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TRENDS IN RESEARCH RELATED TO PHOTONIC CRYSTAL (PHC) FROM 2009 TO 2019: A BIBLIOMETRIC AND KNOWLEDGE MAPPING ANALYSIS

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Abstract

Photonic crystals (PhC) are a periodic structure of two different materials with a unique photonic bandgap that results in advantageous properties for wide applications. The utilization of PhC is spread to various fields and subjects, making it is hard to trace the progress and knowledge. Bibliometric studies have been done in this research to investigate the evolution of PhC-related research over the past decade (2009 – 2019) using the academic online search engine and databases Scopus (Elsevier). The VOSviewer tool was used to support the data analysis of these emerging fields. Scopus's screening process obtained one hundred seventy-five publications related to the PhC topic. Generally, the PhC topic in Scopus included the "Physics, Materials Science and Engineering" subjects. Keywords of finite difference time domain method, waveguide, and refractive index primarily used in the articles indicate the strong correlation. PhC research receives many contributions from countries and communities around the world. It also builds connections, especially for China as a leader in this research. Old developments have prepared photonic crystals for existing and new applications.

Keywords: Bibliometrics, Knowledge mapping, Photonic crystals, Scopus, VOSviewer.

1. Introduction

Photonic crystal (PhC) is a periodic structure of two materials with different dielectric constants, along with one-, two- or three-dimensional space. The PhC has an energy band structure called photonic bandgap (PBG), which selects a specified range of frequencies forbidden to propagate through its structure.PBG structures allow the light to travel through the periodic structure over a specific photon energy range.

Struktur PBG memungkinkan cahaya untuk menjalar melalui struktur periodik pada rentang foton energi spesifik tertentu, namun dipantulkan kembali ketika menubruk kristal dan tidak dapat melakukan perambatan. The PBG structure creates a forbidden zone where light can travel through the periodic structure over a defined photon energy range and is reflected and not allowed to propagate when it is impinging the crystal. This property resulted from the scattering of light interference from the lattice plane. This property resulted from the interference of light scattered from the lattice plane. The periodic modulation of refractive index in PhC is similar to electrons and holes in an atomic lattice in a solid. The first experimental work in 1991 showed that the use of a series of drilled holes in a high refractive index material creates a blocking band that does not allow transmission in that frequency range. [1]. The overall structure of the PBG is a three-dimensional periodic structure that suppresses spontaneous emission in the electromagnetic bandgap. Since then, new designs have been developed and innovated based on this concept. However, improving the overall performance of this device remains a major concern for the full functionality of the device, with performance limits imposed by various manufacturing processes [2]. Theoretically, the photonic band structure can be designed using the calculation of particle wave function in solid-state. It leads to understanding different structures and designs of PhC, which can be used for wide applications.

Yablonovitch [2] and John [3] have proposed independently the concept of PBG structures. Recently, PhC has attracted a lot of attention from researchers through various PhC structures reported in the literature [4-11]. PhC that exhibits strong optical confinement within a small volume is required and has been used in waveguide technology due to its simple structure [1]. In addition, a line defect in the PhC slab provides low loss, which can be advantageous for waveguides in multi-Gbit/s THz communication [12]. Yu et al. [13] have reported PhC waveguide in 0.3 THz bands, exhibiting loss lower than 0.1 dB/cm. It significantly reduces losses through using metallic transmission lines [14]. Furthermore, the PhC in the communication field can use light-source by embedding the light-emission materials into the PhC structure to increase the radiative recombination of charge carriers to control their radiation [15, 16]. The PhC cavity is effectively used to obtain high-frequency tuning efficiency and large rejection ratios, which are significant to on-chip microwave system development in tunable microwave photonic filters [17, 18]. In addition, the PhC has also been widely used in third-generation of photovoltaics because of its unique and beneficial property of PBG and slow photon effect. The distribution and propagation of photons in solar cells can be adjusted by the presence of PhC [19]. High performance of PhC-based solar cell reported in power conversion efficiency (PCE) as 17.58% for nano-disc array [20], 10.5% for hemisphere structure [21], and 15.9 % for inverse opal structure [22]. Besides PhC application for light communications, it can also detect environmental and biological molecules [23]. PhC cavity structures are sensitive to the refractive index change. Therefore, PhC cavity becomes a potential sensor device with high sensitivity and accurate detection limit [24].

