340**	23.9
INDIA	**2267**	11.2
CANADA	**2235**	24
NETHERLAND	**2172**	70.1
KOREA	**2076**	16.7
SWITZERLAND	**1935**	53.8
HUNGARY	**1191**	44.1
LITHUANIA	**865**	9.8
SINGAPORE	**729**	26
IRAN	**523**	5.6
AUSTRALIA	**516**	21.5
ITALY	**510**	18.2
GREECE	**430**	39.1
CZECH REPUBLIC	**325**	40.6
SPAIN	**324**	12.5
AUSTRIA	**316**	21.1
DENMARK	**304**	17.9
BRAZIL	**188**	23.5
ISRAEL	**182**	10.1

Table 3. List many countries based on Times Cited (TC) and Average Article Citations.

Country	Times Cited	Average Article Citations
NETHERLAND	2172	**70.1**
SWITZERLAND	1935	**53.8**
HUNGARY	1191	**44.1**
USA	16519	**41.7**
CZECH REPUBLIC	325	**40.6**
GREECE	430	**39.1**
FRANCE	3959	**32.5**
GERMANY	7181	**26.2**
SINGAPORE	729	**26**
CANADA	2235	**24**
Uk	3340	**23.9**
BRAZIL	188	**23.5**
JAPAN	11160	**22.5**
AUSTRALIA	516	**21.5**
AUSTRIA	316	**21.1**
ITALY	510	**18.2**
DENMARK	304	**17.9**
KOREA	2076	**16.7**
SPAIN	324	**12.5**
CHINA	9099	**12.1**
RUSSIA	4469	**11.3**
INDIA	2267	**11.2**
ISRAEL	182	**10.1**
LITHUANIA	865	**9.8**
IRAN	523	**5.6**

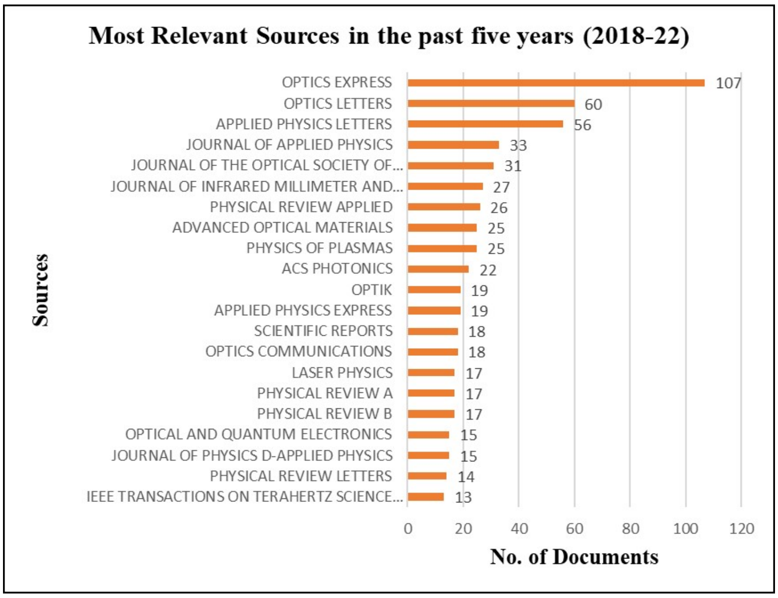

Figure 4. The top 15 most relevant Sources in terahertz generation in the past five years.

nificant impact and influence in the terahertz research field. With 9,159 citations, “Physical Review Letters”, and with 6,734 citations, “Optics Express” also occupies a prominent position. These sources are consistent in their appearance among the ’most locally cited sources’ and the previously analyzed ’most relevant sources’ (refer to 3.4) indicating their sustained importance and impact. The sources listed in the Figure 5 come from a variety of research fields, including physics, optics, photonics, applied physics, and quantum electronics. This indicates that terahertz generation research is interdisciplinary in nature, involving various scientific domains.

3.4.2 Sources local impact

Table 1 list the top 10 high-impact sources that have published research on terahertz generation from 2003-2023. Braun et al. [59] examined the utility of the h-index for assessing the impact of journals. The h-index evaluates a source’s yield and impact on citations [60], whereas the g-index is an indicator that gives more weight to highly cited articles, benefiting sources with many highly cited articles [61]. “Applied Physics Letters” has the highest h-index (53) and g-index (82), highlighting that it has published the most influential and impactful papers on terahertz generation research. The h-index of the top 10 sources ranges from 20 to 53, indicating that there are many highly cited papers on THz generation published in these journals. The g-index is also high, signifying the impact and productivity

