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A comparative study on detecting research fronts in the organic light-emitting diode (OLED) field using bibliographic coupling and co-citation

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Abstract Research fronts represent areas of cutting-edge study in specific fields. They not only provide insights into current focuses and future trends, but also serve as important indicators for government policymaking with regard to technology. This study employed both bibliographic coupling and co-citation as methods to analyze the evolution of research fronts in the OLED field, and compared the outcomes in order to identify the differences between, and assess the effectiveness of, the two methods in detecting such research fronts. This study indicated that both analytic methods can be employed to track the evolution of research fronts. Compared with co-citation, bibliographic coupling identifies a higher number of research fronts, and detects the emergence of the research fronts earlier, thus showing better performance than co-citation in detecting research fronts.

Keywords Research fronts · Bibliographic coupling · Co-citation · Fixed citation window · OLED

Introduction

The concept of research fronts was first introduced by Price (1965) and has received wide attention in recent years. Understanding the latest developments in a particular field not only can provide insights into current focuses and future trends, but also serves as an important indicator for government decision-making on technology policy. More and more

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researchers have adopted bibliometrics to study research fronts, with methods including but not limited to citation, direct citation, bibliographic coupling (Fujita et al. 2012, 2014; Jarneving 2007; Kuusi and Meyer 2007), co-citation (Åström 2007; Cornelius et al. 2006; Fujita et al. 2012, 2014; Shibata et al. 2008), co-words (Braam et al. 1991; Van Den Besselaar and Heimeriks 2006) and so on. Among all these approaches, bibliographic coupling analysis and co-citation analysis have been widely used and have generated extensive research findings.

For clarity, we here provide brief descriptions of these two somewhat easily confused methods. Bibliographic coupling occurs when paper A and paper B both cite the same reference (Kessler 1963). Co-citation occurs when two references, one to paper A and one to paper B, are cited by paper C, indicating a co-citation relationship between paper A and paper B (Marshakova 1973; Small 1973). Both bibliographic coupling and co-citation show linkage between the third paper and the other two papers. While bibliographic coupling uses papers' citations to form clusters, co-citation employs cited papers to form clusters (Egghe and Rousseau 2002; Garfield et al. 1978; Garfield 2001; Glänzel 2003; Glänzel and Czerwon 1996; Lai and Wu 2005; Lo 2010; Morris et al. 2003; Schiebel 2012; Weisband et al. 2005; Yuan and Tang 2010). Ma and Guan (2006) stated that using the bibliographic coupling and co-citation methods for detecting research fronts has become a key component of bibliometrics. Bibliometrics identifies current and future development trends in a given field and can be referred to by technology policymakers for information on scientific trends. Jarneving (2001, 2005) implied that integration of both methods can lead to understanding that catalyzes new directions for detecting research fronts. Bibliographic coupling and co-citation are now commonly used in the study of research fronts, but the majority of researchers employ only one analytic method and seldom integrate the two methods in their studies. Studies that combine both bibliographic coupling and co-citation also obtain different outcomes; some indicate better results for bibliographic coupling (Boyack and Klavans 2010; Shibata et al. 2009); some indicate better results with co-citation (Sharabchiev 1989); some indicate the need for further analysis (Jarneving 2005). There are other results showing no significant difference, however, and both methods were able to detect the research fronts in the specific fields examined (Persson 1994; Zhao and Strotmann 2008).

Boyack and Klavans (2010) compared the accuracies of cluster solutions of a large corpus of 2,153,769 recent articles from the biomedical literature (2004–2008) using four similarity approaches: co-citation analysis, bibliographic coupling, direct citation, and a bibliographic coupling-based citation-text hybrid approach. Each of the four approaches could be considered a way to represent the research fronts in biomedicine. Of the three purely citation-based approaches, bibliographic coupling slightly outperformed co-citation analysis using both of the accuracy measures employed by the authors; direct citation was the least accurate mapping approach by far. The hybrid approach improved upon the bibliographic coupling results in all respects. In addition, Shibata et al. (2009) conducted a comparative study to investigate the performance of methods for detecting emerging research fronts. Three types of citation network (co-citation, bibliographic coupling, and direct citation) were tested in three research domains: gallium nitride (GaN), complex networks (CNW), and carbon nanotubes (CNT). The results showed that direct citation was the best data, but bibliographic coupling also performed better than co-citation in detecting research fronts.

Sharabchiev (1989), exploring the possible applications of cluster analysis of bibliographic references as a scientometric method, demonstrated that co-citation showed the best results. He used immunological topics from the SCI database in 1981 to compare science maps constructed using the bibliographic coupling and co-citation methods. His results showed that bibliographic coupling and co-citation provided comparable results as the two methods complemented each other. Overall, co-citation showed better performance than bibliographic coupling in drawing the science map of immunological topics, indicating that in scientific bibliometrics, co-citation is a better method for examining studies.