The overview above indicates the challenge for researchers to identify the track record of research and development in PhC. It became more difficult to follow the research progress on PhC topics due to increased publications over the last decade. The assessment towards growth and impact of a research topic in PhC is very important for an institution or research group in planning, financing, recruiting, and other preparations related to research continuity. The Industrial Revolution (IR) 4.0 era can facilitate the research to be mapped easily due to the availability and accessibility of digital data on the published articles. Several databases and search engines provide services in finding and accessing journals, institutional repositories, archives, or articles in other academic articles or other articles collections. Examples of well-known and widely used educational resources are Scopus, Web of Science, PubMed, ERIC, ScienceDirect, IEEE Xplore, DOAJ, and JSTOR. Identification of 16 conceptual frameworks or models to identify the research impact assessment has shown that bibliometric analysis is involved significantly in most models [25]. Bibliometrics has become a widely used method for studying the development of a particular subject [26, 27]. The bibliometric information was quantitatively analysed using both mathematical and statistical methods. The mentioned information included the number of publications, the number of citations, h-index, and measures of publishers and authors involved in the topic [28]. Bibliometric analysis has been widely used in many fields such as science, engineering, and technology [29], medical [30], environmental [31], industry [32], social [33], linguistic [34], and business [35].

In this work, we proposed studying and identifying the progress and direction of photonic crystals-related research using bibliometric analysis and visualization. The data are provided by abstract and citation databases, namely Scopus. VOSviewer as the bibliometric analysis tool was used since it has been well-reported in many papers [36-39]. The trend, distribution, contribution, and correlation related to the PhC research have been reported to explore the characteristics of this area.

2.Method

A holistic study was used to summarize the research output in the topic of PhC published in abstract and citation databases. Scopus is one of the primary citation data besides the World of Science (WoS) suitable for scientometric analysis. Scopus was identified as a database with ~40% coverage in natural science and engineering, which is ~5% better than WoS coverage. The vast country distributions of authors were also found in the publication databases from Scopus [26, 27]. The entire article screening process was comprised of four steps. Firstly, we inputted the topic of "photonic crystals" into Scopus and set the limitation time publication from 2009 to 2019. Next, a total of 411 articles were identified covering different disciplines such as engineering, materials science, physics and astronomy, energy, computer science, and mathematics. Lastly, we conducted the second round of screening to distinguish the 411 articles of several works of literature, including reviews, conference papers, journal articles, books, and others. A total of 212 journal articles have been chosen as a sample for analysis in the next step of literature screening. Lastly, out of 212 articles, we conducted the third screening, which only contained photonic crystals, photonic crystals, and 2-D photonic crystals in the title, abstract, or keywords. Thus, 175 identified articles will be used for the sample in the discussion.

Science mapping is essential in bibliometric analysis to represent the developmental status and situation of the discipline. VOSviewer software which Centre developed for Science and Technology Studies, Leiden University, Netherlands) was used for the science mapping procedure in this study. VOSviewer displays the size of nodes to visualization the data. A node symbolizes the input data. The frequency of the data is represented by the node and the word size which is a larger node, and the word describes that the data is contributed evenly and is widely related to research. Nodes of a similar colour belong to the cluster to simplify the search process. The line between two or more keywords means they appeared together in the publication. The thicker the line, the more often it will occur at the same time. The nodes with the same colour belong to a cluster to make the searching process easier. The line between two or more keywords represents that they have appeared together in the publications. The thicker line is visualized, the more co-occurrence between them. This paper used VOSviewer to map the keyword analysis, co-author contributions, and country contributions. On the other hand, the subjects, citations, journal publishers, authors affiliations, and funding sponsors data obtained from Scopus were processed using Microsoft Excel (Microsoft Corporation, United States) to display a table and line chart for easier distribution analysis.

3. Result and Discussion

3.1. The current status of PhC study

In this section, the current status of the PhC study was discussed through the analysis of annual trends of publication, distribution of journal publisher and related subject, and the citation analysis to show the impact of the articles.

3.1.1. The annual trends of PhC publication

Figure 1 shows the annual trend of PhC-related publications in the last decade (2009 – 2019). The graph shows a fluctuating number of annual publications; however, the trend seems to increase through half decades. The highest recorded publications were obtained in 2016, with the silicon-based PhC becoming the most topic in demand. However, this number has decreased by half in 2017 and fluctuate in the following years. It cannot be disputed that the number of publications would leap given the growth not yet completed by referring to the previous patterns, and the application is already a lot.

