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A Scientometric Analysis of Global Terahertz Research by Web of Science Data

BIN LI[1,2], KAI HU[3], AND YIN SHEN[1,4]
[1]Beijing Research Center for Information Technology in Agriculture, Beijing 100097, China
[2]Key Laboratory of Agri-Informatics, Ministry of Agriculture, Beijing 100097, China
[3]School of Internet of Things, Jiangnan University, Wuxi 214122, China
[4]College of Engineering and Technology, Southwest University, Chongqing 400715, China

Corresponding author: Bin Li (agrithz@163.com)

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ABSTRACT Terahertz is a high-tech technology that has been developed rapidly in recent years. Relevant research has been extensively carried out in physics, chemistry, communication, biology, agricultural food safety testing, industrial non-destructive testing, biochemical, medical, and biological imaging. To provide a summary of the research trend in the field, there is a need to analyze the literature by scientometrics. In this work, we have an overview of the literature in the terahertz field, and then analyze the literature from the aspects of terahertz source, terahertz detector, terahertz spectroscopy and imaging, and terahertz applications respectively. The focus of this work is to automatically extract the trend by co-words and co-citation network analysis, and the comparative point of view is used to understand two closely related but different fields of terahertz basic research and terahertz application research. Through the scientific basis measurement, the research characteristics of these two fields, including annual outputs, active journals, key authors, key research directions and hotspots, important research projects and the countries behind them are immediately obtained.

INDEX TERMS Terahertz, scientometrics, measurement, applications.

I. INTRODUCTION

Terahertz (THz) is electromagnetic radiation whose frequency lies between the microwave and infrared regions of the spectra. The frequency is between 0.1 and 10 THz, and the wavelength is about 0.03 to 3 mm. The developments in THz technology were once hindered for lack of hardware but the invention of the femtosecond laser in 1980s promoted the advancement in THz research and applications. Due to their high permeability, low energy, and fingerprint characteristics, THz's application areas are widely explored in safety detection, metamaterials, biomedicine, semiconductors, food, agriculture, medicine, and etc. Therefore, there is more and more published literature in the field available for researchers. THz is a brand-new research area. In order to help researchers to understand and master the development of the terahertz field and to find its key applications, many review articles were completed by manually summarizing the published work. Review articles generally tend to favor the researcher's familiar field, which may lack accuracy and objectivity. To compensate this drawback, there is a need to summarize the research through information extraction.

Scientometrics is a branch of science of scientific activities which apply mathematical methods such as mathematical statistics and computational techniques to scientific activities and process for quantitative analysis, and find out the regularity of scientific activities. Scientometrics has been effectively applied in studying the productivity of scientific and technological knowledge, evaluating the scientific and technological capabilities of the society, and the scientific and technological competitiveness and scientific research performance of the country and the region. Moreover, it also provides powerful quantitative means and quantity support for exploring the law of interactions among science, technology, and social economy, as well as the production relations of scientific research fields such as science and technology establishment,

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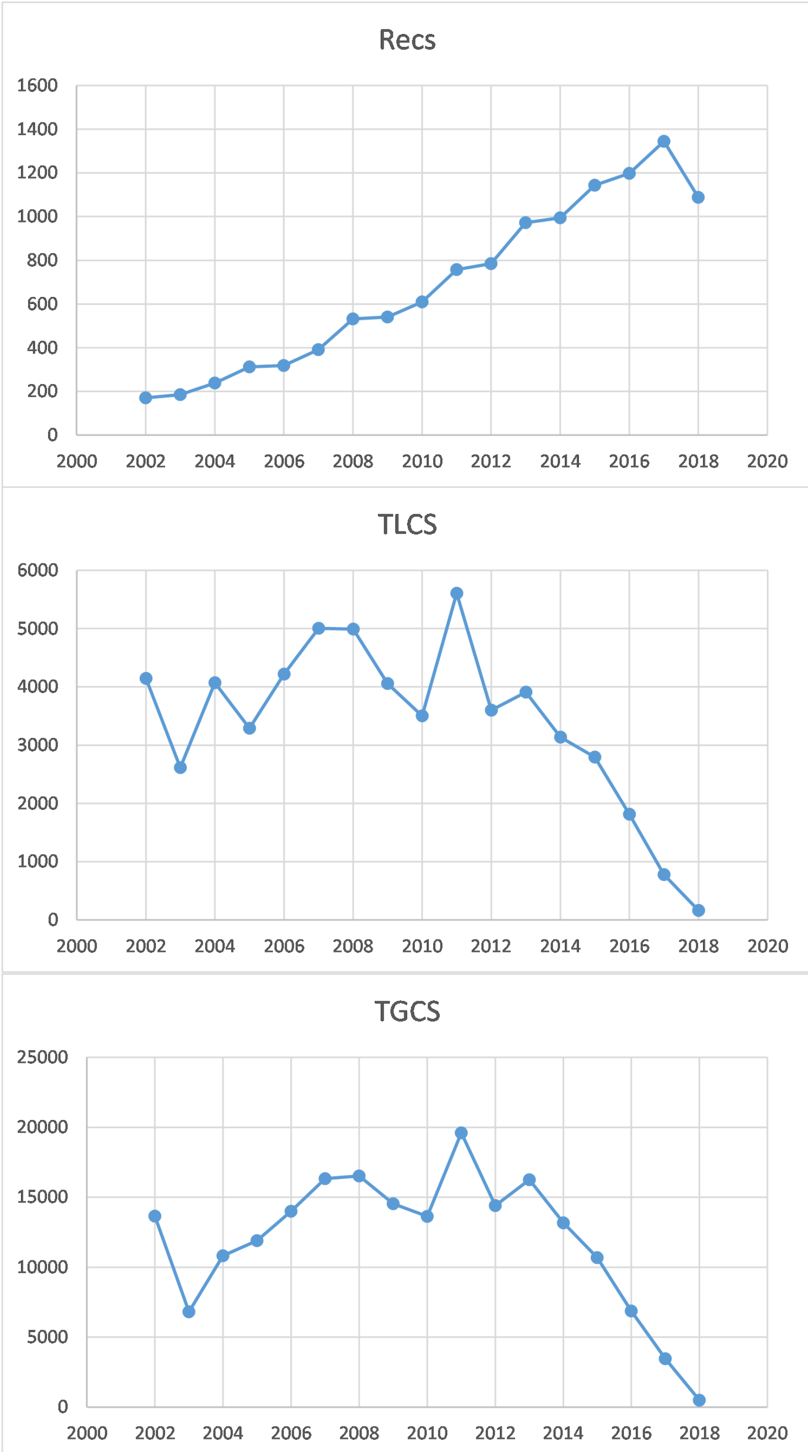

FIGURE 1. Publications published annually in the terahertz field.

organization, system, and cooperation. The research of scientometrics can be divided into four categories: one is to fit the variable data into experience and probability distribution; the second is to make scientific or subject geographical distribution map; the third is to conduct performance research, impact research and evaluation research on scientific activities; and the fourth is the study of various quantitative indicators. Many works have been done for improving the scientometric theories and the methodologies are rather abundant including computer science, social science, and other interdisciplinary [1], [2]. With these methods, many domains are borrowing the methods and tools to help their domain understanding like board discipline analysis of smart agriculture [3], food safety [4] or very specific sub-domains like night-time light (NTL) [5]. However, the method has not been applied in the rapidly development field of terahertz. A work on THz research and applications by using Scientometrics is thus very important.

In this work, the scientometrics literature analysis and measurement methods are applied to the terahertz literatures. Through analysis and understanding of the hotspots and development trends of terahertz research, from the perspective of original knowledge creation, combined with quantitative index research, and with the help of co-words and co-citations, we make the terahertz field science or discipline geographical distribution map, which will provide information for relevant research institutions and government agencies to grasp research trends.

The research field of terahertz is mainly divided into terahertz technology principle research and terahertz application research. The principle research is mainly divided into terahertz generation and detection, terahertz spectroscopy and imaging system research; and the application research can be roughly divided into two categories: terahertz sensing and communication. By understanding and mastering the role and detection mechanism of terahertz and matter, terahertz applied research is subdivided into biology, medicine and pharmacy, semiconductor and other industrial applications, security detection, information and communication technology, earth and space science, agricultural food safety and basic science applications.