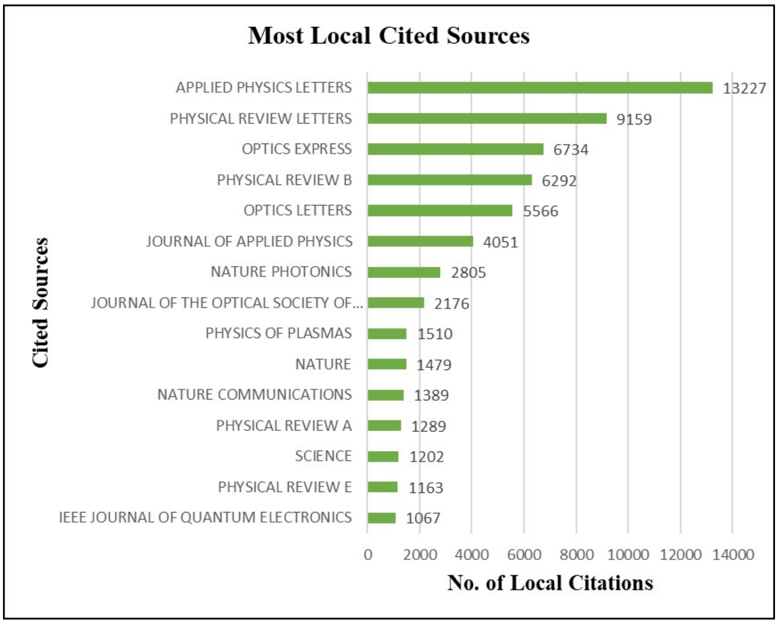

Figure 5. The top 15 most local cited sources in terahertz generation (2003-2023).

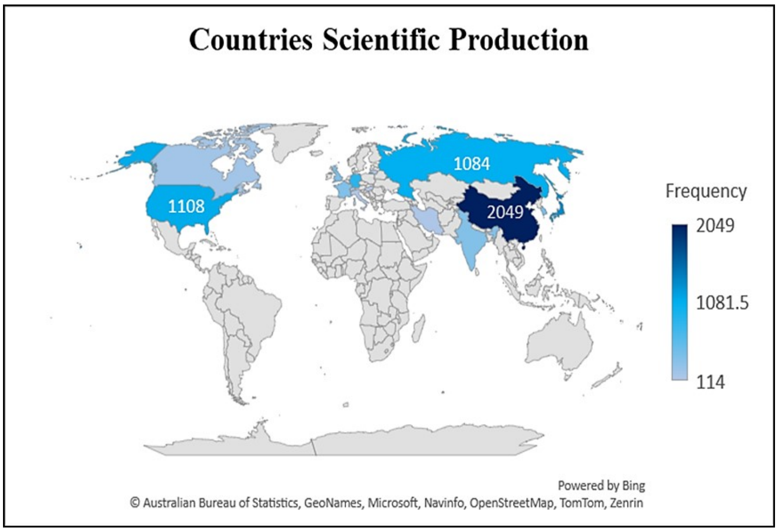

Figure 6. Global terahertz generation research across countries (2003-2023).

of research published in these sources. Additionally, there is a strong correlation between the rankings of the sources on the h-index and g-index, demonstrating that these metrics are consistent in evaluating the impact and influence of sources.

3.5 Countries engaged in this field

3.5.1 Countries' scientific output

According to Figure 6, terahertz generation research has been extensively explored in 63 nations. China leads the scientific production in terahertz generation research, with 2049 publications showcasing its significant contribution to the field. Other countries leading in terahertz generation research are Japan (1323), the USA (1108), Russia (1084), and Germany (855). Countries like South Korea (410), the UK (388), France (382), India (373), and Canada (207) also contribute significantly. The top 10 countries account for 82.54% of the total publications (3,630), suggesting that the research output is mainly concentrated in Asia, North America, and Europe. Developed nations like the USA, Japan, Russia, Germany, and the UK have a considerable impact, while smaller countries such as Switzerland (153), Lithuania (131), and Hungary (114) actively participate. The global diversity of countries involved in terahertz generation research signifies a collaborative and widespread interest. The findings underline the importance of international collaboration, research infrastructure, and funding support in advancing terahertz generation research.

3.5.2 Most cited countries

Tables 2 and 3 list a large number of most cited countries in the field of THz generation research based on the Times Cited (TC) and Average Article Citations, respectively. The USA (16,519), Japan (11,160), China (9,099), and several European countries such as Germany (7,181), France (3,959), and the United Kingdom (3,340) dominate the global Terahertz generation research in terms of total research output and citations. However, there are differences in their research productivity and quality. Countries like

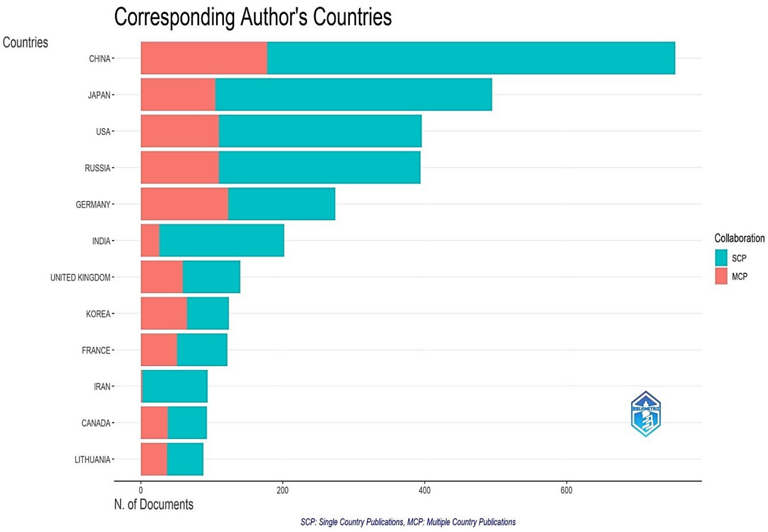

Figure 7. Countries of the corresponding authors based on the SCP and MCP.