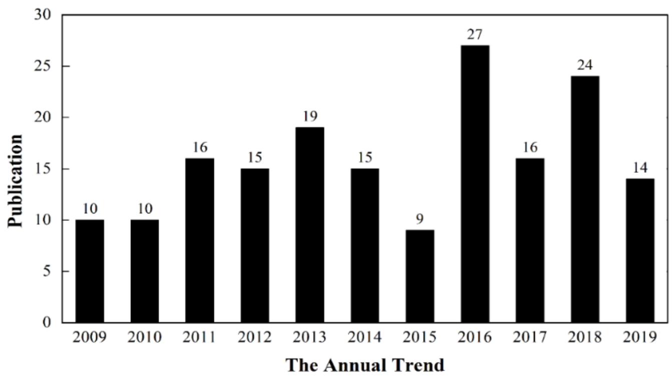


Fig. 1. The annual trend of PhC-related publications between 2009 and 2019.

3.1.2. The distribution of journal publisher

All 175 articles with related keywords of 'photonic crystals' were published in 90 journals. A total of 69 articles which are 39.42% of them were published in the top 10 journals, while the 106 remaining articles were spread in 80 journals that published no more than 1 to 2 PhC-related articles. The top 10 journal publishers are shown in Fig. 2 which as many as 7 of them are journals with the title 'optics' indicating their main subject. Considering that this is an approach to manipulating light, then the existence of PhC in optics journals is fair due to the strong correlation between topics. Only the top 3 journals have published more than 10 papers, namely Optics Express, Optik, and Optics Communication. The PhC topic is highly accepted for publication in prestigious journals indicated by the high quartile, namely Q1 (Optics Express), Q2 (Optik), and Q2 (Optics Communication), with a high cite-score are 6.7, 3.7, and 4.1, respectively.

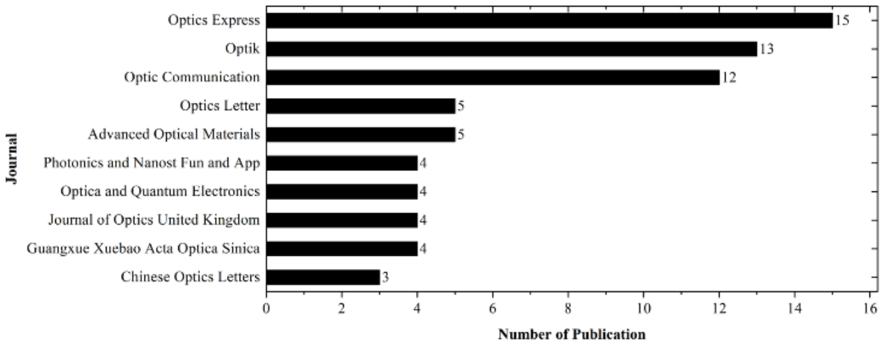


Fig. 2. The top 10 journals with PhC -related publications.

3.1.3. The distribution of related subject

The 175 articles related to this topic were categorized into 15 subjects, where the top 10 subjects are shown in Fig. 3. The majority of every PhC study belongs to Physics and Astronomy as physics is the fundamental study for these topics. The second and third subjects, namely materials and engineering, represent the main topic of study, where the majority is discussed in designing and fabricating the materials and their structures. Meanwhile, the last 7 subjects can be concluded as the target applications described in the introduction as these subjects are closely related to the application of PhC in waveguides, filters, light sources, photovoltaics, and sensors. Due to the high number of publications with subject Chemistry (23), Chemical Engineering (6), and Biochemistry (5), we can predict that PhC applications are mainly used for sensors development.

3.1.4. The citation analysis of impactful publication

The number of citations reflects the quality and impact of the papers [40]. Figure 4 shows 10 articles with the highest citation as the data obtained from Scopus, where the four highest cited articles exceed 100 citations each. By averaging the number of citations of these 10 papers, the citation rate obtained is around 74 citations. Aksnes et al. describe 15 reasons the publication to be popularly cited. Some of these are described in the background of the study, explanation of methodology, mentioning the pioneers, identifying original publications, and giving credit for corresponding work [41].

Figure 5 shows that the citation rate is also influenced by the journal publisher cite-score apart from quality and papers information and suitability. For example, Wu S et al. and Nam Y et al. has published an article entitled "Control of two-dimensional excitonic light emission via photonic crystal" and "Solar thermophotovoltaic energy conversion systems with two-dimensional tantalum photonic crystal absorbers and emitters" in 2D Materials and Solar Energy Materials and Solar Cells journals, respectively. Both papers have gathered a lot of citations that could be influenced by specific compatibility of topics and published in high cite-score of the journals.