II. DATA ACQUISITION AND DATA ANALYSIS METHODS

A. DATA ACQUISITION

Based on the SCI citation database, more information hidden behind scientific activities can be explored from the scientific map generated by THz literatures. In this work, the bibliographic data set was retrieved from the most famous Science Database, Web of Science (WoS). In particular, the Science Citation Index (SCI) and the Social Science Citation Index (SSCI) are used as target data indexes because they are the most easily identifiable data sources. These two databases provide fewer articles than search engines such as Google Scholars or Bing Academic, but the papers in these indexes will be of higher quality.

The research bibliographic data set will be obtained by the search criteria. We obtained our datasets for terahertz science and technology and its applications through the following search criteria:

DATABASE: Web of Science Core Collection
Theme: (“Terahertz”) and theme: (“THz”)
Time span: 2002-2018
Refined by: DOCUMENT TYPES: (ARTICLE)

Through these conditions, 11585 records were obtained. These bibliographic data sets contain very complete metadata information, including authors, research institutes, journals, citation counts, and citations. Using the information provided, basic bibliographic information can be extracted, and keyword term maps, research institution maps, and co-cluster maps can be created based on the co-occurrence network. Basic information can quickly provide an overview of the research field. Web-based views can help visualize the focus and clustering of core research.

B. DATA ANALYSIS METHODS

1) DATA ANALYSIS METHODS AND SOFTWARE

The contribution of scientometrics theory is known for the quality of research. Quantitative indicators of scientometrics such as impact factor (IF) and H index are familiar to most researchers, other indexes provide a quick overview of certain characteristics of the attributes and can help identify important studies. Take the All Local Reference Score (TLCS) and Global Reference Score (TGCS) as examples; these indexes were used by the well-known bibliometric software HistCite, developed by Dr. Garfield. The TLCS indicates that the paper or author is referenced from the current data set, while the TGCS indicates that the paper or author is referenced from the entire WoS database. Comparing TLCS and TGCS, TLCS represents recognition from the current domain or current dataset collection, and TGCS represents the recognition of the entire scientific community. Therefore, this can help identify important research in the field and well-known research through these values.

2) APPLICATION FOR NETWORK ANALYSIS

Authors, journals, research institutions, and countries in the literature provide a direct description of basic elements of research activities. To further understand this area, we also need to understand the active themes of each specific research direction in the terahertz field. Unlike numeric values, we present keywords in a network based on the co-occurrence of keywords. Through the network, different keywords have very different keyword frequencies and we can understand the research focus of the entire research trend. Based on a co-word network, bibliographic software can help visualize concepts as density maps. These numbers are generated by the software of VoSviewer. VoSviewer and CiteSpace are the bibliometric analysis software for constructing and viewing bibliometric maps in this work. They support the co-citation and co-citation analysis of the literature, which can be used to map scientific interactions in various knowledge fields, directly creating a co-author network, co-word network, and co-cited reference networks based on Web of science files. VoSviewer provides the static visualizations for co-word or co-cited references network, CiteSpace allows users to deliberately layout the network structure.

Numerical methods are popular because of the ease of calculation and high efficiency. However, the disadvantages are also obvious. The ranking given by the numerical method does not indicate the relationship between the objects, whether it is a journal, an author, or a thesis. In order to solve the problem, many network-based methods have been

TABLE 1. Active journals in the terahertz field.

Journal	Recs	TLCS	TGCS
Applied Physics Letters	**973**	2929	26889
Optics Express	**882**	10133	22746
IEEE Transactions on Terahertz Science And Technology	**438**	2148	5358
Journal of Infrared Millimeter And Terahertz Waves	**395**	1838	4156
Optics Letters	**382**	4686	10092
Journal of Applied Physics	**328**	584	6341
Physical Review B	**284**	0	7298
Scientific Reports	**212**	0	1979
Optics Communications	**205**	1011	2224
Applied Optics	**185**	1225	2490
Acta Physica Sinica	**157**	179	600
Spectroscopy And Spectral Analysis	**147**	144	239
Electronics Letters	**131**	731	1839
IEEE Journal of Selected Topics In Quantum Electronics	**131**	780	2538
Journal of The Optical Society of America B-Optical Physics	**127**	1348	2956

proposed and have a long history. For example, the most famous method in the field of scientific metrology may be co-word network analysis. The co-word network analysis can construct a joint word network through processing bibliographic documents and collecting all the co-word relationships. Important sub-networks or critical clusters can be obtained through link reduction methods such as minimum spanning tree or pathfinder network. Therefore, the primary cluster can be obtained.

Similar to the co-word network, other networks such as the reference-based network, the coauthor network, and the bibliographic coupling network are all available from the structured data set. These web-based methods will also be applied to the analysis in this work.

III. BASIC BIBLIOMETRIC ANALYSIS

A. YEARLY OUTPUT

Publications published annually can reveal the extent of research activity in the field. In addition, in the information of TLCS and TGCS, the publication quality of publications can be analyzed to understand whether publications play an important role in the field or the entire scientific community.

Tonouchi's work in 2007 of the "Cutting-edge terahertz technology" received a high global citation of 2,918 times [6]. Kohler *et al.* [7], Ferguson *et al.* [8] and Siegel PH Terahertz technology received high global citations. Chen *et al.*'s work of 2006 "Active terahertz metamaterial devices" received a high global citation [9]. Federici al.'s work of 2005 "THz imaging and sensing for security applications - explosives, weapons and drugs" received more than 700 global citations [10]. Wang *et al.*'s work in 2005 "Metal wires for terahertz wave guiding" received more than 600 global citations. Tao *et al.*'s work in 2004, "A metamaterial absorber for the terahertz regime: Design, fabrication and characterization" obtained more than 600 global citations [11]. Yan *et al.*'s "Tunable infrared plasmonic devices using graphene/insulator stacks" in 2012 received more than 600 global citation [12]. Jepsen *et al.*'s "Terahertz spectroscopy and imaging - Modern techniques and applications" obtained more than 600 global citations[13].

In the past five years, the research is also very active, amount of papers increases intensively. As a report states from Chinese social media,[1] more than 600 papers on the only topic of "Terahertz spectroscopy and imaging" have been published in the SCI-Index database and the number of related papers is also increasing.

[1] https://mp.weixin.qq.com/s/CGdy1BuGvTJgtuRW_UPBaw

TABLE 2. Important journals in terahertz research.

Journal	Recs	TLCS	TGCS
Optics Express	882	10133	22746
Optics Letters	382	4686	10092
Applied Physics Letters	973	2929	26889
Nature Photonics	37	2684	6077
IEEE Transactions on Terahertz Science And Technology	438	2148	5358
Journal of Infrared Millimeter And Terahertz Waves	395	1838	4156
Nature	9	1782	4871
Journal of The Optical Society Of America B-Optical Physics	127	1348	2956
Applied Optics	185	1225	2490
Nature Materials	9	1137	2869
Optics Communications	205	1011	2224
Chemical Physics Letters	57	987	2008
Nano Letters	70	873	2910
IEEE Journal of Selected Topics In Quantum Electronics	131	780	2538
Electronics Letters	131	731	1839

B. ACTIVE JOURNALS

Journals are the main arena for all topics and academic activities. According to the number of records Recs, it can quickly locate the major contributor journals in the terahertz field. The top 5 are Applied Physics Letters, Optics Express, IEEE Transactions on Terahertz Science and Technology, IEEE Transactions on Terahertz Science and Technology and Optics Letters, too. The top 15 active journals in the Hertz research field are shown in Table 1.

However, the publication amount not necessarily means impacts. According to the TLCS order, we locate important publications in the terahertz field. The top 7 are Optics Express, Optics Letters, Applied Physics Letters, Nature Photonics, IEEE Transactions on Terahertz Science and Technology, Journal of Infrared Millimeter and Terahertz Waves and Nature. The top 15 important journals in the terahertz research field are shown in Table 2.