Jarneving (2005) showed that comparative studies between bibliographic coupling and co-citation required further work. Comparison of the mapping results generated by the two methods was accomplished by matching word profiles of groups of papers contained in a particular co-citation cluster with word profiles of clusters of bibliographically coupled papers. The findings suggested that the research fronts were portrayed in considerably different ways by each of the two methods applied. Jarneving concluded that the results of his study would support further more detailed and qualitative comparative study of these methods. The original data set encompassed 73,379 articles from the 50 most cited environmental science journals listed in *Journal Citation Report*, science edition, retrieved from the Science Citation Index on CD-ROM.

Persson (1994) and Zhao and Strotmann (2008) found no significant difference between bibliographic coupling and co-citation analysis. Persson employed 209 genuine articles published in the *Journal of the American Society for Information Science*, taken from the 1986–1990 SSCI® CD-ROM. To find the intellectual base of these articles, a co-citation analysis was conducted. A map of the most co-cited authors showed considerable resemblance to a map of information science produced by other methods. Citation-based bibliographic coupling was applied to the same set of documents in order to define research fronts. It was also shown that the research front map showed a close correspondence with the map of the intellectual base. Zhao and Strotmann (2008) selected the information science (IS) field and examined its intellectual structure both in terms of current research activities as seen from author bibliographic-coupling analysis, and in terms of intellectual influences on research as shown by author co-citation analysis. They examined how these two aspects of the intellectual structure of the IS field are related, and how they were both developed during the "first decade of the Web," 1996–2005. They found that these two citation-based author-mapping methods complemented each other and that in combination they provided a more comprehensive view of the intellectual structure of the IS field than either could provide on its own.

It can be seen from previous studies that citation analysis including direct citation analysis, bibliographic coupling analysis and co-citation analysis can be useful approaches to detect research fronts. Of the three approaches, bibliographic coupling and co-citation are symmetrical research methods, so there is a high comparability between the detection abilities and efficiencies of these two approaches. They have frequently been used at the same time in detecting the research fronts of a specific field (Jarneving 2005; Persson 1994; Sharabchiev 1989; Zhao and Strotmann 2008), and also used separately (Åström 2007; Cornelius et al. 2006; Jarneving 2007; Kuusi and Meyer 2007). However, as yet no consensus has emerged as to which of them has better detection performance. A more detailed and systematic comparative study is needed.

Our study puts emphasis on both the bibliographic coupling and the co-citation methods, with fixed citation windows, to detect research fronts and compare the effectiveness of the two analytic methods in the field of organic light-emitting diodes (OLED) from 2000 to 2009. We divided the period of study into two fixed citation windows: 2000–2004 and 2005–2009. Bibliographic coupling and co-citation analysis were then conducted on the clusters of highly cited articles in each citation window to examine the differences between the research fronts detected by each method and to see which method is more effective in detecting research fronts.

Research design and implementation

An organic light-emitting diode (OLED) is a light-emitting diode in which the emissive electroluminescent layer is a film of organic compound that emits light in response to an electric current. It is one of the latest display technologies, and creates displays that are less power-hungry than the previously existing liquid–crystal display (LCD) technologies. This study retrieved highly cited OLED-related articles from the Science Citation Index Expanded (SCIE) database of Web of Science (WOS) to conduct fixed citation window analysis via bibliographic coupling and co-citation, followed by cluster analysis to obtain research fronts from the two fixed citation windows. A comparative study was then conducted on detecting research fronts in OLED using bibliographic coupling and co-citation. The research design and research subjects used by this study are described below.

Research design

Compiling OLED research front data files

The first step of our research was to compile research front data files for the OLED field in 2000–2009. Highly cited OLED-related articles in this period were retrieved from the Science Citation Index Expanded database of WOS for investigation. In existing studies, some scholars set fixed thresholds when selecting highly cited articles. For instance, both Braam et al. (1991) and Åström (2007) regarded documents that were cited more than a specified number of times as highly cited papers. Nevertheless, in our study the number of OLED articles vary greatly from year to year. In order to avoid being influenced by articles from a particular year, we chose not to define highly cited articles proportionally or based on a specific number of citations. In addition, the research fronts identified will be sparse if the number of highly cited articles is excessive, but research fronts cannot be detected effectively if there are insufficient highly cited articles. Thus, we define highly cited articles as the top 20 most cited papers in each year. Articles with same number of citations as the article ranked 20th are included in our analysis.

Determining fixed citation window

To better compare the effectiveness in detecting research fronts, this study used fixed citation windows to analyze highly cited articles for bibliographic coupling and co-citation. In most related studies on research fronts, researchers employed fixed five-year citation windows. Cornelius et al. (2006) map dynamic research fronts of entrepreneurial studies by co-citation analysis in three 5-year periods (1986–1990, 1993–1997, 2000–2004). Åström (2007) also set 5 years as the citation window when detecting research fronts in library and information science. The citation windows in Glänzel (2012), Persson (1994), Boyack and Klavans (2010), Zhao and Strotmann (2008) are also 5 years. Consistent with these previous studies, our analysis are time-sliced into two 5-year periods (2000–2004, 2005–2009).