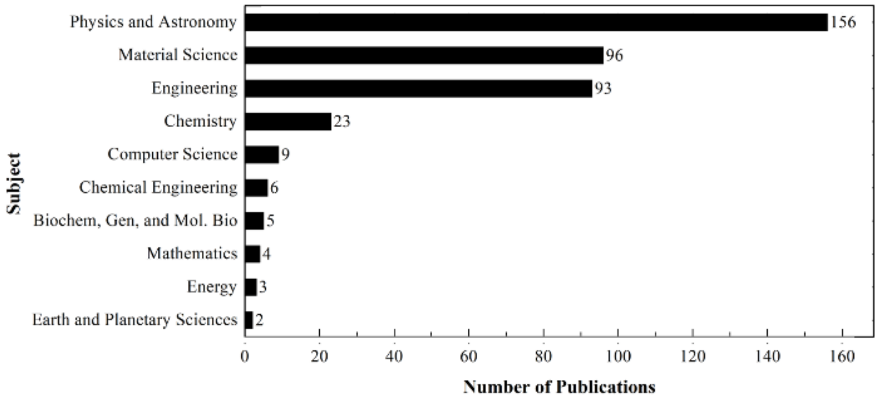


Fig. 3. The top 10 subjects related to PhC publications.

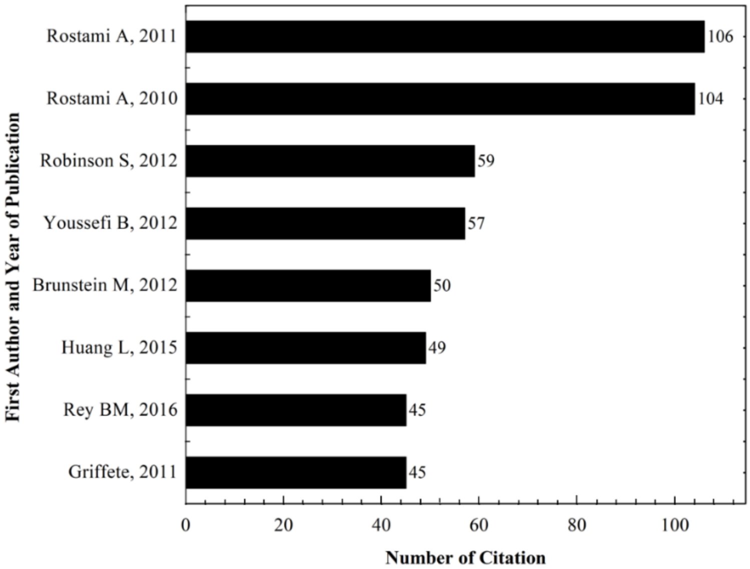


Fig. 4. The top 10 cited PhC articles, identified by the first author and year of publication.

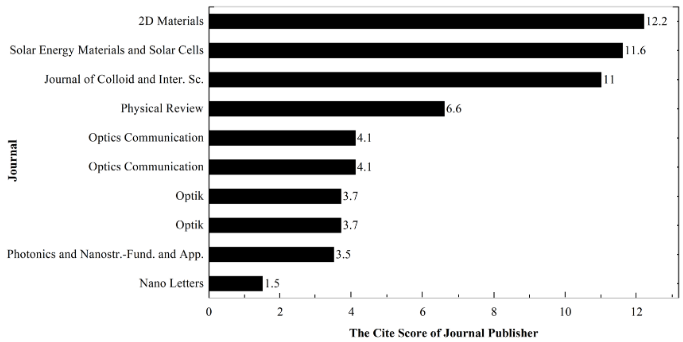


Fig. 5. The cite score of journal publisher of top 10 cited PhC article, the journal (down to top) related with the article (right to left) in Fig. 4.

3.2. The keyword analysis of strong correlation of PhC study

The distribution of keywords has been analysed to study this topic. In this section, several keywords will be discussed including, the co-occurrence network map, the top 10 keywords in PhC publications, the keywords density visualization map, and the keywords timeline view. These visualizations were obtained using VOSviewer with the following settings: minimum number of occurrence of keywords 5; the number of keywords 1768; and the threshold 97. VOSviewer has divided the keywords of PhC-related publications into 6 clusters. The result is shown in Fig. 6 and listed in Table 1 with a description of the frequency and link strength to indicate the keyword attachment to the PhC research topic. The keyword "photonic crystals" has the highest frequency of 167. Other keywords with the highest frequency included "finite difference time domain method" (61), "photonic crystal"(51), and "time-domain analysis" (42). But the frequency of occurrence does not affect the link strength of other keywords. Based on its frequency, the word "photonic crystals" has a link strength of 1081, which indicates domination, while the words "photonic crystal" have a weak link strength (370) compared to the keyword "time-domain analysis" (395), which has a lower frequency.