We also collected the active journals and important journals based on the past five years, as shown in Table 3 and Table 4, respectively. Several new journals have emerged in the top list. From Table 3 and Table 1, we can tell that Journal of Physics D-Applied Physics, Physics of Plasmas, and OPTIK are more active than the old classical journals like Electronics Letters, IEEE Journal of Selected Topics in Quantum Electronics, and Journal of The Optical Society of America B-Optical Physics. They may become the new power in this research field

The trends of the research is changing continuously. As shown in Table 4, the domain important journals are listed. The important journals also changed in the past five years. Applied Physics Letters, Nature, Journal of the Optical Society of America B-Optical Physics, Nature Materials, Chemical Physics Letters, IEEE Journal of Selected Topics in Quantum Electronics, and Electronics Letters have become less important in the domain important journal list, which might mean the research in recent years are becoming more and more specific, focusing on very concrete applications or detailed research problems.

C. IMPORTANT AUTHORS

The author is an important clue to understand the development of the field. A large number of authors in the terahertz field are collected in Table 5. These authors have three rankings, including Recs, TLCS, and TGCS. The ranking in Figure 2 is sorted according to Recs, which is the number of articles published in this search set. Yao JQ, Linfield EH, Davies AG, Zhang Y, Koch M, and Zhang XC are researchers who have published a large number of articles in the field of terahertz, but Zhang XC, Linfield EH, Davies AG, Tonouchi M, Jepsen PU, Koch M have the highest domain impacts.

As can be seen from Table 5, the top 15 authors have obtained more than 2000 TLCS, and the corresponding TGCS has been obtained more than 6000 TGCS. Those who pay attention to research issues in the field of terahertz are more concentrated. However, as can be seen from the TLGS, the author Ferguson B's Recs has only seven, that is, only seven papers, but it has obtained 1019 TLCS, indicating that the researcher's work is very important in the field of terahertz.

TABLE 3. Active journals from 2014 to 2018.

Journal	Recs	TLCS	TLCS
Optics Express	388	1343	2835
Applied Physics Letters	311	0	2917
IEEE Transactions On Terahertz Science And Technology	307	747	1838
Journal Of Infrared Millimeter And Terahertz Waves	244	681	1273
Scientific Reports	198	0	1525
Optics Letters	163	731	1527
Optics Communications	117	220	543
Physical Review B	104	0	686
Journal Of Applied Physics	94	0	501
Applied Optics	93	203	451
Spectroscopy And Spectral Analysis	81	44	71
Journal of Physics D-Applied Physics	79	0	539
Physics Of Plasmas	74	0	290
Acta Physica Sinica	65	0	103
Optik	58	55	128
ACS Photonics	56	137	408
Chinese Physics B	56	0	125
IEEE Photonics Technology Letters	54	193	371
AIP Advances	53	0	145
Physical Review Letters	52	0	835

Top ten authors from 2014 to 2018 are also collected in term of TLCS and TGCS. Note the Recs are not used as the ranking indicator in this period, because the time span has only five years. TLCS and TGCS are more representative for short-term rankings.

From the important authors from 2014 to 2018 in the table, we can find authors with high TLCS and TGCS come from various countries. Important authors have variations too, for example, only Linfield EH and Davies AG are still in the top 10 list, which mean that these important authors are still playing important roles in current or recent several years.

D. COUNTRIES OF THIS FIELD

In the field of terahertz, countries also play an important role in influencing research trends. Therefore, active countries in the terahertz field are collected by descending the Recs, TLCS, and TGCS values.

In the terahertz field, the United States is a leader in TLCS and TGCS, and Recs ranks the second, which means that it is a research center. Japan's TLCS ranked the second, Germany's TGCS ranked the second, Japan's TGCS ranked the third, Germany's TLCS ranked the third, China ranked the first in Recs, but TLCS and TGCS ranked the fourth. This shows that China's terahertz research field is at a rapid development stage.

E. IMPORTANT INSTITUTION

There are nearly 300 research institutes that published more than 20 papers in the terahertz field. By sorting research institutions in descending order according to the number of papers in the current search set, the top 20 are shown in Figure 5. The top 5 institutions are Chinese Acad Sci, Osaka Univ., Russian Acad Sci, Tianjin Univ., Capital Normal Univ., the Chinese Academy of Sciences has the most research papers, and the papers of Osaka University and the Russian Academy of Sciences are comparable. And the number of papers in Tianjin University, Capital Normal University, University of Electronic Science and Technology, Northeastern University of Japan, and the University of Cambridge is similar. Note the institute is counted every time when it appears in the co-author address list. So listed institutes may have the highest collaboration capability. Important institute

TABLE 4. Important journals from 2014 to 2018.

Journal	Recs	TLCS	TGCS
Optics Express	388	1343	2835
Applied Physics Letters	311	0	2917
IEEE Transactions on Terahertz Science And Technology	307	747	1838
Journal of Infrared Millimeter And Terahertz Waves	244	681	1273
Scientific Reports	198	0	1525
Optics Letters	163	731	1527
Optics Communications	117	220	543
Physical Review B	104	0	686
Journal of Applied Physics	94	0	501
Applied Optics	93	203	451
Spectroscopy And Spectral Analysis	81	44	71
Journal of Physics D-Applied Physics	79	0	539
Physics of Plasmas	74	0	290
Acta Physica Sinica	65	0	103
Optik	58	55	128
ACS Photonics	56	137	408
Chinese Physics B	56	0	125
IEEE Photonics Technology Letters	54	193	371
AIP Advances	53	0	145
Physical Review Letters	52	0	835

like CNRS, MIT as independent organizations may have important impacts.

The ranking of Recs, TLCS, and TGCS in the terahertz research literature is shown in Figure 6. If the papers are sorted according to the number of citations in the current data set, important research institutions in the terahertz field can be found. The top 5 institutions are Osaka Univ., Univ. Cambridge, Rensselaer Polytech Inst., MIT, and Univ. Adelaide.

Note that there are limitations in our analysis. Firstly, we did not exclude the self-citation in the analysis because the tool available now does not support that analysis function. In addition, the situation of one organization having many sub-organizations is not well separated. For example, Chinese Academy of Science consists of more than 100 institutes, they are, however, treated as one institution in the analysis, because current tools do not support identifying out sub-organizations of one academic department. This should be considered in future work.

IV. CO-WORD ANALYSIS AND CO-CITATION NETWORK ANALYSIS

A. CO-WORD NETWORK AND DENSITY MAPPING ANALYSIS

Using keyword lists of terahertz research literature, we visualized the domain knowledge. At the same time, the co-word network is also used to generate the density mapping, as seen in Figure 2. Through the visualizations, we can see the development direction and hotspots of terahertz sources from

TABLE 5. The terahertz domain author rankings ordered by Recs, TLCS and TGCS.

Author	Recs	TLCS	TGCS	Author	Recs	TLCS	TGCS	Author	Recs	TLCS	TGCS
Yao JQ	**167**	240	721	Zhang XC	109	**2422**	6900	Zhang XC	109	2422	**6900**
Linfield EH	**146**	2339	6475	Linfield EH	146	**2339**	6475	Linfield EH	146	2339	**6475**
Davies AG	**133**	2011	5707	Davies AG	133	**2011**	5707	Davies AG	133	2011	**5707**
Zhang Y	**133**	437	1354	Tonouchi M	96	**1770**	4127	Padilla WJ	27	993	**4758**
Koch M	**119**	1566	3555	Jepsen PU	69	**1638**	3494	Averitt RD	41	996	**4325**
Zhang XC	**109**	2422	6900	Koch M	119	**1566**	3555	Beere HE	101	1299	**4310**
Beere HE	**101**	1299	4310	Beere HE	101	**1299**	4310	Tonouchi M	96	1770	**4127**
Ritchie DA	**101**	1198	4067	Tredicucci A	49	**1199**	3793	Ritchie DA	101	1198	**4067**
Tonouchi M	**96**	1770	4127	Ritchie DA	101	**1198**	4067	Hu Q	59	1127	**3810**
Zhang CL	**96**	326	1007	Hu Q	59	**1127**	3810	Tredicucci A	49	1199	**3793**
Wang L	**90**	215	917	Hebling J	44	**1077**	2638	Koch M	119	1566	**3555**
Xu DG	**84**	103	372	Ferguson B	7	**1019**	2089	Jepsen PU	69	1638	**3494**
Cao JC	**82**	176	1033	Roskos HG	58	**1010**	2740	Knap W	76	798	**3432**
Kawase K	**80**	675	1773	Averitt RD	41	**996**	4325	Siegel PH	18	560	**3227**
Faist J	**79**	648	2498	Padilla WJ	27	**993**	4758	Reno JL	70	949	**3115**
Ito H	**77**	745	2154	Reno JL	70	**949**	3115	Kumar S	48	923	**3024**
Knap W	**76**	798	3432	Kumar S	48	**923**	3024	Taylor AJ	34	864	**2756**
Tani M	**76**	773	1881	Fischer BM	39	**910**	1942	Roskos HG	58	1010	**2740**
Hangyo M	**74**	602	2103	Wallace VP	28	**897**	2211	Hebling J	44	1077	**2638**
Zhang J	**73**	133	779	Kohler R	12	**879**	2366	Faist J	79	648	**2498**