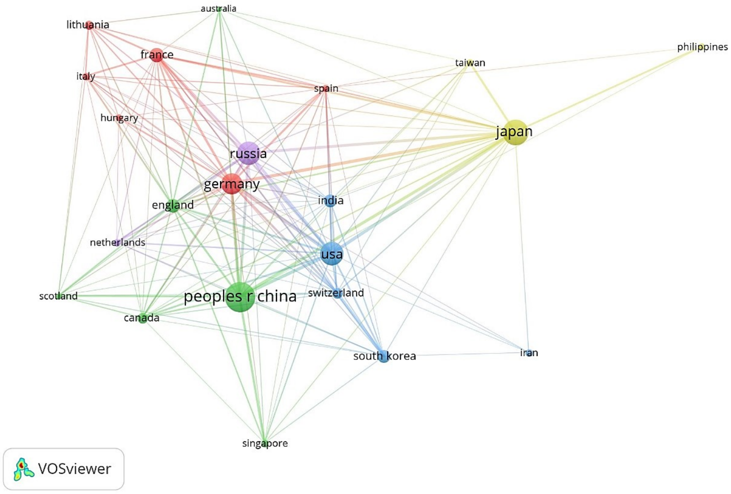

Figure 8. Network visualization of country co-authorship in the THz generation (2003-2023).

the Netherlands (70.1), Switzerland (53.8), and Hungary (44.1) produce very high-quality research, as evidenced by their high average article citations, even though their total research volume is relatively lower. In contrast, countries such as China (12.1), Russia (11.3), India (11.2), and Iran (5.6) have lower average article citations despite having a higher TC. While a strong correlation exists between TC and average article citations for most countries, the correlation is weaker for China, India, Russia, and Iran, highlighting the need to improve research quality.

3.5.3 Countries of corresponding authors'

Figure 7 illustrates the primary contributors to "Global Terahertz Generation Research" by categorizing them into single and multiple-country publications (MCP). In the context of Single-country publication (SCP), a document is considered to have all its authors originating from the same country. Conversely, Multi-country publication (MCP) denotes the count of documents that involve at least one co-author from a different country. In general, it measures a country's level of international collaboration. China leads the SCP list with 575 articles, followed by Japan (390) and the US (286), indicating that researchers from these countries have made significant contributions to the field through domestic collaborations and publications. China again leads in MCP (178) list, followed by Germany (123), the USA (110), Russia (110), and Japan (105) also showing significant contributions through multi-country publications.

Table 4 presents the countries of the corresponding authors based on the ranking of the MCP ratio. With the Philippines (0.636) and Korea (0.524) leading the list, many European countries like the Netherlands (0.452), Germany (0.449), the UK (0.421), Lithuania (0.420), and France (0.418) have a high MCP-Ratio, indicating high international research collaboration and co-authorship. In contrast, India (0.129) and Iran (0.021) have lower MCP ratios, suggesting they

Table 4. The corresponding authors' countries based on the MCP-Ratio.

Rank	Country	Articles	SCP	MCP	MCP-Ratio
1.	Philippines	33	12	21	0.636
2.	Korea	124	59	65	0.524
3.	Netherlands	31	17	14	0.452
4.	Germany	274	151	123	0.449
5.	United Kingdom	140	81	59	0.421
6.	Lithuania	88	51	37	0.420
7.	France	122	71	51	0.418
8.	Canada	93	55	38	0.409
9.	Switzerland	36	23	13	0.361
10.	Russia	394	284	110	0.279
11.	USA	396	286	110	0.278
12.	China	753	575	178	0.236
13.	Japan	495	390	105	0.212
14.	India	202	176	26	0.129
15.	Iran	94	92	2	0.021

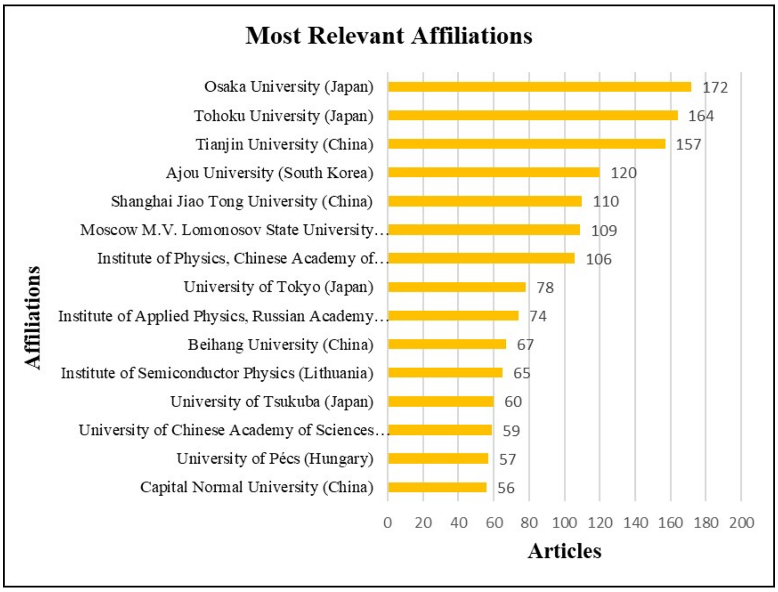

Figure 9. Top 15 most relevant affiliations in terahertz generation (2003-2023).

should improve international research collaborations. Furthermore, China and Japan have a high volume of total articles and domestic single-country publications, making them the leaders in field research quality and quantity.