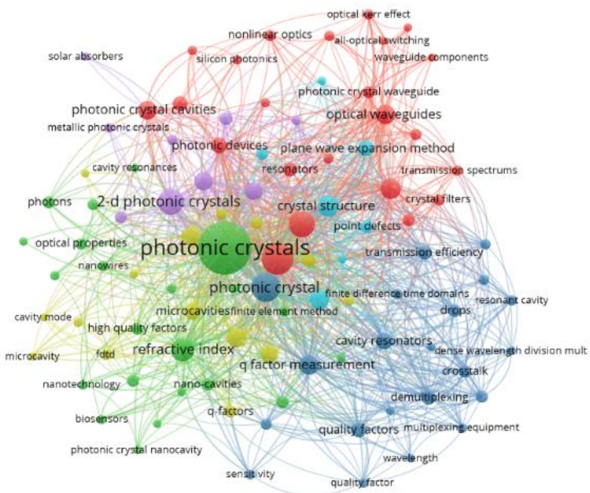


Fig. 6. Keywords co-occurrence network of PhC-related publications.

Table 1. The top 10 keywords of the PhC -related publications.

Rank	Keywords	Frequency	Total Link Strength
1.	Photonic crystals	167	`1081
2.	Finite difference time domain method	61	551
3.	Time-domain analysis	42	395
4.	Photonic crystal	51	370
5.	Refractive index	33	285
6.	Waveguides	26	258
7.	2-D photonic crystals	42	254
8.	Q factor measurement	24	221
9.	Optical waveguides	23	213
10.	Two-dimensional photonic crystals	24	213

The co-occurrence or the condition where two or more keywords appeared simultaneously is indicated by a line that connects them. Thus, thick lines visualize more frequent occurrences between them [42]. The total link strength of a node is the sum of the link strengths of that node compared to other nodes [43]. The node, "photonic crystals", has thicker lines with "finite difference time domain method", "time-domain analysis", "photonic crystal", "refractive index", "waveguides", "2-D photonic crystals", "q factor measurement", "optical waveguides" and "two-dimensional photonic crystals". These are all nodes with a link strength of over 200 links. The relationships between "photonic crystal" and "2-D photonic crystal" and "two-dimensional photonic crystals" indicate that the two-dimensional structure of PhC gets most of the attention as compared to 1D and 3D. While the link between "photonic crystal" with "finite difference time domain method" and "time-domain analysis" implies its popularity, that can be used to predict the effectivity of the FDTD method for PhC simulation.

3.3. The co-authorship contribution on PhC study

The research project needs strong collaboration to finish and perform significantly. Cooperation in research is significant for the quality of publication as a product and beneficial for the contributors as the authors themselves, the affiliation, the funding institution, and the country. This section discussed the involvement of these elements in photonic crystal's research progress. The analysis is discussed using network visualization from VOSviewer completed by a line chart.

3.3.1. The author contribution and collaboration analysis

The author's contribution to PhC-related research is shown in a line chart in Fig. 7. The authors' contributions are counted from their published papers obtained from Scopus databases. This chart only displays the top 10 authors, and only four authors exceed the number of publications more than three times. The majority of authors have published three papers or fewer related to PhC topics. These authors might be collaborating with other co-authors. This relation can be seen in the co-author collaboration network in Fig. 8.

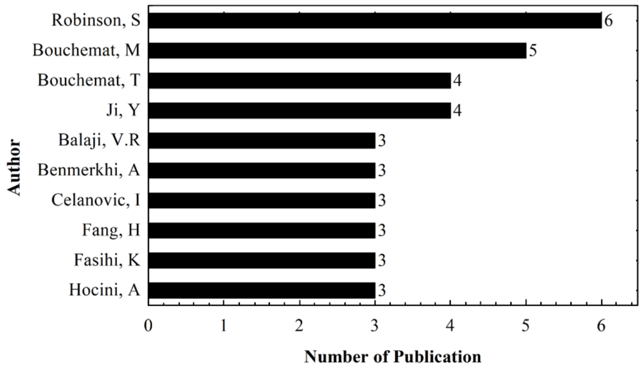


Fig. 7. The top 10 authors contribution in PhC -related publications.

Based on PhC analysis using the co-authorship VOSviewer, the search results have identified 667 authors' names. The minimum threshold for publication for each author is three papers, of which twenty-six authors were included in the threshold. From this analysis, nine clusters were obtained illustrated by different colours of nodes and links.