*TGCS means that the authors are cited by authors in this field or studies out of the field; TLCS means that the authors are cited only by authors in this field, namely in the colle-cted datasets (11585 records of papers)

the knowledge level. Then, the terahertz research is reinterpreted using different classifications. In term of wireless communication, the research can be classified into pulse and continuous. In term of working principle, the research can be classified as an optical method to generate terahertz source (high frequency band), an electronic based method (solid state electronic device, low bands, other methods.)

Many related keywords, such as radiation [13]–[19], pulses [20], [21], generation [22]–[24], time-domain spectroscopy, absorption [25], metamaterials [9], [11], dynamics [26] *et al.*, are emerging in the co-word network and the density mapping. They represent the general knowledge of the domain research. The knowledge level analysis is discussed as follows [27]–[29]:

1) THz SOURCES [13], [18], [22]

Sources of THz generation can be roughly divided into two categories, broadband sources which are typically based on the conversion of ultrashort optical pulses into a few-cycle THz pulses and continuous wave (CW) sources which tend to be more spectrally narrow. There are mainly the following methods to generate THz: ① Optical method: For optical generation of THz radiation, there are mainly two general categories. The first is an ultrafast photocurrent in a photoconductive switch or semiconductor using electric-field carrier acceleration or the photo-Dember effect [30]–[32], and the second method is, THz waves are generated by nonlinear optical effects such as optical rectification (limited to femtosecond laser excitation), difference-frequency generation (DFG) [33], optical parametric oscillation [34], [35], or ambient air-plasma generation [36], [37]. ② Terahertz Quantum-cascade lasers (THz QCL): For the THz QCL method, the THz waves are emitted by means of electron relaxation between subbands of quantum wells [38], [39], and there are semiconductor-based THz sources [40], [41] and powerful continuous-wave THz sources [33], [42], [43]. The first THz QCL was developed in 1994 and had a lasing frequency of about 70 THz. THz QCL has the characteristics of high speed, low cost and good portability [40], [42]. ③ Solid-state electronic devices [44]: The devices have now entered the low frequency end of the THz. UTC-PD (Uni-traveling-carrier Photodiode) uses a photomixing technique to produce high-quality sub-THz solid state electronic devices, which is much more promising devices [41], [45]–[47].④ Other sources: THz groups have also studied other sources, such as resonant tunneling diodes (RTDs) [48], THz plasma-wave photomixers [45], [49], and Bloch oscillators [50]. Large facilities for generating high-power THz beams, such as the free-electron laser are also important for fundamental science [38], [51]–[53].

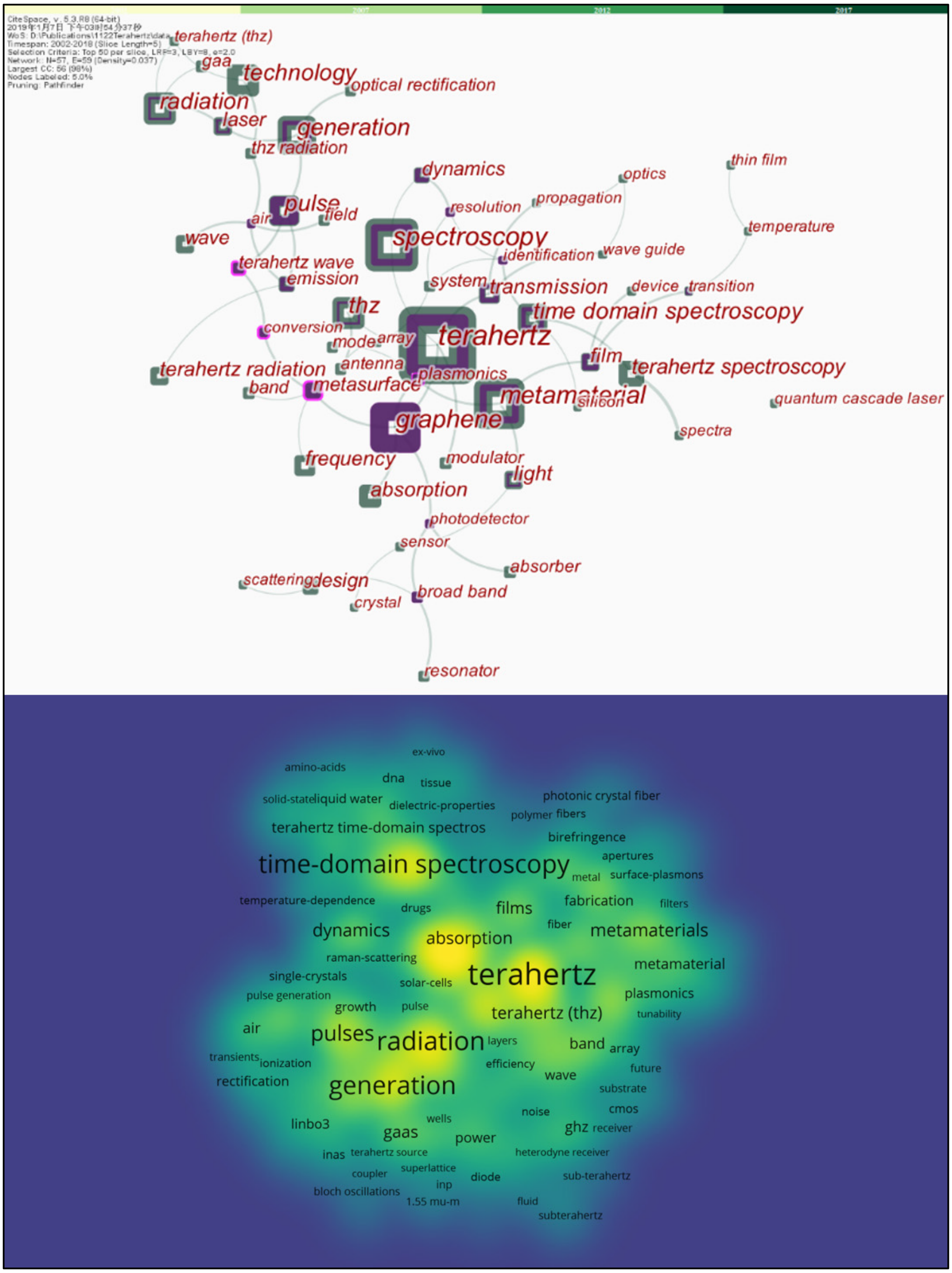

FIGURE 2. Co-work network and density mapping analysis of the THz research (2002 to 2018 is sliced into four periods by every five years).

2) TERAHERTZ DETECTORS

Terahertz detectors are also important topics in the field. There are three main detection methods. Thermal detection methods are based on detecting the temperature rise induced by the absorption of THz radiation, coherent detection methods are based on optical gating and semiconductor detection methods are based on detecting the THz photon directly. Related research topics include high-sensitivity detectors [54], [55], terahertz detection arrays [56], [57] and terahertz dynamic devices such as superconducting dynamic inductance detectors (KID) [58], [59] / superconducting phase change edge detectors (TES) [60], [61]. Terahertz detectors that can operate at room temperature are the hot topics [42], [50], [62], [63]. Other techniques include Photoconductive antenna [64], [65], Electro–optic sampling techniques [66], [67], DTGS (deuterated triglycine sulphate)

TABLE 6. Important authors from 2014 to 2018 in term of TLCS and TGCS ranking.