3.5.4 Country co-authorship analysis

Figure 8 presents a network map illustrating the collaborative relationships among prominent countries engaged in terahertz generation research. A criterion of a minimum of 25 documents was employed to identify countries for inclusion. Out of the total, 22 countries that met this threshold are organized into five distinct clusters: Cluster 1 is denoted in red, Cluster 2 in green, Cluster 3 in blue, Cluster 4 in yellow, and Cluster 5 in purple. These clusters essentially signify groups of countries that engage in more interconnected collaborations. In essence, a cluster represents a grouping of items, with countries being the items in this context. The lines connecting the items represent co-authorship connections between these countries. The visual elements within the map, such as the size of labels and circles associated with each country, are influenced by the country's weight (number of documents). Likewise, the thickness of the links between countries reflects the strength of their co-authorship connections, indicating the number of joint publications authored by researchers from those countries. Furthermore, the spatial separation observed between two items in the visualization offers a rough indication of the degree of proximity in terms of co-authorship relationships between those respective nations. Japan has collaborated with all 21 countries, followed by Germany at 19. The links with the highest strength are USA-Germany: 47, USA-Japan: 35, and USA-China: 35. This indicates

Table 5. The corresponding authors' countries based on the MCP-Ratio.

Authors	No. of Doc.	GC
ZHANG X	**96**	2883
YAO J	**79**	866
TONOUCHI M	**70**	1431
LI Y	**67**	1054
HUANG Y	**65**	1076
ZHANG L	**65**	863
WANG Y	**59**	714
ZHANG J	**57**	1177
KROTKUS A	**54**	674
LEE S	**51**	1254
ZHANG Y	**51**	1005
JAZBINSEK M	**50**	1613
LIU J	**50**	808
WANG X	**50**	795
LI Z	**49**	314

Table 6. The corresponding authors' countries based on the MCP-Ratio.

Authors	No. of Doc.	GC
TAYLOR A	11	**3327**
ZHANG X	96	**2883**
GOSSARD A	14	**2365**
KIM K	28	**2171**
HEBLING J	35	**2160**
CHEN H	13	**2139**
AVERITT R	6	**2022**
ZIDE J	2	**1916**
PADILLA W	2	**1910**
RASING T	15	**1856**
KIMEL A	13	**1786**
JAZBINSEK M	50	**1613**
TONOUCHI M	70	**1431**
KIRIL YUK A	2	**1382**
ITO H	30	**1376**

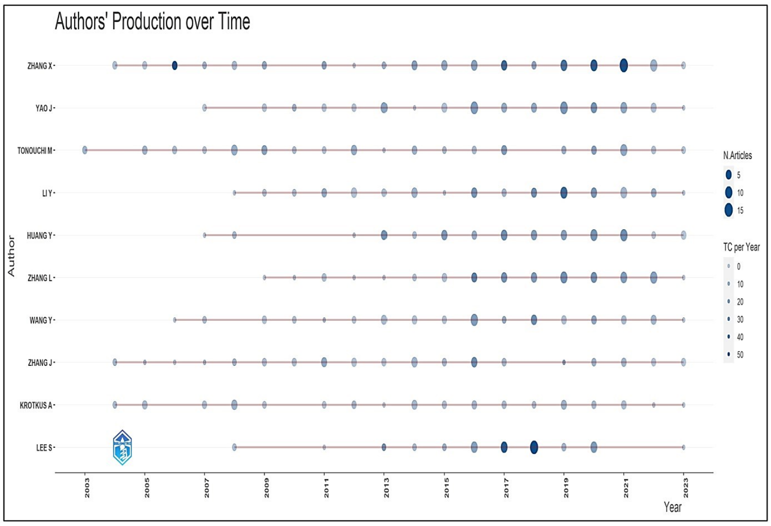

Figure 10. Top 10 authors production over time from 2003-2023.

that collaboration between the USA and other countries like Germany, Japan, and China is the strongest. Some outlier countries with low connectivity are the Philippines (3 links), Iran (6 links), and Taiwan (8 links), i.e., they have links only to a select few countries. The network analysis reveals the US, Germany, Japan, China, and Russia as the most central and influential countries in terms of research output and impact. Overall, the network is dominated by major developed economies in Asia, Europe, and North America.

3.6 Important affiliations

Figure 9 illustrates that there is a prominent presence of affiliations from countries in East Asia such as, China, Japan and South Korea, as evidenced by institutions such as Osaka and Tohoku University (Japan), Tianjin University (China), and Ajou University (South Korea), which have published a significant number of articles, with counts of 172, 164, 157, and 120, respectively. However, notable contributions are not limited to East Asia, as exemplified by "The Institute of Applied Physics, Russian Academy of Sciences (Russia)", "The Institute of Semiconductor Physics (Lithuania)", and the "University of Pécs (Hungary)", which have actively engaged in terahertz generation research, with article counts of 74, 65, and 57, respectively. Furthermore, esteemed universities like the "Moscow M.V. Lomonosov State University (Russia)" (109 articles) and the "University of Tokyo (Japan)" (78 articles) have made significant contributions, highlighting the broad interest and engagement in terahertz generation research across various regions and institutions worldwide. The list has 6 institutions from China, 4 from Japan, 2 from Russia, and Hungary, Lithuania, and South Korea, each with one institution.