Figure 7 shows that several authors including Wang Y, Li J, Robinson S, Bouchemat T, and dan Bouchemat M are represented by large nodes, indicating high research productivity. This collaborative network for co-authors reveals the most prolific PhC researchers in the analysed publication collection and maps the diverse research groups that these authors formed through clusters of different colours. Li J. became a connector between the two clusters where the Wang Y, Song Y, Li H, Wang X, Fang H, and Zhao J clusters were united through one of the joint studies with the Qin Y, Hu W, Ren H, Jin Y, and Jiang C clusters. Meanwhile, a separate researcher, such as Fasihi K, Sun Y, and Celanovic, does not mean that they do not have a group, but they only collaborate internally.

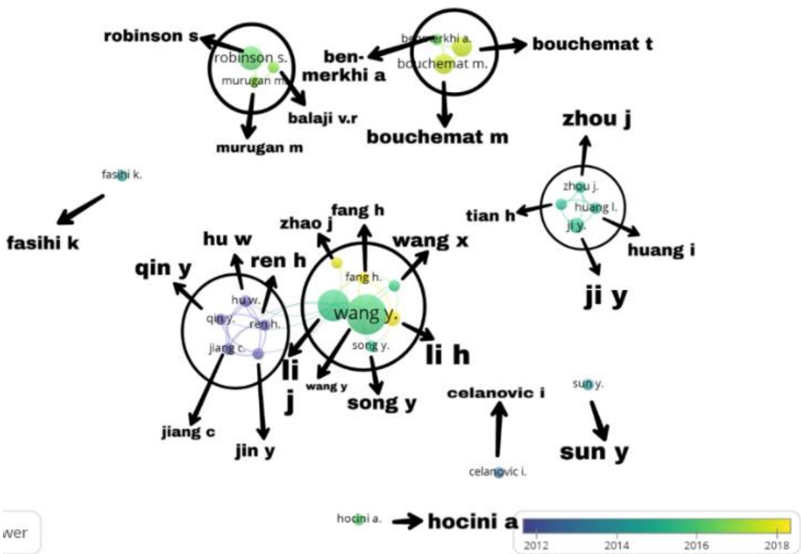


Fig. 8. Co-author collaboration in PhC-related publications.

3.3.2. The affiliation co-authorship analysis

The top 10 contributor affiliation in PhC research is shown in Fig. 9. Four institutions from China included on the list are the Institute of Semiconductor Chinese Academy of Sciences (1st), Beijing University of Posts and Telecommunication (2nd), Shenzhen University (4th), and Huangzhong University of Science and Technology (8th). They correlated and influenced each other's results in this section, which shows China at the top. Other countries included in the top 10 contributor's affiliation are Iran, France, Italy, and Japan.

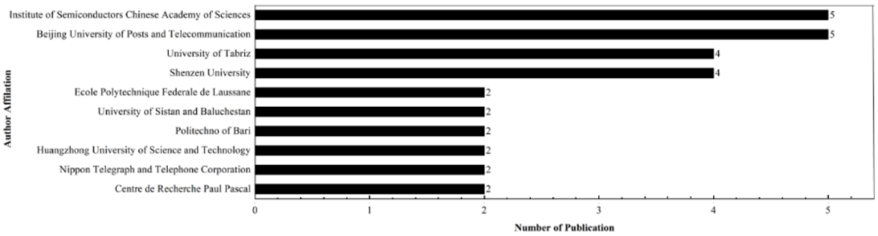


Fig. 9. The top 10 affiliations of authors correspond to PhC -related publications.

3.3.3. The funding sponsor analysis

The funding or sponsor has a significant influence on the productivity of the research. Figure 10 shows that China is the main contributor to PhC-related studies because four of the top five are China-based institutions. China's natural national science foundation contributes six times more than the average contribution of other institutions, showing the enormous role this institution plays in developing PhC studies, especially in China. Other countries included in the top 8 funding sponsors are the United States, United Kingdom, and Japan.