Author	Recs	TLCS	TGCS	Author	Recs	TLCS	TGCS
Vitiello MS	34	58	**642**	Akyildiz IF	13	**210**	438
Hauri CP	25	141	**629**	Jornet JM	16	**180**	416
Zeitler JA	27	87	**484**	Han C	12	**170**	336
Zhao K	36	133	**481**	Hauri CP	25	**141**	629
Linfield EH	60	95	**472**	Ducournau G	21	**139**	345
Davies AG	59	94	**470**	Rana S	17	**136**	201
Vicario C	14	125	**454**	Zhao K	36	**133**	481
Akyildiz IF	13	210	**438**	Nagatsuma T	22	**131**	311
Johnston MB	12	36	**430**	Habib MS	8	**126**	167
Bonn M	14	16	**427**	Hasanuzzaman GKM	8	**125**	173

*TGCS means that the authors are cited by authors in this field or studies out of the field; TLCS means that the authors are cited only by authors in this field, namely in the collected datasets (5767 records of papers from 2014 to 2018)

TABLE 7. Top ten countries of terahertz research ranked by Recs, TLCS, and TGCS.

Country	Recs	TLCS	TGCS	Country	Recs	TLCS	TGCS	Country	Recs	TLCS	TGCS
China	3182	6636	24872	USA	2461	19327	72611	USA	2461	19327	72611
USA	2461	19327	72611	Japan	1681	9372	31509	Germany	1237	8601	31691
Japan	1681	9372	31509	Germany	1237	8601	31691	Japan	1681	9372	31509
Germany	1237	8601	31691	China	3182	6636	24872	China	3182	6636	24872
UK	960	6415	23078	UK	960	6415	23078	UK	960	6415	23078
Russia	698	1472	8266	France	664	2839	12939	France	664	2839	12939
France	664	2839	12939	Australia	298	2730	7446	Russia	698	1472	8266
South Korea	513	2182	6692	South Korea	513	2182	6692	Australia	298	2730	7446
Canada	344	1844	6439	Italy	318	1915	7281	Switzerland	269	1892	7363
Italy	318	1915	7281	Switzerland	269	1892	7363	Italy	318	1915	7281

crystals [68], bolometers [69], [70], SBDs (Schottky barrier diode) and SIS (superconductor–insulator–superconductor) junctions are widely used as conventional THz detectors [31], [71], [72]. The topics also include the uni-travelling-carrier photodiode [73], [74] and THz single-photon detectors, which were developed using a single-electron transistor [75].

3) TERAHERTZ APPLICATION TECHNOLOGY

Terahertz time-domain spectroscopy, terahertz imaging and terahertz communication. ① Terahertz time-domain spectroscopy (THz-TDS) is a relatively new terahertz technology [76], a coherent detection technique, which mainly consists of femtosecond lasers, terahertz radiation generating devices and their detection devices, and time delay controller. It uses the terahertz transmission or reflection spectrum information of the sample, obtains the amplitude information and phase information of the terahertz pulse, and directly obtains the optical parameters such as the absorption coefficient and the refractive index of the sample by the Fourier Transform. THz-TDS has the advantages of wide bandwidth, high signal-to-noise ratio, high detection sensitivity, and stable operation at room temperature, so it can be widely used in detecting of a variety of samples. The THz-TDS can be divided into transmissive and reflective models, which can be used for both transmissive and reflective detection. ② Terahertz imaging technology [77], [78]: Since Hu and Nuss in the United States first established the world's first terahertz imaging device in 1995, many scientists have carried out research works such as electro-optic sampling imaging, tomography, and terahertz single-pulse time domain and near-field imaging. Typical transmissive

TABLE 8. Top 20 research institutions in the field of terahertz research ranked by Recs, TLCS, and TGCS.

Institution	Recs	TLCS	TGCS	Institution	Recs	TLCS	TGCS	Institution	Res	TLCS	TGCS
Chinese Acad Sci	**651**	1298	5242	Osaka Univ	328	**3424**	9593	Univ Cambridge	232	3102	**9846**
Osaka Univ	**328**	3424	9593	Univ Cambridge	232	**3102**	9846	Osaka Univ	328	3424	**9593**
Russian Acad Sci	**327**	738	4635	Rensselaer Polytech Inst	164	**2874**	9171	Rensselaer Polytech Inst	164	2874	**9171**
Tianjin Univ	**263**	484	1634	MIT	163	**2268**	7666	MIT	163	2268	**7666**
Capital Normal Univ	**254**	767	2232	Univ Adelaide	88	**1905**	4149	Tohoku Univ	245	1620	**5279**
Univ Elect Sci & Technol China	**248**	421	1999	Tohoku Univ	245	**1620**	5279	Chinese Acad Sci	651	1298	**5242**
Tohoku Univ	**245**	1620	5279	Univ Leeds	188	**1547**	4564	Russian Acad Sci	327	738	**4635**
Univ Cambridge	**232**	3102	9846	TeraView Ltd	57	**1445**	3634	Univ Leeds	188	1547	**4564**
Univ Leeds	**188**	1547	4564	Chinese Acad Sci	651	**1298**	5242	Sandia Natl Labs	90	1138	**4199**
RIKEN	**182**	1082	3407	Tech Univ Denmark	103	**1272**	3032	Univ Adelaide	88	1905	**4149**
Rensselaer Polytech Inst	**164**	2874	9171	Univ Marburg	89	**1252**	2900	Scuola Normale Super Pisa	71	1165	**4088**
MIT	**163**	2268	7666	Scuola Normale Super Pisa	71	**1165**	4088	Los Alamos Natl Lab	74	1025	**3847**
Huazhong Univ Sci & Technol	**158**	342	1226	Sandia Natl Labs	90	**1138**	4199	CALTECH	113	948	**3688**
Univ Tokyo	**150**	603	2823	Univ Calif Santa Barbara	84	**1107**	3651	Univ Calif Santa Barbara	84	1107	**3651**
Shanghai Jiao	**121**	172	1088	RIKEN	182	**1082**	3407	TeraView	57	1445	**3634**

terahertz imaging systems include femtosecond lasers, optical delay stations, optically gated terahertz emitters, terahertz beam collimation and focused optics, imaged samples, optically gated terahertz receivers, current preamplifier and digital signal processor. The basic principle of terahertz ray imaging is to use the terahertz imaging system to process and analyze the information recorded by the transmission spectrum or reflection spectrum of the imaging sample to obtain the terahertz image of the sample. Based on the unique properties of terahertz radiation, coupled with the ability to image in a reasonable amount of time, a large number of applications have been foreseen, such as biomedical diagnostics and packaged food products for water content monitoring and packaging, fault detection of integrated circuits and so on. ③ Terahertz communication: German researchers first discovered that terahertz waves can be used to transmit audio signals. This leads to the establishment of new high-speed, short-range wireless communication networks. The ‘‘terahertz communication’’ era means: the effective data rate exceeds 1 Tbit/s (usually with photocarriers) and terahertz

TABLE 8. *(Continued.)* Top 20 research institutions in the field of terahertz research ranked by Recs, TLCS, and TGCS.

Tong Univ								Ltd			
CNRS	**115**	810	3589	Los Alamos Natl Lab	74	**1025**	3847	CNRS	115	810	**3589**
CALTECH	**113**	948	3688	Univ Pecs	44	**967**	2292	RIKEN	182	1082	**3407**
Nanjing Univ	**113**	245	1308	Rice Univ	76	**957**	2791	Oklahoma State Univ	105	895	**3207**
Univ Tsukuba	**110**	570	2309	CALTECH	113	**948**	3688	Univ Montpellier2	95	721	**3206**
CNR	**107**	325	1956	Univ Freiburg	35	**920**	2458	Tech Univ Denmark	103	1272	**3032**

carrier communication. There are many reasons for making terahertz frequency communication more attractive, such as the utility of frequency bands and communication bandwidth. The potential applications of terahertz communication rely primarily on the practicality of effective continuous wave radiation sources, coherent detectors and regulators in this frequency range. The shortcomings of terahertz in communication are, the water vapor in the atmosphere has a strong absorption of terahertz radiation and the existing terahertz radiation source is very inefficient and the available power is relatively small, which restrict the development and application of terahertz in the field of communication.