Bibliographic coupling analysis and co-citation analysis

As previously mentioned, top 20 most cited articles were selected as highly cited papers. Out of all these papers, we measure the coupling strength and co-citation strength of each pair. Bibliographic coupling occurs when paper A and paper B both cite the same reference, and the "coupling strength" of two given papers depends on the number of citations they share. Co-citation occurs when references to both paper A and paper B are cited by paper C, and the "co-citation strength" of two given papers depends on the number of co-citations they share. A lower number of pairs from bibliographic coupling and co-citation indicates a weaker correlation between two articles. Furthermore, articles with low frequency of coupling and low co-citation strength may interfere and lead to less meaningful results (Culnan 1986). In order to concentrate on the strongest documents and avoid interference, this study follows the methods employed by Morris et al. (2003) and Morris and Boyack (2005) on research fronts in anthrax research; Chen and Morris (2003) on research fronts in botulinum toxin research; and Yang et al. (2009) on research fronts in cystic fibrosis body composition research, setting five as the ideal threshold of frequency of bibliographic coupling and co-citation.

Cluster analysis

After filtering out articles that did not meet the threshold, cluster analysis was conducted to isolate research fronts in the OLED field. This study applied hierarchical cluster analysis using the UCINET software package. Pearson's correlation coefficient was used to measure similarity, and the complete link method was used to calculate the distances between clusters. In the process of hierarchical clustering, the selection of correlation coefficient is also important. Different levels lead to different classifications of clusters. That is, the selection of level affects the number of clusters and the size of data sets. Currently, there is no set rule for the selection of levels—it is up to the author's assessment to reach a balanced clustering solution (Knoke and Yang 2008). To ensure optimal results and comparisons, the level in this study was between 0.350 and 0.450, and appropriate levels were selected according to the clustering analysis results. After clusters were obtained from the analysis, a subject expert in OLED research joined the study to verify the titles and keywords in the articles and assist in classifying the research fronts represented by these articles. Subsequently, further analysis was conducted to track the evolution of the research fronts in OLED. Consultation with fellow researchers during our research improved the credibility of the results.

Comparing detective ability of bibliographic coupling and co-citation analysis

The final step is to compare the detect results of bibliographic coupling and co-citation analysis to see which method is more effective in detecting research fronts. The number of detected research fronts of the two methods will be compared to see which one is able to uncover more research fronts. We also compare their sensitiveness. The method which can detect research fronts timely is considered with higher detective efficiency.

Research subjects

OLEDs, also known as organic electroluminescent (OEL) devices, have the active light-emitting properties and rapid response time of LED devices and the energy-saving features and slimness of LCD devices. In addition, OLED displays are easy to process, low in cost, and can be used for flexible displays (Chen and Hwang 2007). With these advantages, OLED has the potential to become a significant display technology for the new generation. Considering the numerous strengths and features of OLEDs, it is important to take a closer look at the research fronts in the OLED field. Therefore, through this study we hope to provide insights into current and future trends in OLEDs using highly cited papers and employing both bibliographic coupling and co-citation analysis for a comparative study. In this study, the search terms used in the SCIE database of WOS were "OLED," "organic LED," "organic light-emitting diode," "organic electroluminescent," "polymer light-emitting diodes," and "polymer LED," with publication date set from 2000 to 2009 and the document type exclusively set as "Article."

Highly cited articles in OLED

The research sample for this study comprises original articles and highly cited articles in the field of OLED from the SCIE database of WOS prior to September 14, 2009. The number of OLED-related original articles and the number of highly cited articles annually are listed in Table 1. As indicated in Table 1, the total number of original articles on OLEDs in the 10-year period was 12,086. After verification of titles, keywords, abstracts and authors, 7,101 related articles were identified, of which 58.8 % were related to OLED. For each year, the 20 articles with the highest number of citations were selected as "highly cited articles." Appropriate adjustments were then made according to the number of times the papers were cited. Apart from 2005 (22 articles), 2007 (22), 2008 (21), and 2009 (25), the number of highly cited articles for each year was 20, with a total of 210 articles. The number of citations serving as the threshold for "highly cited" was highest in 2000, when papers had to be cited at least 152 times to meet the threshold; the lowest threshold number was seven, in 2009. Since articles published in 2009 are fairly recent in comparison to those from earlier years, a low threshold for "times cited" is reasonable.

OLED knowledge frameworks

According to relevant studies by Divayana (2011), Buckley (2013), Mertens (2014), Chen and Hwang (2005, 2007), Hwang and Chen (2004), and Koo (2006, 2008), OLED knowledge domains can be classified into three categories: processes, applications, and materials. Processes include vacuum plating and wet coating; applications include OLED displays and OLED lighting. With regard to materials, topics include charge injection and transfer materials, organic light-emitting materials, small-molecule light-emitting materials, polymer light-emitting materials, luminous efficiency, component design, light-emitting mechanisms, and organic thin-film field-effect transistor materials, as illustrated in Fig. 1. After identifying relevant research fronts from the fixed citation windows, the research fronts were then grouped into these categories for further analysis.