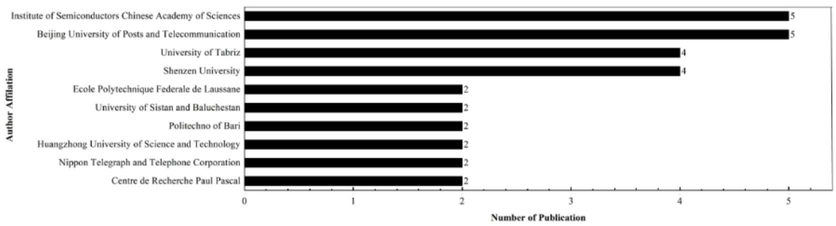
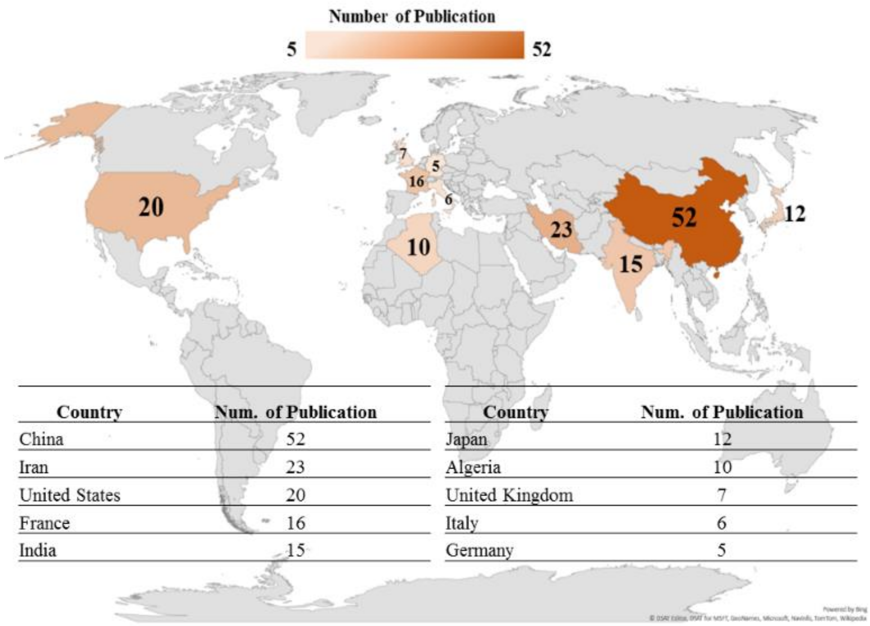


Fig. 10. Institution collaboration in funding PhC -related publications.

3.3.4. The country co-authorship analysis

The country co-authorship reflects the information disclosure and the communication domestically as well as between two or more countries. The distribution of the top 10 authors from countries that publish PhC -related papers can be seen in Fig. 11. The grey field on the map indicates the low contribution of a country that publishes not more than 4 articles throughout the years from 2009 – 2019. Only 5% country has a high contribution to the PhC research shown in orange. China occupies the top position as the country with the most PhC publications with 52 papers. The result is associated with the most contributed funding sponsor in the previous section.



Country	Num. of Publication	Country	Num. of Publication
China	52	Japan	12
Iran	23	Algeria	10
United States	20	United Kingdom	7
France	16	Italy	6
India	15	Germany	5

Fig. 11. The top 10 countries of authors correspond to PhC-related publications.

In Fig. 12, the massive PhC research in China is also proven by the country collaboration network obtained from VOSviewer. Large nodes represent influential countries. The relationship between nodes defines the cooperative relationship between institutions. The distance between nodes and the thickness of the link represents cooperation between countries. China has a lot of collaboration with other top 10 countries, intense with the United Kingdom, Italy, France, and Algeria, and strong enough with the United States. It clearly shows the strength of China to be the top country. In other words, we can conclude that international collaboration is one of the critical high publication rates.

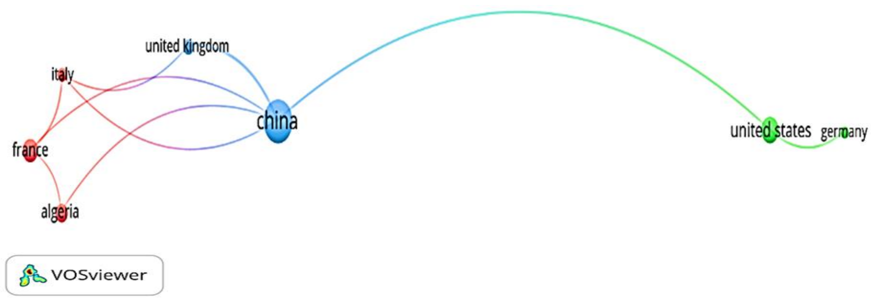


Fig. 12. Country collaboration network to PhC-related publications.