B. CO-CITED REFERENCE NETWORK AND REFERENCES IN TERAHERTZ RESEARCH DOMAINS

Co-cited references and corresponding density mapping are visualized in Figure 3. Every node in the figure stands for a reference cited by the paper in our data collections. The node size is corresponding to the citation count of the paper, thus bigger size means high impact for the field.

We also collected the information (the corresponding labels and the corresponding references) for the Fig. 3. We can thus further understand the domain focal literatures, as seen in Table 9 and 10. In Table 9, the representative keywords are automatically extracted using the following methods, namely the Latent Semantic Index (LSI), Log-Likelihood Ratio (LLR), and Mutual Information (MI). They are based on the community detection methods working on the original co-cited reference network.

With the labels of the clusters, the domain focal references are briefly descripted, but the references are not clear, so we put each top three cited references in each cluster in Table 10. Note the top cited references are not same as the collected document using our searching conditions. They are the selected from the co-cited reference clusters, which contains more papers than the original dataset. Because every paper will cite 20 or more papers. The representative cited references are from these cited references, therefore, many of them are review papers.

By analyzing the literatures, we can find that the following disciplinary are related, thus THz research are being used in the following research domains:

1) BIOLOGICAL, MEDICAL, AND PHARMACEUTICAL SCIENCES

The use of THz spectroscopy for the study of biomolecules began in 2000. Tumor visualization for medical and biological are the current hot topics for applications research [83], [100]. THz imaging in the medical field and terahertz biomedical applications, including special neurons and blood chemistry monitoring and terahertz in the field of early diagnosis of skin burns or skin cancer, oral disease diagnosis, in vivo DNA identification and other fields were reported by researchers [70], [80], [101]. Prof. Fu Weiling, the director of the Laboratory, and his team used terahertz spectroscopy to achieve rapid detection of various clinical pathogens, with a detection time of 10 s, for clinical medical applications [78], [85]. In just a few years, THz spectra of various biomolecules of different classes such as nucleotides, sugars, DNA, proteins, and amino acids have been reported. Studies have shown that they have a sensitive spectral response to THz waves and have their own

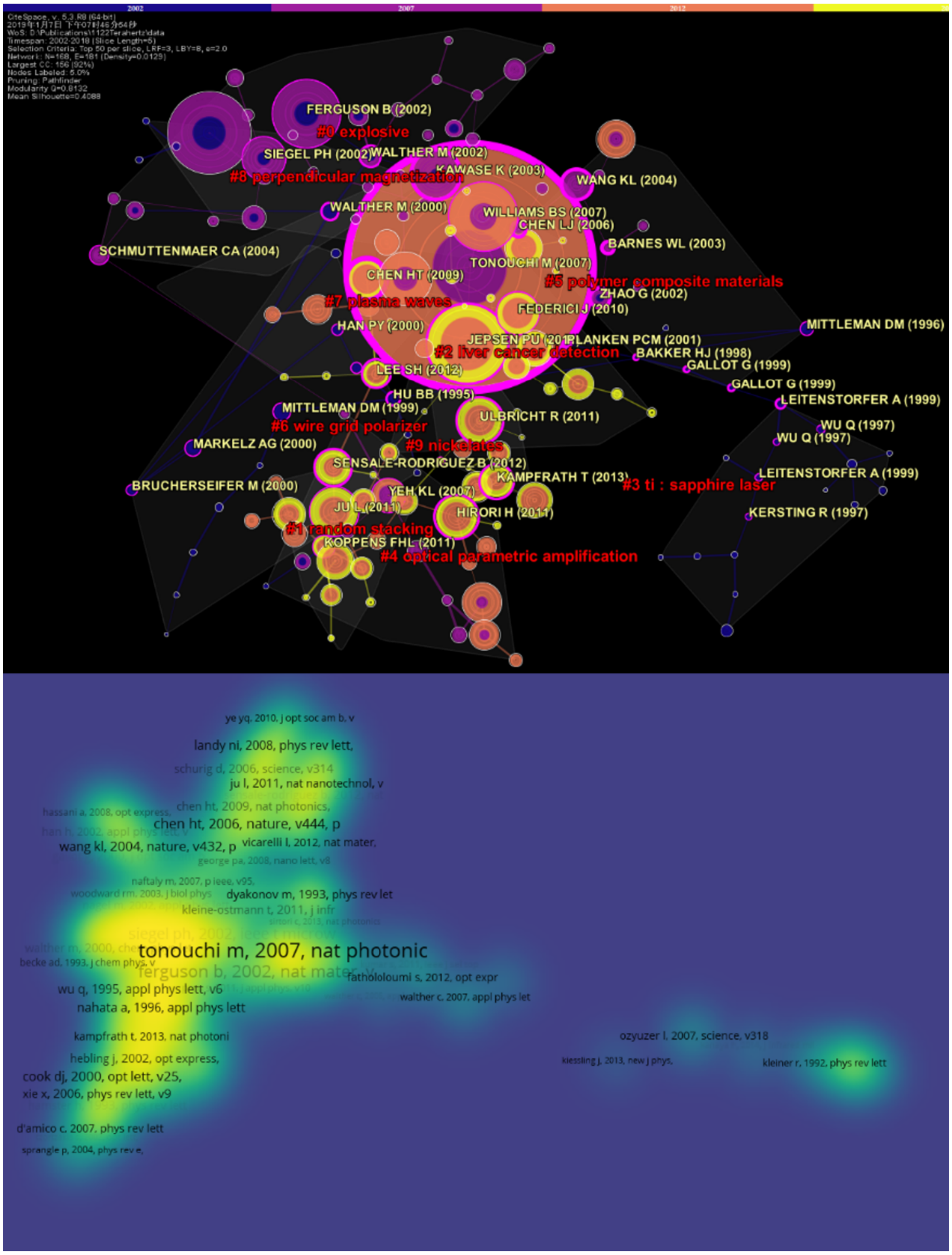

FIGURE 3. Co-cite references network and density mapping for THz research.

characteristic absorption in the THz band. The characteristic absorption mainly comes from the collective vibration mode of the molecules. THz spectra of nearly 20 protein amino acids and their chiral enantiomers, exocyclic compounds have been obtained, and one can already distinguish them using the THz spectrum of amino acids [78]. While obtaining the THz experimental spectrum of biomolecules, researchers are also seeking a theoretical explanation mechanism for the THz experimental spectrum, including the attribution of characteristic absorption peaks of the spectrum, their corresponding molecular vibration-transition modes and interactions between molecules, etc. Some quantum chemical calculation methods, such as density functional theory, ab-initio theory (HF), semi-empirical algorithm, etc.,

TABLE 9. The corresponding clusters in Fig 3. (Figure 3 use the mutual information as labels).