Study results

This study compares bibliographic coupling and co-citation analysis of the evolution of research fronts to determine which method is more effective in detecting research fronts. The following paragraphs are concerned with bibliographic coupling and co-citation frequency analysis, research front analysis, and overall analysis.

Table 1 OLED original and highly cited articles between 2000 and 2009

Year	Original articles	Related articles	Related articles percentage (%)	Extracted articles	Times cited threshold
2000	601	358	59.6	20	152
2001	591	351	59.4	20	118
2002	791	491	62.1	20	121
2003	782	470	60.1	20	121
2004	1,051	596	56.7	20	101
2005	1,340	806	60.1	22	80
2006	1,570	937	59.7	20	59
2007	1,645	955	58.1	22	38
2008	1,857	1,075	57.9	21	21
2009	1,858	1,062	57.2	25	7
Total	12,086	7,101	58.8	210	–

Retrieved September 14, 2010

Bibliographic coupling and co-citation frequency analysis

This study examined two fixed citation windows: 2000–2004 and 2005–2009. The bibliographic coupling and co-citation frequency results are listed in Table 2.

The table above shows that the distribution of frequency of bibliographic coupling for the two fixed citation windows is relatively consistent; only in frequencies 0, 1, and 10–14 are some differences apparent. Approximately 60 % obtained 0 frequency. The most frequently occurring coupling strength was one pair, accounting for approximately 15–20 % of articles. Only 0.1 % had more than 20 pairs from bibliographic coupling.

A lower number of pairs from bibliographic coupling and co-citation indicates a weaker correlation between two articles. Furthermore, articles with low frequency of coupling and low co-citation strength may interfere and lead to less meaningful results (Culnan 1986). In order to concentrate on the strongest documents and avoid interference, this study follows the methods employed by Morris et al. (2003) and Morris and Boyack (2005) on research fronts in anthrax research; Chen and Morris (2003) on research fronts in botulinum toxin research; and Yang et al. (2009) on research fronts in cystic fibrosis body composition research, setting five as the ideal threshold of frequency of bibliographic coupling and co-citation. After setting the threshold for coupling strength, the statistics show that 305 pairs in the first citation window comprised 6.2 % of the total, and 432 pairs in the second citation window comprised 7.3 % of the total.

The co-citation strengths for the two fixed citation windows are also relatively consistent, showing difference in only frequencies 0 and 1. Approximately 70 % obtained 0 frequency. The most frequently occurring coupling strength was one pair, which applied to approximately 11–12 % of the articles. After setting the threshold for co-citation strength, the statistics show that 325 pairs in the first citation window comprised 6.6 % of the total, and 377 pairs in the second fixed citation window comprised 6.3 % of the total.