3.7 Relevant authors of this field

3.7.1 Most active authors

Understanding the development of a field often requires investigating the individuals who have contributed to it. The top 15 researchers in the field of terahertz generation are

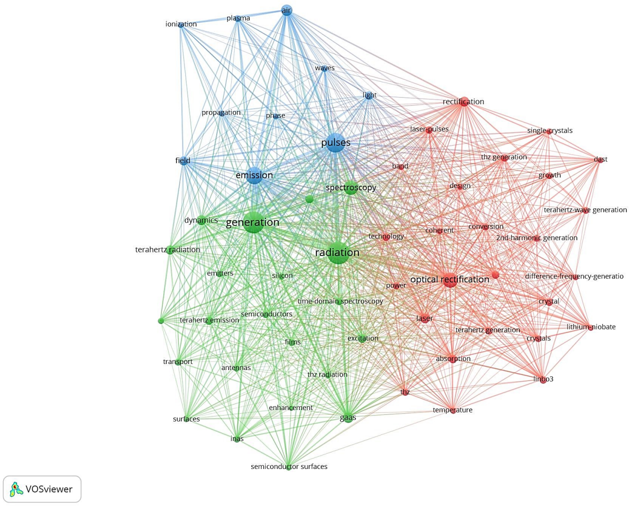

Figure 11. Co-occurrence of "Keyword Plus" on terahertz generation research.

Table 7. The 15 authors with the highest h-index and g-index scores.

Authors	h-index	g-index
ZHANG X	**28**	51
LEE S	**23**	32
TONOUCHI M	**22**	35
ITO H	**21**	30
SHENG Z	**21**	34
ZHANG J	**21**	33
HEBLING J	**20**	35
HUANG Y	**20**	30
JAZBINSEK M	**20**	39
KAWASE K	**20**	34
LI Y	**20**	30
ZHANG Y	**20**	30
OTSUJI T	**19**	31
CHEN Y	**18**	27
KWON O	**18**	32

Table 8. The 15 authors with the highest h-index and g-index scores.

Authors	h-index	g-index
ZHANG X	28	**51**
JAZBINSEK M	20	**39**
TONOUCHI M	22	**35**
HEBLING J	20	**35**
SHENG Z	21	**34**
KAWASE K	20	**34**
ZHANG J	21	**33**
LEE S	23	**32**
KWON O	18	**32**
OTSUJI T	19	**31**
WANG H	18	**31**
ITO H	21	**30**
HUANG Y	20	**30**
LI Y	20	**30**
ZHANG Y	20	**30**

included in Tables 5 and 6. There are two rankings for these authors: "Number of Documents" and "Global Citations" (GC). GC indicates that authors are referenced not only by peers within their specific field but also by researchers from other disciplines, as noted by Li et al. [62]. Noteworthy authors who have contributed significantly to the field include Xi-Cheng Zhang (96 publications) affiliated with "The Institute of Optics, University of Rochester, USA," Yao J (79 publications) from Tianjin University, China, and Tonouchi M (70 publications) associated with "The Institute of Laser Engineering, Osaka University, Japan." These authors have significantly contributed to the field with their extensive publication output. Other authors, such as Li Y (67), Huang Y (65), and Zhang L (65), have also made substantial contributions with their respective numbers of documents. However, the document amount does not always indicate influence. We identify influential authors in the terahertz generation field using the GC order in Table 6. Taylor A is the highest cited author with GC (3327), while it is observed that Xi-Cheng Zhang remains a significant author in both rankings, with a substantial GC (2883) emphasizing their prolific research output and citation impact. Zide J and Padilla W stands out in Table 6 with a remarkable GC (1916) and (1910) respectively, despite having fewer documents (2). Gossard A (doc. 14, GC 2365), Averitt R (doc. 6, GC 2022), and Kirilyuk A (doc. 2, GC 1382) too, have received significant attention and recognition within the terahertz generation field. Notably, Tonouchi M also appears in both rankings, indicating their consistent contribution to the field with a substantial number of documents (70) and a respectable GC (1431).

Figure 10 displays the top 10 authors' production over time based on the 'No. of Documents' ranking. The bubble size represents the 'No. of Articles' published and colour intensity the no. of times they were cited (Times Cited), i.e., TC per year. Tonouchi M is the most active author with the most extended timeline (2003-2023), followed by Zhang X, Zhang J, and Krotkus A, each with a timeline (2004-2023). Zhang L and Zhang X each produced ten articles in 2022 and received 15.5 and 9 TC per year, respectively, highlighting their continuous contribution to the Terahertz generation field. Yao J, Li Y, Huang Y and Wang Y have also contributed actively.