Cluster ID	LSI (latent semantic index)	LLR (log likelihood Ratio)	MI (Mutual Information)
0	terahertz; absorption coefficient;	graphene (40.21, 1.0E-4); terahertz time-domain spectroscopy (thz-tds) (34.1, 1.0E-4);	explosive (1.23); crystallographic etching (1.23);
1	terahertz; subwavelength structure;	graphene (129.95, 1.0E-4); broadband (30.12, 1.0E-4);	random stacking (0.5); nano-photonics (0.5);
2	terahertz; polarization splitter;	metasurface (40.36, 1.0E-4); polarization conversion (27.81, 1.0E-4);	liver cancer detection (0.99); noise floor (0.99);
3	thz radiation; emission efficiency;	coherent electromagnetic radiation (29.65, 1.0E-4); t-ray imaging (25.88, 1.0E-4);	ti : sapphire laser (0.1); large aperture (0.1);
4	terahertz waves; high-speed optical techniques;	light polarisation (23.58, 1.0E-4); multiwave mixing (23.58, 1.0E-4);	optical parametric amplification (0.23); high resolution (0.23);
5	semiconductor; carrier mobility;	birefringence (20.22, 1.0E-4); super-cell structure (17.31, 1.0E-4);	polymer composite materials (0.28); near-field scanning optical microscopy (0.28);
6	spectroscopy; device design;	thin films (65.13, 1.0E-4); thz time-domain spectroscopy (44.47, 1.0E-4);	wire grid polarizer (0.23); dispersion relation (0.23);
7	metamaterials; electro-optic modulators;	metamaterials (43.52, 1.0E-4); metamaterial (14.72, 0.001);	plasma waves (0.75); asynchronous optical sampling (0.75);
8	quantum cascade lasers; gallium arsenide;	quantum cascade lasers (51.37, 1.0E-4); quantum-cascade laser (27.37, 1.0E-4);	perpendicular magnetization (0.51); semiconductor superlattices (0.51);
9	terahertz spectroscopy; cw spectroscopy;	ultrashort pulse (10.68, 0.005); single cycle pulse (10.68, 0.005);	nickelates (0.32); optical frequency comb (0.32);

are used to calculate the vibration absorption spectra of molecules in the THz band. The results and the experimental results are mutually corroborating and provide spectral prediction outside the experimental effective spectral range [70], [80].

However, there are still some difficulties for current research in this area. In the research of biomaterials, most of the current research is directed to solid biomaterials, the purpose is to overcome the absorption of water in biological materials, and the activity of biomolecules is reflected in water environment [102]. The kinetics of water solution biomolecules learning process research is an important research topic with challenges. In terms of theoretical calculations, the single-molecule theoretical model has great limitations and cannot reflect the formation mechanism of solid-state THz spectra well. The ideal theoretical simulation of solid-state materials should take into account the effects of crystal structure and temperature [102].

2) INFORMATION AND COMMUNICATION TECHNOLOGY(ICT), SENSING AND COMMUNICATIONS APPLICATIONS, OTHER INDUSTRIAL APPLICATIONS, AND MILITARY APPLICATIONS

For the realization aspect of THz-ICT, several important events have happened. In August 2016, the China State Council issued the ''13th Five-Year National Science and Technology Innovation Plan'', and development and application of terahertz communication technology and corresponding silicon-based terahertz technology was included as one of the key development and breakthrough technologies. Large-capacity communication network, terahertz multiplexed data transmission test, ultra-high bandwidth wireless network communication and terahertz wireless technology are opening up a new field for wireless communication, its data transmission rate is 10 times that of current technology [96].

For sensing Terahertz TDS and FDS, analytical technological methods are applicable to various materials,

TABLE 10. Representative literatures in the clusters.

Cluster ID	Author	year	refs	
#0	Ferguson B	2002	[8]	explosive (1.23); crystallographic etching (1.23);
	Kawase K	2003	[79]	
	Siegel PH	2002	[80]	
#1	Ju L	2011	[81]	random stacking (0.5); nano-photonics (0.5);
	Sensale-rodriguez B	2012	[82]	
	Vicarelli L	2012	[44]	
#2	Federici J	2010	[83]	liver cancer detection (0.99); noise floor (0.99);
	Kleine-ostmann T	2011	[84]	
	Song HJ	2011	[85]	
#3	Sarukura N	1998	[86]	ti : sapphire laser (0.1); large aperture (0.1);
	Leitenstorfer A	1999	[87]	
	Huber R	2000	[88]	
#4	Hirori H	2011	[89]	optical parametric amplification (0.23); high resolution (0.23);
	Kim KY	2008	[22]	
	Yeh KL	2007	[90]	
#5	Chan WL	2007	[91]	polymer composite materials (0.28); near-field scanning optical microscopy (0.28);
	Wang KL	2004	[92]	
	Zhao G	2002	[93]	
#6	Mittleman DM	1999	[94]	wire grid polarizer (0.23); dispersion relation (0.23);
	Markelz AG	2000	[95]	
	Brucherseifer M	2000	[96]	
#7	Tonouchi M	2007	[6]	plasma waves (0.75); asynchronous optical sampling (0.75);
	Chen HT	2006	[9]	
	Chen HT	2009	[97]	
#8	Kohler R	2002	[7]	perpendicular magnetization (0.51); semiconductor superlattices (0.51);
	Williams BS	2007	[98]	
	Fathololoumi S	2012	[99]	
#9	Jepsen PU	2011	[13]	nickelates (0.32); optical frequency comb (0.32);
	Ulbricht R	2011	[26]	

research fields, including biology, pharmacy, medical science, industrial non-destructive evaluation, material science, environment monitoring, security, astronomy and basic science. Examples include DNA Chips, skin-cancer diagnosis, large-scale integrated (LSI) circuit testing, explosives inspection, and so on [76], [103].

The THz band of the electromagnetic spectrum has not been widely used, and the main reason is the lack of fabrication of transceiver technology and the attenuation of THz electromagnetic waves through the Earth's atmosphere is very serious [96]. The biggest advantage of THz sensors over infrared and visible light sensors is that they can break the maximum noise limit of the latter two. In the past few decades, THz sensors have become more practical than ever before because they have broken through many technical bottlenecks in making THz sensors [13], [26], [96]. First, THz detectors and mixer technology have been rapidly developed, including Schottky tunable mixers, superconductor-insulator-superconductor tunnel junction mixers, and superconducting bolometers. Second, THz solid state source technology and Schottky varactor frequency multiplier technology have also made amazing progress. Third, the auxiliary technology of THz sources in the millimeter wave and near infrared bands has also made great progress [13], [26].

At present, with the rapid development of terahertz wave generation and detection technology, terahertz spectroscopy and imaging technology are gradually shifting from laboratory research to practical applications in many fields, including safety imaging detection, aerospace, and explosive molecular detection [102]. The terahertz technology shows good industrial application prospects in the process supervision from the paper industry, to the remote measurement of opaque plastic pipes, to the detection of defects in semiconductor materials, and the analysis of chemical gas components [102].

Terahertz radars have wide application scenarios in military usage. Technically, compared with infrared radars and liars, terahertz radars have a wider field of view and better search capabilities, and have good ability to penetrate smoke and sand. They can be used to detect enemy's hidden weapons, camouflage ambush and Military equipment in smoky dust can achieve all-weather work. Compared with ordinary microwave and millimeter-wave radars, terahertz radars have shorter wavelengths and wider bandwidths. They have the advantages of strong information carrying capacity, high detection accuracy, and high angular resolution. Therefore, they have advantages in battlefield reconnaissance, target recognition, and tracking, having broad application prospects

Terahertz radar can be used as a fire control radar and precision tracking radar, because terahertz radar is suitable for short-range fire control systems because of its small size, light weight, and high maneuverability [13]. In addition, the multipath effect and ground clutter will adversely affect the low-angle tracking of the air defense artillery system. In this case, the narrow beam and high resolution of the terahertz radar show great advantages. Terahertz radar can also be used as a guidance radar and missile seeker, terahertz radar can obtain higher measurement accuracy and resolution, it is suitable for guidance radar, but because of its short range, it can usually only be used as terminal guidance [104]. Coupled with its weight and volume advantages, it is also suitable for missile seekers. This is one of the most promising applications for terahertz radars. One example is a 94 GHz air-to-surface missile seeker. Also, terahertz radar can be used as a battlefield surveillance radar. Terahertz radar has high angular resolution for ground mapping and target surveillance, it can obtain clearer radar imaging [105], so it can be used in battlefield surveillance radar. Lastly, Terahertz radar can be used as a low-angle tracking radar, because the terahertz wave multipath effect and ground clutter interference are smaller, microwave radar and terahertz radar can be used to implement detection and tracking [106]. Among them, microwave radar is used for long-range detection and tracking, and terahertz radar is used for low-angle track. In addition, terahertz radars can be used for space measurements of atmospheric temperature, water vapor, ozone profiles, and cloud heights and tropospheric winds.