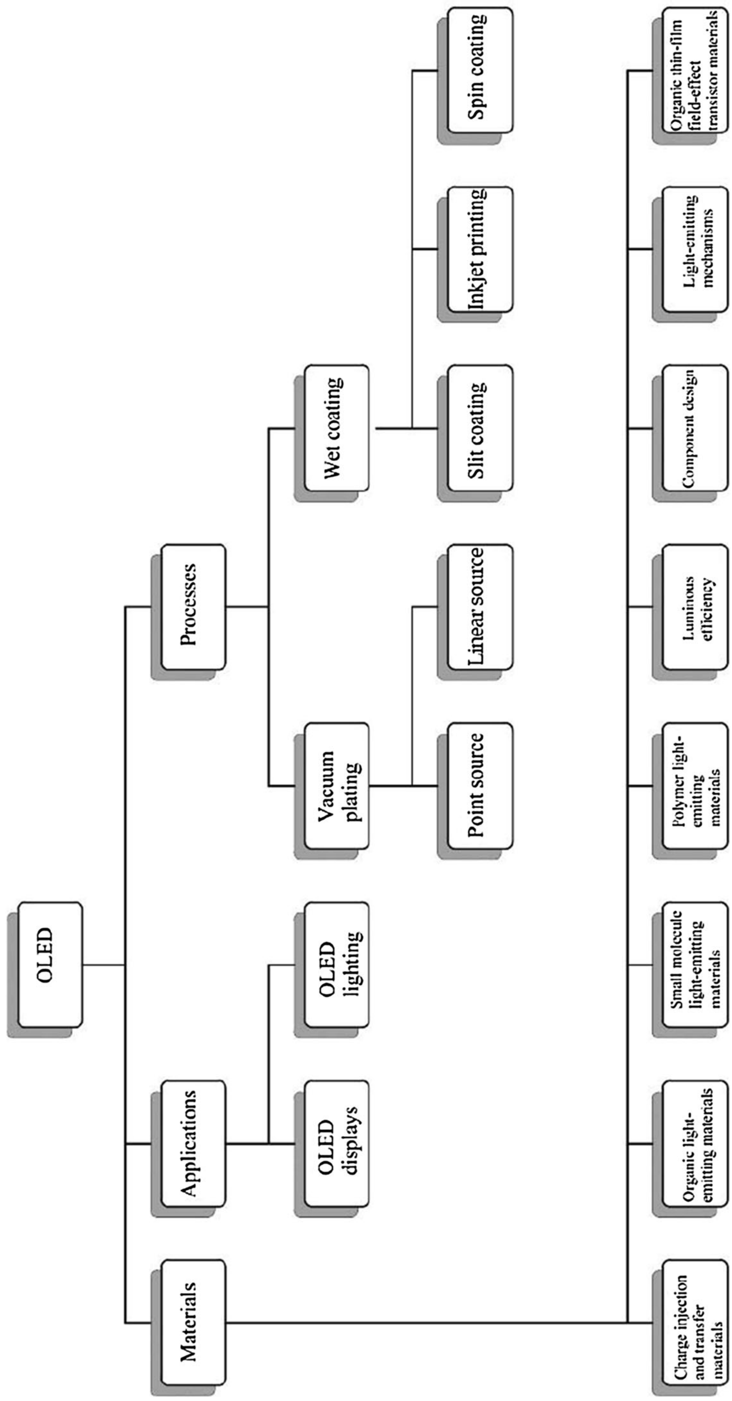

Fig. 1 OLED knowledge domains chart

Table 2 Frequency of bibliographic coupling and co-citation

Frequency	2000–2004 (100 articles)		2005–2009 (110 articles)	
	BC	CC	BC	CC
0–4	4,645 (93.8 %)	4,625 (93.4 %)	5,563 (92.7 %)	5,618 (93.7 %)
0	2,874 (58.1 %)	3,591 (72.5 %)	3,717 (62.0 %)	4,444 (74.1 %)
1	955 (19.3 %)	600 (12.1 %)	862 (14.3 %)	661 (11.0 %)
2	391 (7.9 %)	241 (4.9 %)	468 (7.8 %)	262 (4.4 %)
3	253 (5.1 %)	120 (2.4 %)	314 (5.2 %)	134 (2.2 %)
4	172 (3.4 %)	73 (1.5 %)	202 (3.4 %)	117 (2.0 %)
5–9	279 (5.6 %)	160 (3.2 %)	353 (5.9 %)	234 (3.9 %)
5	134 (2.7 %)	49 (1.0 %)	156 (2.6 %)	77 (1.3 %)
6	61 (1.2 %)	37 (0.7 %)	78 (1.3 %)	68 (1.1 %)
7	44 (0.9 %)	24 (0.5 %)	52 (0.9 %)	39 (0.7 %)
8	24 (0.5 %)	27 (0.5 %)	37 (0.6 %)	25 (0.4 %)
9	16 (0.3 %)	23 (0.5 %)	30 (0.5 %)	25 (0.4 %)
10–14	22 (0.5 %)	81 (1.7 %)	62 (1.1 %)	69 (1.1 %)
15–19	1 (0.0 %)	33 (0.7 %)	10 (0.2 %)	27 (0.5 %)
20+	3 (0.1 %)	51 (1.0 %)	7 (0.1 %)	47 (0.8 %)
Overall	4,950 (100 %)		5,995 (100 %)	

BC bibliographic coupling, *CC* co-citation

Research front analysis

Considering the numerous strengths and features of OLED devices, it is important to take a closer look at research fronts in the OLED field. However, recent studies on these research fronts are relatively sparse, with mainly Kajikawa and Takeda's (2009) study that showed organics and polymers as two of the most important domains in OLED, and Boyack et al.'s (2009) report that analyzed patents from 1977 to 2004 to identify the five most debated topics in OLED out of nine in solid-state lighting. Therefore, through this study we hope to understand the current and future trends of research fronts in the OLED field.

With a high threshold for highly cited articles and for coupling and co-citation strength, cluster analysis may lead to only two to three highly cited articles for each research front. For this study, a cluster with three or more articles is substantial but small enough not to result in sub-clusters, showing more meaningful outcomes. Therefore, clusters with at least three articles can be qualified as the basis for identifying research fronts. The following results were obtained from cluster analysis of the two fixed citation windows using bibliographic coupling and co-citation.

Research front analysis from bibliographic coupling

Based upon UCINET's hierarchical clustering analysis of highly cited articles from the periods 2000–2004 and 2005–2009, at designated levels of 0.3643 and 0.3517, totals of 11 and 11 research fronts respectively were identified using bibliographic coupling, as listed in Fig. 2.

Figure 2 shows 15 research fronts identified within the fixed citation windows, with seven research fronts that are present in both the first and the second citation windows.