3.7.2 Author's local impact

Tables 7 and 8 present the local impact of 15 top authors based on two metrics, h- and g-index, respectively. Many authors like Zhang X, Lee S, Tonouchi M, Jazbinsek M, and Sheng Z appear in both rankings, indicating that they are highly impactful authors with a high number of papers and citations. Zhang X has the highest h and g-index of 28 and 51, respectively, indicating that he has produced a high number of highly cited articles. In contrast, authors such as Hebling J, Huang Y, Jazbinsek M, Kawase K, Kwon O, Otsuji T, Li Y, Zhang Y, and Chen Y generally have lower h and g-indices with respect to the author Zhang X, signifying a more modest influence on the global terahertz generation field. Furthermore, the average h-index and g-index of the authors in the list are 20.07 and 33.40, respectively, indicating that the authors in the list are highly productive and impactful in the field of terahertz generation research.

3.8 Important documents

3.8.1 Most globally cited documents

The top 15 globally cited papers in Terahertz generation, shown in Table 9, were published between 2003 and 2013. Global citations refer to the total number of times a document is mentioned in other documents across a whole database like WoS or Scopus. Basically, it shows how much of an influence a document has on the entire collection of references. For many documents, a substantial proportion of global citations may originate from different fields of study. "Physical Review Letters" is the journal with the most cited papers (3), followed by the "Journal of the Optical Society of America B-Optical Physics" (2). The paper "Active terahertz metamaterial devices", published by Hou-

Table 9. Top 15 globally cited papers in the terahertz generation field (2003-2023).

S. No.	Document	DOI	Local Citations	Global Citations
1.	CHEN H, 2006, NATURE	10.1038/nature05343	0	**1907**
2.	KIRILYUK A, 2010, REV MOD PHYS	10.1103/RevModPhys.82.27.1	23	**1210**
3.	POLYNKIN P, 2009, SCIENCE	10.1126/science.1169544	3	**710**
4.	HIRORI H, 2011, APPL PHYS LETT	10.1063/1.3560062	142	**647**
5.	KIM K, 2008, NAT PHOTONICS	10.103/nphoton.2008.153	0	**623**
6.	XIE X, 2006, PHYS REV LETT	10.1103/PhysRevLett.96.075005	237	**579**
7.	KIM K, 2007, OPT EXPRESS	10.1364/OE.15.004577	0	**530**
8.	BIGOT J, 2009, NAT PHYS	10.1038/NPHYS1285	0	**439**
9.	DAMICO C, 2007, PHYS REVLETT	10.1103/PhysRevLett.98.235002	160	**421**
10.	HEBLING J, 2008, J OPT SOC AMB-OPT PHYS	10.1364/JOSAB.25.0000B6	0	**421**
11.	KRESS M, 2004, OPT LETT	10.1364/OL.29.001120	159	**348**
12.	SCHNEIDER A, 2006, J OPT SOC AMB-OPT PHYS	10.1064/JOSAB.23.001822	0	**347**
13.	LEEMANS W, 2003, PHYS REV LETT	10.1103/PhysRevLett.91.074802	0	**337**
14.	DREYHAUPT A, 2005, APPL PHYS LETT	10.1063/1.1891304	69	**301**
15.	LIU X, 2013, SCI REP	10.1038/srep02718	0	**300**

Table 10. Top 15 locally cited papers in the terahertz generation field (2003-2023).

S. No.	Document	DOI	Local Citations	Global Citations
1.	XIE X, 2006, PHYS REV LETT	10.1103/PhysRevLett.96.075005	**237**	579
2.	DAMICO C, 2007, PHYS REV LETT	10.1103/PhysRevLett.98.235002	**160**	421
3.	KRESS M, 2004, OPT LETT	10.1364/OL.29.001120	**159**	348
4.	HIRORI H, 2011, APPL PHYS LETT	10.1063/1.3560062	**142**	647
5.	CLERICI M, 2013, PHYS REV LETT	10.1103/PhysRevLett.110.253901	**106**	272
6.	TANABE T, 2003, APPL PHYS LETT	10.1063/1.1592889	**91**	191
7.	BEAUREPAIRE E, 2004, APPL PHYS LETT	10.1063/1.1737467	**84**	199
8.	LIU K, 2006, PHYS REV B	10.1103/PhysRevB.73.155330	**83**	157
9.	BABUSHKIN I, 2010, PHYS REV LETT	10.1103/PhysRevLett.105.053903	**83**	150
10.	KRESS M, 2006, NAT PHYS	10.1038/nphys286	**74**	215
11.	YANG Z, 2007, ADV FUNCT MATER	10.1002/adfm.200601117	**70**	223
12.	DREYHAUPT A, 2005, APPL PHYS LETT	10.1063/1.1891304	**69**	301
13.	TANIUCHI T, 2004, J APPL PHYS-a	10.1063/1.1713045	**68**	161
14.	VICARIO C, 2014, PHYS REV LETT	10.1103/PhysRevLett.112.213901	**65**	211
15.	BERGE L, 2013, PHYS REV LETT	10.1103/PhysRevLett.110.073901	**63**	117

Table 11. Top 15 locally cited references with DOI and Citations.