3) EARTH AND SPACE SCIENCE, AND AGRICULTURE SCIENCE AND FOOD SAFETY

The Earth Observing System Microwave Limb Sounder (EOS-MLS) is equipped on NASA's Aura satellite. The EOS-MLS includes a heterodyne radiometer, an international astronomy facility, the Atacama Large Millimeter Array (ALMA). It will detect electromagnetic waves passing through atmospheric windows between 30 and 950 GHz. The monitoring could help probe the invisible dark universe [13], [98].

The agricultural and food (agri-food) industry plays an essential role for human life, as agri-food products are directly related to people's health and social development [27], [102]. The potential of THz technique in agri-food industry has been shown in several aspects such as agricultural bio-molecular material detection, quality and safety detection of agricultural products, physiology inspection of crops and pollutions detection in agricultural environment, which revealed its great potential and application prospects of terahertz technology in agro-food field [102]. With the rapid development of ultra-fast laser circuit hardware, terahertz technology has been greatly developed in agricultural fields such as agricultural products quality, farmland environment and agro-botanical, due to its unique optical-electrical properties, and has achieved certain research progress. As a result, in-depth study of the interaction mechanism between terahertz waves and substances to be detected is a prerequisite for understanding and applying terahertz technology [102]. However, there are still some challenges for the application in this area. Agricultural biological tissues generally have water-containing characteristics, while terahertz waves have strong sensitivity to moisture, so the requirements for the detection environment are quite high, and the environment must be kept dry and clean. Further research work is needed to achieve high-precision, fast-loss measurement of agricultural applications.

4) RECENT DYNAMIC FROM 2014 TO 2018

Moreover, the bibliographical coupling networks are also collected by considering the recent academic dynamics. As shown in Figure 4, the recent activities are depicted in a different way of Figure 3, using the papers in the 5756 records from 2014 to 2018 as the nodes and the similar reference as the relations. So the figure gives a close look at the recent dynamics.

The colour density corresponds to the citation count of the paper named with name and year. From green to yellow, the citation counts increase. Moreover, the clusters are identified in the network view, eight colours including green, yellow, light blue, deep blue, purple, red, orange, and pink are shown in the figure. Green cluster includes the work

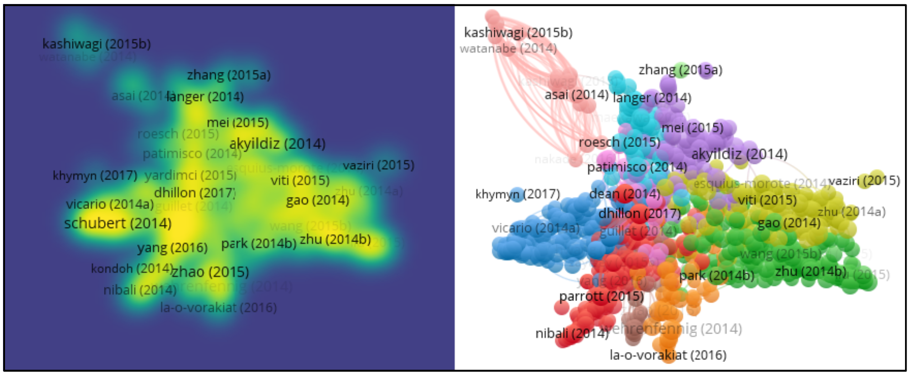

FIGURE 4. Bibliographical coupling network and density mapping for THz research from 2014 to 2018.

on the topic of Quantum cascade lasers [41], [107]. Yellow cluster includes the work on the topic of Terahertz Photodetectors [62], [108]. Red cluster include the work on the topic of Terahertz Raman Spectroscopy [109], [110]. Light blue cluster includes the works on the topic of Photoacoustic Spectroscopy [111], [112]. Deep blue cluster include the works on the topic of terahertz high-harmonic generation [113], [114]. Orange cluster includes the works on the topic of Power Conversion Efficiencies in terahertz research [115], [116]. Purple cluster includes the works on the topic of terahertz band for communication [117], [118]. Pink cluster includes the work on the topic of generation of electromagnetic waves [119], [120].

From the perspective of terahertz instrument itself, increase basic research and key technology breakthroughs, and the adoption of low-cost CMOS and new materials may reduce the cost and improve the performance; From the perspective of terahertz application, it is also possible to reduce the cost by strengthening application exploration and realizing large-scale application by finding 'killer applications'.

High power terahertz radiation sources and the research and preparation of high sensitive terahertz devices focus on developing the function of new materials, new technologies of terahertz devices and high power, low cost, portable, thus can work at room temperature of terahertz radiation source. The trends require all kinds of new type of terahertz applications, and open up more potential usages, promote the transition from laboratory to commercial, so the study of terahertz new materials will also allow greater attention. Predictably, with deeper and broader new materials, new technology to infiltrate the terahertz field, research and development will focus on the function and the direction of miniaturization, intelligence, integration. The promotion of terahertz science and technology will play a role of business research and broaden its application scope. If the terahertz technology application development becomes easier, the value will also be constantly in the new application scenarios. Terahertz science and technology development will surely bring more opportunities.

V. CONCLUSION

Several bibliometric methods are applied. Some conclusions can be drawn as follows:

1. The publication trends are in an upward, the year of 2011 has the largest TGCS, meaning that the most high-impact publications are published in this year, **Fig. 1**.
2. The top active journals include Applied Physics Letters and Optics Express, **Table 1;** however,in term of the domain recognition, Optics Express, Optics Letters, and Applied Physics Letters are the top most recognized journals, **Table 2**.
3. Many authors are active in this emerging field, Zhang XC, Linfield EH, and Davies AG are the domain recognized authors. And these three authors also have very high impacts in term of all-science community, **Table 5**.
4. Countries worldwide are actively working in this field, with China publishing the largest number of papers, but USA has the highest TLCS and TGCS, followed with Japan (having second largest TLCS and third largest TGC and Germany (having the third largest TLCS and second largest TGCS), **Table 7**.
5. Representative institutions in this fields like Osaka University and University of Cambridge having the largest TLCS and TGCS, respectively. Chinese Academy of Science is also a representative institution publishing the largest number of papers in this field in term of the institution, **Table 8**.
6. This work analyzes the literature in several different research directions using the co-word network and co-cited reference network. The research directions include THz sources, Terahertz detectors/sensors, Terahertz spectroscopy and imaging based on the co-word network analysis, **Fig 2**. From the co-cited references network, the research is studied from the perspective of disciplinary or application level, including biological, medical, and pharmaceutical sciences; semiconductor and other industrial applications; semiconductor and other industrial applications; earth and

space science; basic science; agriculture and food safety; sensing and communications applications, **Fig 3 and Table 9**.

For a long period of time, one of the obstacles in the application of terahertz technology is that the equipment is complicated and expensive, and the information acquisition, analysis and processing technology needs to be further put into practical use. In general, terahertz technology research is still in its infancy, especially in biomedical applications, and it still has great difficulties. Its interaction mechanism with substances needs to be further studied. At present, the cost of terahertz equipment is gradually decreasing, and equipment is developing toward low cost and miniaturization. Small terahertz devices have emerged on the market, which have laid the foundation for practical and feasible candidates for the applications of terahertz technology in the agricultural sector.

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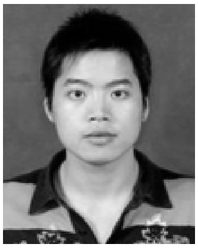
BIN LI received the Ph.D. degree from China Agriculture University, Beijing, China. He is currently an Associate Research Fellow working with the Beijing Research Center for Information Technology in Agriculture and the Key Laboratory of Agri-Informatics, Ministry of Agriculture, China. He has been a Master Tutor. He has authored over 30 articles in related journals. His researches primarily focus on terahertz spectroscopy, image recognition, and machine vision technology.

KAI HU received the Ph.D. degree from Wuhan University. He is currently working as a Lecturer with the School of Internet of Things, Jiangnan University. His research interests include geographical information science, library information science, and scientometric. He has published ten articles in the related journals.



YIN SHEN was born in Sichuan, China, in 1987. He is currently pursuing the Ph.D. degree with the College of Engineering and Technology, Southwest University, Chongqing. He is also a joint Training Student with the Beijing Research Center for Information Technology in Agriculture. He has authored over ten articles in related journals. His main research interests include computer vision, deep learning, and image recognition.