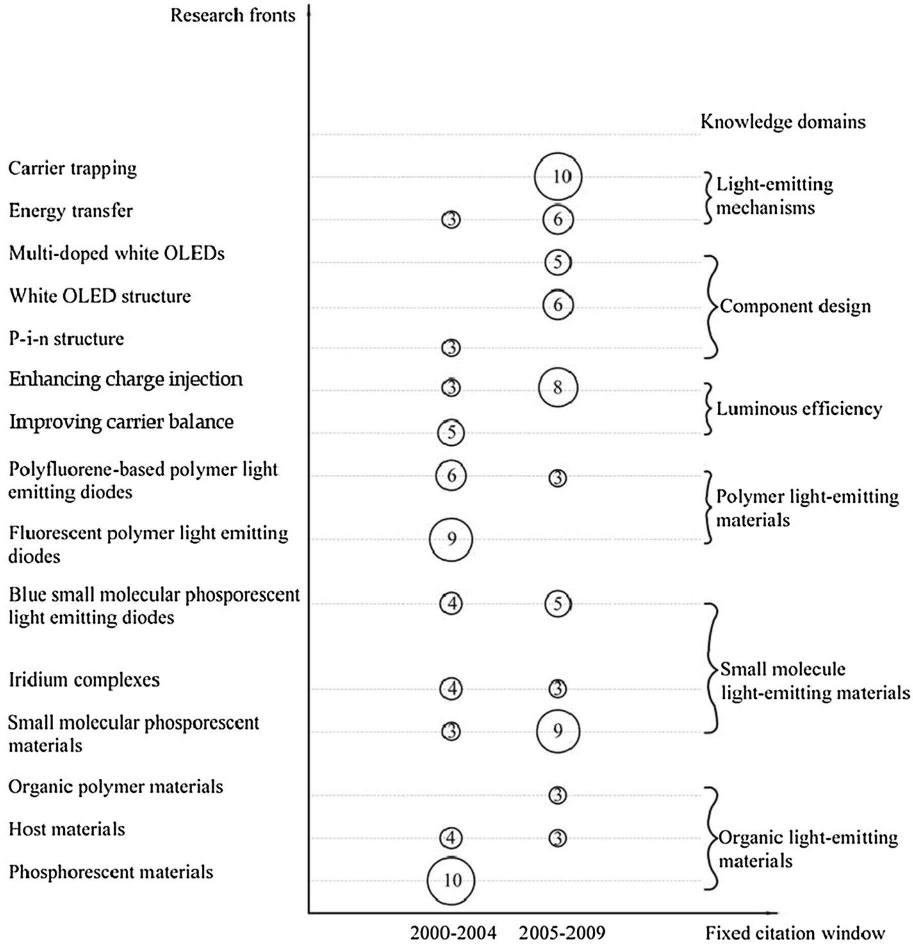

Fig. 2 OLED research fronts evolution map using bibliographic coupling

These seven research fronts are polyfluorene-based polymer light-emitting diodes, host materials, iridium complexes, blue small-molecular phosphorescent light-emitting diodes, small-molecule phosphorescent materials, energy transfer, and enhancing charge injection. Among these research fronts, four fronts—blue small-molecular phosphorescent light-emitting diodes, small-molecular phosphorescent materials, energy transfer, and enhancing charge injection—showed increases in the number of articles. Three research fronts—polyfluorene-based polymer light-emitting diodes, host materials, and iridium complexes—showed decreases in the number of articles. Four research fronts that were present in the first citation window were not found in the second citation window, namely phosphorescent materials, fluorescent polymer light-emitting diodes, improving carrier balance, and p-i-n structure. Four research fronts appeared only in the second citation window: carrier trapping, white OLED structure, multi-doped white OLEDs, and organic polymer materials.

The 11 research fronts in the first citation window were associated with six knowledge domains in OLED (rank by proportion): polymer light-emitting materials (27.8 %), organic light-emitting materials (25.9 %), small-molecule light-emitting materials (20.3 %), luminous efficiency (14.8 %), light-emitting mechanisms (5.6 %), and component design (5.6 %). In the second citation window, the 11 research fronts also were associated with six knowledge domains in OLED: small-molecule light-emitting materials (27.9 %), light-emitting materials (26.2 %), component design (18.0 %), luminous efficiency (13.1 %), organic light-emitting materials (9.8 %), and polymer light-emitting materials (5.0 %). This finding shows that the two citation windows showed identical knowledge domains, although they were proportionally different. Among these knowledge domains, small-molecule light-emitting materials, light-emitting materials, and component design were growing knowledge domains, while organic light-emitting materials, polymer light-emitting materials, and luminous efficiency were declining knowledge domains.

Research fronts analysis from co-citation

Based upon UCINET's hierarchical clustering analysis of highly cited articles from the periods 2000–2004 and 2005–2009, at designated levels of 0.3812 and 0.3871, a total of seven and eight research fronts respectively were identified using co-citation, as listed in Fig. 3.

Figure 3 shows 12 research fronts identified within the fixed citation windows, of which three research fronts were present in both the first and the second citation windows: phosphorescent materials, energy transfer, and small-molecule phosphorescent materials. In the second citation window, the number of articles increased for energy transfer, decreased for phosphorescent materials, and remained the same for small-molecule phosphorescent materials, compared to the first citation window. Four research fronts no longer appeared in the second citation window: polyfluorene-based polymer light-emitting diodes, organic small-molecule materials, blue small-molecular phosphorescent light-emitting diodes, and p-i-n structure; five research fronts appeared only in the second citation window: iridium complexes, white OLED structure, transparent conductive film of carbon nanotubes, enhancing charge injection, and organic thin-film field-effect transistor materials.