Rank	Cited references	DOI	Citations
TONOUCHI M, 2007, NAT PHOTONICS	10.1038/NPHOTON.2007.3	638	
FERGUSON B, 2002, NAT MATER	10.1038/NMAT708	379	
COOK DJ, 2000, OPT LETT	10.1364/OL.25.001210	334	
KIM KY, 2008, NAT PHOTONICS	10.1038/NPHOTON.2008.153	260	
HAMSTER H, 1993, PHYS REV LETT	10.1103/PHYSREVLETT.71.2725	258	
KIM KY, 2007, OPT EXPRESS	10.1364/OE.15.004577	247	
XIE X, 2006, PHYS REV LETT	10.1103/PHYSREVLETT.96.075005	237	
KOHLER R, 2002, NATURE	10.1038/417156A	173	
ZHANG XC, 1992, J APPL PHYS	10.1063/1.350710	169	
SEIFERT T, 2016, NAT PHOTONICS	10.1038/NPHOTON.2016.91	165	
DAMICO C, 2007, PHYS REV LETT	10.1103/PHYSREVLETT.98.235002	160	
THOMSON MD, 2007, LASER PHOTONICS REV	10.1002/LPOR.200710025	160	
KAMPFRATH T, 2013, NAT PHOTONICS	10.1038/NPHOTON.2013.184	159	
KRESS M, 2004, OPT LETT	10.1364/OL.29.001120	159	
HEBLING J, 2002, OPT EXPRESS, V10, P1161	10.1364/OE.10.001161	156	

Tong Chen of "Los Alamos National Laboratory", USA, in 2006 in the journal Nature, received the highest global citations (1907). Some papers, such as "KIM K, 2008, NAT PHOTONICS" and "HEBLING J, 2008, J OPT SOC AM B-OPT PHYS," have received a significant number of global citations despite having no local citations, suggesting their wide-reaching impact beyond specific research communities. In addition, the top 15 documents are produced by writers from many nations, such as the United States, China, Germany, Japan, South Korea, France, and Italy. This indicates a high level of collaboration among researchers from multiple institutions and countries working in the terahertz generation field.

3.8.2 Locally cited documents

Table 10 depicts the top 15 locally cited documents in Terahertz generation field. Local citations represent the number of citations a document obtained from other documents in the collection being analyzed. It determines the significance of a document inside the analysed collection. The analysis revealed that the most cited paper is XIE X, 2006, PHYS REV LETT, with 237 local citations and 579 global citations, followed by D'AMICO C, 2007, PHYS REV LETT, with 160 local citations and 421 global citations. "Physical Review Letters" is the most popular journal among these documents, with six papers published in this journal. Kress M is the most productive author, with two papers in top 15 local cited documents. The United States is the most productive country, with four papers published in the top 15 local cited documents, followed by Japan, Germany, France, and Italy.

3.9 Cited references

Table 11 provides the top 15 locally cited references in terahertz generation research published between 1992 and 2016, indicating that THz generation research has been extensively studied for over three decades. However, many highly cited references are relatively recent, published from 2007 onwards. The most cited paper is "Cutting-edge terahertz Technology" by Masayoshi Tonouchi of the "Institute of Laser Engineering, Osaka University, Japan," which has been cited 638 times. The next most cited papers are "Materials for terahertz science and technology" by Bradley Ferguson & Xi-Cheng Zhang of the "The university of Adelaide, Australia" and "Institute of Optics, University of Rochester, USA," respectively and "Intense terahertz pulses by four-wave rectification in air" by D. J. Cook and R. M. Hochstrasser with 379 and 334 citations, respectively. The majority of the references are journal articles published in high-impact journals like Nature Photonics with 4 references, Physics Review Letters (3), Optics Letters (2), and Optics Express (2), showing that high-quality research in the field of Terahertz generation is being published in reputed peer-reviewed journals. Some authors, like K. Y. Kim of "Material Physics and Applications Division, Los Alamos National Laboratory, USA," with references "KIM KY, 2008, NAT PHOTONICS, V2, P605", "KIM KY, 2007, OPT EXPRESS, V15, P4577" and a total of 507 citations as the first author has made substantial contributions to the field. Furthermore, the works listed in Table 10 can be considered seminal research studies that have shaped the Terahertz generation research.

3.10 Keyword plus co-occurrence analysis

Figure 11 presents the network visualisation of frequently co-occurring KeyWords Plus in terahertz generation research. It is worth mentioning that KeyWords Plus refers to words or phrases that frequently appear in the titles of works cited by an article, but not in the title of the article itself. KeyWords Plus terms are better able to capture the depth and variety of an article's content [63]. The minimum number of KeyWord Plus occurrences was adjusted to 50 to improve the appearance of the network map. Fifty-nine words met the threshold and were grouped into 3 clusters. Cluster 1 (Red, 26 items) focuses on laser-based techniques for terahertz generation using nonlinear optical effects and crystals. This cluster contains keywords related to "optical rectification" "2nd-harmonic generation", "difference frequency generation", "lithium-niobate", and "laser pulses". Cluster 2 (Green, 22 items) focuses more on terahertz emission from semiconductor materials and devices. It contains keywords like "antennas", "films", "GaAs", "InAs", "silicon", and "semiconductor surfaces". Cluster 3 (Blue, 10 items) is more general, covering topics like terahertz "propagation", "pulses", "emission", "ionization", and "plasma" effects. The KeyWord Plus co-occurrence analysis and network visualisation provide a high-level overview of the main research directions, connections between topics, and emerging themes within the terahertz field.