3.4. Future perspectives

Our study aims to investigate the current status, scope, and co-authorship contribution and collaboration of photonic crystals-related research. The result can be used as an overview for researchers and institutions to consider the future research plan and policies. The bibliometric study showed throughout the years 2009 – 2019 with increasing interest in PhC from the researcher and publishers. The current status of the PhC study has shown growth potential, although the number of publications reduced last year. The acceptance rate from high quartile publisher journals is one of the supporting factors of increment, influencing the number of publications and the citation rate, which shows a connection between each article. Photonic crystals represented the most in the "Physics", "Materials Science" and "Engineering" category in Scopus, the subject related to its application placed as a secondary subject. The range of research can be seen from the high-frequency keyword. The "photonic crystals" seem to show the trends to simulation using "finite difference time domain method" and "time-domain analysis" methods. The development of "2-D photonic crystals" was directed to the "refractive index" based sensors and "waveguide" applications. Community collaboration is proved as an influencing factor for PhC -related research. China showed a massive contribution from each element, such as author, institution, and founding sponsor, resulting in its country becoming the most productive in PhC - related publication.

From these results, we can predict the future in the development of photonic crystals: (1) Firstly, this research has the possibility of continuing the current trends in sensors and waveguides application. The medical sensors market is projected to increase by 6.8% in 2020 – 2025. The key drivers responsible for the growth of this market include the increase of technological advancement in the medical device industry, increasing government concerns and support in medical technology development, growing geriatric population, increasing demand for home-based medical care, and advances in portable mobile-connected devices need. The photonic crystal is a potential principle to build an ultrasensitive, robust, and re-useable optical biosensor. The PhC waveguide significantly reduces the loss by around ~200% compared to the conventional device, where this performance is advantageous towards the development of terahertz devices [14]. In addition, the terahertz technology market is expected to grow at a CAGR of 31.83% to reach USD 489.8 Million by 2022. The growth of the terahertz technology market is driven by the increasing awareness about modern laser technologies and high-power electronic emitters using optoelectronic approaches. Specifically, increasing demand for terahertz technology-based products from the homeland security and medical sectors contribute to the laboratory research applications which can highly adapt to these products. (2) Secondly, the study may be shifted to the new trends of research application where photovoltaics is one the field with the greatest possibility due to its emergence of the "solar absorber" keyword in the list. The photonic crystals provide valuable property for third-generation solar cells such as perovskite solar cells [19]. It can be performed in one or more layers in the solar cell, namely the transport electron layer, solar absorber layer, and back reflector layer [19]. Therefore, in future research, the development of photonic crystals-based solar cells is increased significantly as its global solar energy market was valued at $52.5 billion in 2018 and to meet the demand, which is projected to reach $USD 223.3 billion by 2026, with growth at a CAGR of 20.5% from 2019 to 2026.

While some interesting results have been obtained from bibliometric analysis and visualization of photonic crystals, this study has some weaknesses. The volume of the retrieved publications (175) was very low to depict clear trends. Secondly, we only record the last decade of publication while the concept of photonic crystals is known first published in 1987. A complete data analysis will be better to include the entire span of the years. Lastly, the downloaded documents from Scopus with most of the articles were written in English, leading to an unaccountable publication from other languages.

Many reports discussed on bibliometric analysis, such as

(i) Digital learning [28]

(ii) Computer science [44]

(iii) Vocational school [45]

(iv) High school [46]

(v) Covid-19 research [47]

(vi) Scientific publications [48]

(vii) Chemical engineering [49]

(viii) Materials research [50]

(ix) Special Needs Education [51]

(x) Publication of Techno-Economic Education [52]

(xi) Engine performance [53]

(xii) Dataset portrays decreasing number of scientific publication [54]

(xiii) Application in robotic hand systems [55]

(xiv) Research effectiveness in a subject area among top class universities [56]

(xv) Educational Research [57]

(xvi) Management bioenergy [58]

(xvii) Magnetite Nanoparticle [59]

(xviii) Nanocrystalline Cellulose Production Research [60]

Although above bibliometric analyses have been well-reported, we believe that the present bibliometric analysis will give additional information on the research relating to photonic crystal. Indeed, this will bring benefits for further developments.

4. Conclusion

Studies on the progress, range, and influencing factors of the photonic crystals research have been discussed in this bibliometric discussion. The result is expected to provide comprehensive information for the researchers and stakeholders as considerations in compiling plans and policies. The PhC research growth, which is exceptionally slow, shows the prestigious journal's support to publish this topic can be seen clearly. The collaboration from the contributor's elements of the articles can encourage the authors to study the PhC-related topic. PhC-related research has been built connectivity between 5% of the world, where China is the most productive country in terms of publications. Topics that strongly correlate with the research progress 2009 – 2019 are the finite difference time domain method, waveguide technology, and sensors application. In PhC future research, waveguide and sensors application are still promising due to the market's terahertz and medical sensors demand. However, it is also possible to shift to solar cell applications as renewable energies are well developed.

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