In the first citation window there were seven research fronts, associated with five knowledge domains (ranked by proportion): organic light-emitting materials (47.1 %), polymer light-emitting materials (21.6 %), small-molecule light-emitting materials (17.6 %), light-emitting mechanism (7.8 %), and component design (5.9 %). In the second citation window there were eight research fronts, associated with six knowledge domains: small molecule light-emitting materials (39.2 %), component design (21.6 %), light-emitting mechanisms (15.6 %), organic light-emitting materials (11.8 %), luminous efficiency (5.9 %), and organic thin-film field-effect transistor materials (5.9 %). These findings show that there were four research fronts that were present in both citation windows, of which light-emitting mechanism, small-molecule light-emitting materials, and component design were growing knowledge domains; organic light-emitting mechanism was a declining knowledge domain; polymer light-emitting materials was a disappearing knowledge domain; and luminous efficiency and organic thin-film field-effect transistors materials were emerging knowledge domains.

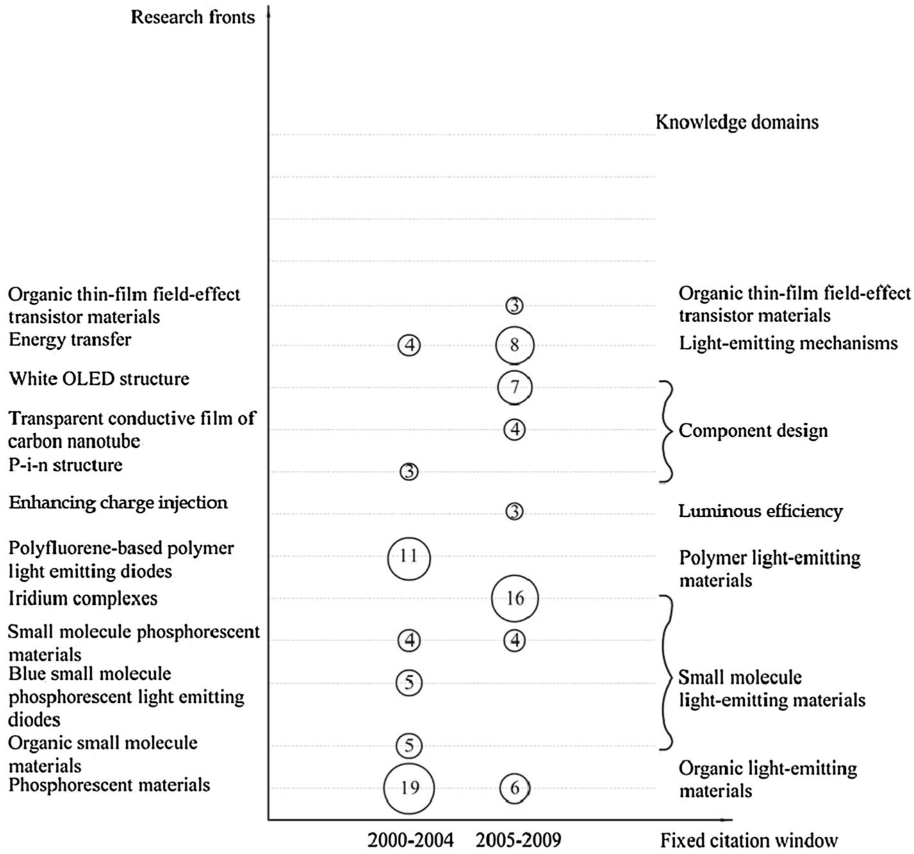

Fig. 3 OLED research fronts evolution map using co-citation

Comparisons

Within the two fixed citation windows, UCINET's hierarchical clustering analysis produced 11 and 11 research fronts with bibliographic coupling, while co-citation analysis obtained seven and eight research fronts. Table 3 is provided to better illustrate the research fronts and the differences between the two different methods. It shows that across the two citation windows, a total of 15 research fronts were obtained by bibliographic coupling and a total of 12 by co-citation analysis. Taken together, the two methods yielded a total of 18 research fronts, of which nine were identified by both methods. Across the two fixed citation windows, bibliographic coupling on average produced 11 research fronts within each citation window, while co-citation analysis produced eight research fronts, indicating better performance for bibliographic coupling in obtaining research fronts. The table also shows that two research fronts, small-molecule phosphorescent materials and energy transfer, were identified in both fixed citation windows by both bibliographic coupling and co-citation, showing these two research fronts to be the most actively pursued topics in OLED. Beside these two most active research fronts, polyfluorene-based polymer light-emitting diodes, blue small-molecular phosphorescent light emitting diodes, iridium

Table 3 Comparison of research fronts using bibliographic coupling and co-citation