4. Conclusion

This bibliometric analysis provides an extensive and thorough insight into the global landscape of terahertz generation research. With the development of infra-red femtosecond lasers and advancements in nonlinear optical materials, the field of terahertz generation research has witnessed substantial growth and development over the past two decades. Hence a systematic and quantitative approach was required. This study analyzed over 3,600 publications to identify the key journals, institutions, authors, countries and trends shaping the field. The field witnessed an average annual growth rate of 4.42 percent from 2003 to 2022. The total number of publications rose from 48 in 2003 to 238 in 2022, peaking at 279 publications in 2021. This growth indicates the increasing importance of this research area. Key journals, such as "Applied Physics Letters" and "Optics Express," have played a significant role in disseminating knowledge in the field, with 328 and 296 articles, respectively. "Applied Physics Letters" has also received the highest number of local citations (13,227) and boasts the highest h-index (53) and g-index (82). These statistics highlight the journal's impact and relevance in the terahertz generation research community. The analysis also revealed China as the eminent country in terms of the number of publications (2,049), followed by Japan (1,323), the USA (1,108), and Russia (1,084). In terms of citations, the USA (16,519), Japan (11,160), and China (9,099) lead the way. However, the Netherlands (70.1), Switzerland (53.8), and Hungary (44.1) produce high-quality research, as evidenced by their high average article citations. The findings also indicate that China has the highest number of single-country publications (SCP) with 575 articles, followed by Japan (390) and the USA (286). Country co-authorship analysis shows that Japan has collaborated with all 21 countries, followed by Germany at 19. The strongest links are between the USA-Germany (47), USA-Japan (35), and USA-China (35), indicating robust collaboration in this research area. Prominent affiliations in terahertz generation research include Osaka University (Japan), Tianjin University (China), and Ajou University (South Korea), with 172, 157, and 120 articles, respectively. The top productive authors based on the number of documents are Xi-Cheng Zhang (96) from "The Institute of Optics, University of Rochester, USA", Yao J (79) from "Tianjin University, China", and Tonouchi M (70) from "The Institute of Laser Engineering, Osaka University, Japan". Xi-Cheng Zhang also has the highest h-index (28) and g-index (51), demonstrating their local impact. The most globally cited document is "Active terahertz metamaterial devices" by Hou-Tong Chen of "Los Alamos National Laboratory, USA", published in 2006 in the journal Nature, with 1,907 citations. The most cited reference is "Cutting-edge terahertz Technology" by Masayoshi Tonouchi, cited 638 times. Keyword co-occurrence analysis revealed three primary clusters: Cluster 1 (laser-based techniques for terahertz generation using nonlinear optical effects and crystals), Cluster 2 (terahertz emission from semiconductor materials and devices), and Cluster 3 (general subjects like terahertz propagation, pulses, emission, ionization, and plasma effects).

While THz radiation has shown great promise for applications across spectroscopy, imaging, and communications, the "THz gap" remains a significant challenge. Conventional THz sources lack efficiency, tunability, and power. The literature review of the research papers revealed critical gaps in developing novel techniques and materials to generate intense, broadband, and coherent THz beams. Specifically, there is a need for further research on:

Nonlinear optical materials with improved phase-matching and damage thresholds at high THz intensities. Emerging options like organic crystals, metamaterials, and 2D materials could be explored.

THz generation from spintronic devices and topological insulators. These can offer solid-state, compact sources, but their conversion efficiencies still need to improve. More theoretical and experimental work is required to understand the underlying spin-to-charge conversion mechanisms.

Better understanding of THz generation from laser-matter interactions. While laser-based methods like optical rectification show promise, challenges remain in optimizing laser parameters, pulse formats, and target materials.

Hybrid THz sources that combine semiconductor, superconductor, and photonic technologies. This could lead to room-temperature, integrable, and tunable microchip devices.

In summary, the literature review analysis revealed critical gaps in materials science, device engineering, and laser-matter interaction physics that need to be addressed to realize efficient and practical THz sources. Filling these research gaps will be key to overcoming the "THz gap" and enabling impactful applications across industries.

It is important to note that this bibliometric study on Terahertz generation has some limitations. Firstly, the study's data was sourced exclusively from the Web of Science (WoS) core collection. This approach neglected potentially relevant data from other widely recognised databases, such as SCOPUS and Google Scholar, thereby restricting the scope of the data analysis. Secondly, as the data was sourced from the WoS core collection, the study could not include any data prior to 2003; henceforth, the study period is limited to 2003–2023. However, the data for the current year (2023) is incomplete. This time constraint may have led to the omission of significant research trends and findings in the field of terahertz generation from both recent and earlier years, and lastly, out of the 3,630 documents analyzed, 2,102 lacked "author keywords" (DE), and 334 lacked "Keywords Plus" (ID). This incomplete metadata restricted the co-occurrence analysis to "KeyWords Plus" only, leaving the "Author Keywords" relatively unexplored and potentially missing out on relevant connections and insights.

In conclusion, this analysis achieved its objective to map the global terahertz generation research. The results can help new researchers identify key sources to follow, potential collaborators, and promising research directions.

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Ethical approval

This manuscript does not report on or involve the use of any animal or human data or tissue. So the ethical approval is not applicable.

Authors Contributions

Rohit Kumar conceived the present research idea. Siddharth Bhardwaj and Sukhmander Singh worked on the analysis of results and the drafting of the manuscript.

Availability of data and materials

Data presented in the manuscript are available via request.

Conflict of Interests

The author declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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