Knowledge domains	Research fronts	2000–2004		2005–2009	
		BC	CC	BC	CC
Polymer light-emitting materials	Fluorescent polymer light-emitting diodes	★(9)			
	Polyfluorene-based polymer light-emitting diodes	★(6)	★(11)	★(3)	
Small-molecule light-emitting materials	Small-molecule phosphorescent materials	★(3)	★(4)	★(9)	★(4)
	Blue small-molecular phosphorescent light-emitting diodes	★(4)	★(5)	★(5)	
	Iridium complexes	★(4)		★(3)	★(16)
Light-emitting mechanism	Carrier trapping			★(10)	
	Energy transfer	★(3)	★(4)	★(6)	★(8)
Organic light-emitting materials	Host materials	★(4)		★(3)	
	Phosphorescent materials	★(10)	★(9)		★(6)
	Organic small-molecule materials		★(5)		
	Organic polymer materials			★(3)	
Luminous efficiency	Improving carrier balance	★(5)			
	Enhancing charge injection	★(3)		★(8)	★(3)
Organic thin-film field-effect transistor materials	Organic thin-film field-effect transistor materials				★(3)
Component design	White OLED structure			★(6)	★(7)
	Multi-doped white OLEDs			★(5)	
	p-i-n Structure	★(3)	★(3)		
	Transparent conductive film of carbon nanotubes				★(4)

★ Indicates that the research front is present in the citation window, and the number represents the number of articles

BC bibliographic coupling, *CC* co-citation complexes, phosphorescent materials, and enhancing charge injection are five additional research fronts that are present in both citation windows, indicating their significance. The only research front that was identified in 2000–2004 using both bibliographic coupling and co-citation analysis, but was not found in 2005–2009 by either method, was p-i-n structure, which is therefore identified as a disappearing front. White OLED structure, which began to be present during 2005–2009, is called an emerging front.

In addition, six research fronts were detected exclusively by bibliographic coupling, while only three other research fronts were detected exclusively using co-citation analysis. Relevant literature (AlSalhi et al. 2011; Chen and Hwang 2007; Kamtekar et al. 2010; Lambeth 2004; Lee et al. 2014; Lin 2009; Liu et al. 2006; Madhava Rao et al. 2013; Park et al. 2009; Sebastian et al. 2009; Segal et al. 2007; So et al. 2007; Sun et al. 2014; Zink et al. 2014) was referred to, and four experts were consulted, to verify the above research fronts. Among the research fronts mentioned above, six derived from bibliographic coupling are identified as important. Also, bibliographic coupling detected two research fronts, iridium complexes and enhancing charge injection, earlier than co-citation analysis.

To sum up, bibliographic coupling is able to identify a greater number of important research fronts and to detect the emergence of research fronts earlier than co-citation, showing better performance in detecting research fronts. This result is identical to those of studies by Boyack and Klavans (2010) and Hsu (2010). Therefore we recommend that future studies employ bibliographic coupling to identify research fronts in fixed citation windows.

Conclusion

This study used both bibliographic coupling and co-citation methods with fixed citation windows to detect research fronts in OLED from 2000 to 2009 and compare the effectiveness of the two analytic methods. Highly cited articles—the 20 most cited articles in OLED annually—were used in this study, and for bibliographic coupling and co-citation, the threshold for coupling and co-citation strength was set at five. After filtering out articles that did not reach the threshold, cluster analysis was conducted to identify research fronts in OLED. Finally, a comparative study was conducted on the effectiveness of the two methods in detecting research fronts in OLED.

This study shows that while both bibliographic coupling and co-citation can detect research fronts adequately, bibliographic coupling shows better performance, detecting more important research fronts better and earlier than co-citation analysis when using fixed citation windows. Researchers are encouraged to employ bibliographic coupling to study research fronts in future studies.

These two analytic methods have been used to conduct related analysis in published literature, and can be perceived as scientific and objective methods for data collection. Due to time constraints, for this study we were unable to consult with more experts in OLED to better ensure the accuracy of the research fronts. Upham and Small (2010) stated that consultation with 30 experts to ensure the accuracy of research fronts provided positive comments and constructive criticism, which is important in identification of research fronts. In future studies, researchers are encouraged to expand on expert interviews and focus group talks to validate the research findings and provide better advice to technology policymakers on current and future development.

The bibliographic coupling and co-citation methods are now commonly used in the study of research fronts. As these two methods provide different facets of the field, each method has its own characteristics and shortcomings. This study employed both bibliographic coupling and co-citation, and conducted comparative studies to enhance the accuracy of the research fronts found. However, since both these methods are indirect methods of citation, many studies have combined bibliographic coupling or co-citation with other citation methods to obtain research fronts with better results. Small et al. (2013) combined direct citation and co-citation to identify emerging topics. Also, Fujita et al. (2012) detected research fronts using different types of combinational citation, including combined direct and co-citation, direct citation and bibliographic coupling, co-citation and bibliographic coupling, and direct citation, co-citation and bibliographic coupling. Therefore, in future studies researchers are encouraged to combine bibliographic coupling and/or co-citation with direct citation, co-words, keyword analysis, or co-author analysis to achieve better results in obtaining research fronts for government decision-making on technology policy.

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