Scientometrics (2016) 109:1835–1853
DOI 10.1007/s11192-016-2133-9

A comparative study on three citation windows for detecting research fronts

Mu-Hsuan Huang[1] · Chia-Pin Chang[2]

Received: 11 May 2016 / Published online: 26 September 2016

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 crucial indicators for technology-related government policymaking. This study examined research fronts by using three citation window types (i.e., fixed citation windows, citing half life, and sliding windows). Organic light-emitting diodes (OLEDs) were adopted as the research area in comparing the evolution and development of research fronts from the three citation windows. The bibliographic coupling method was applied to identify the research fronts by using 210 highly cited articles in OLED research. The results indicated that among the three citation windows, sliding windows returned the highest number of research fronts, hence exhibiting maximal effectiveness. Furthermore, regarding effectiveness in detecting emerging fronts, both fixed citation windows and citing half life identified four emerging fronts, whereas sliding windows identified 11 emerging fronts, demonstrating optimal effectiveness.

Keywords Research fronts · Bibliographic coupling · Citation windows · Fixed window · Sliding window · Citing half life · OLED

Introduction

Research fronts represent pioneer studies in a specific field. Understanding the development of research fronts can help researchers comprehend the latest research focus and future trends. Research fronts also provide critical information for planning national

✉ Mu-Hsuan Huang
mhhuang@ntu.edu.tw

[1] Department of Library and Information Science, National Taiwan University, No. 1, Sec. 4, Roosevelt Road, Taipei 10617, Taiwan

[2] Archives Service Division, National Archives Administration, National Development Council, No. 439, Zhongping Road, New Taipei City 24220, Taiwan

development blueprints and setting technology development policies. Because confirming and analyzing research fronts are valuable in increasing national competitiveness, numerous countries have invested substantial resources or established relevant institutes for studying research fronts with the objective of creating new national growth.

To study the research fronts of specific fields, researchers typically use citation analysis. They set citation windows to divide the time range they study into several intervals; subsequently, they continue the following related analysis. The citation windows are the citation time range of articles in specific fields. When the appropriate citation windows are determined for analysis, the influence of articles in a certain field can be fully determined, rendering quantitative data highly representative. Because no accurate and recognized citation window is available, researchers choose citation windows according to their research purposes. Impact factor (IF), the most authoritative index of journal assessment, has also been questioned by numerous researchers because they consider it inappropriate to use only a 2-year citation window to derive the IF for assessing the influence of journals. Van Leeuwen et al. (1999) believed that the average citation peaks range from 2 to 3 years in physics, 2.5 to 3 years in chemistry, and 3 to 4 years in numerous technological sciences; hence, using a 2-year citation window for deriving the IF may not be the most appropriate choice. Numerous researchers have proposed methods for modifying the 2-year citation window applied for evaluating the IF. Glänzel and Schoepflin (1995) suggested a 3-year citation window, Aguillo (1996) suggested a 4-year citation window, Jacsó (2009) suggested a 5-year citation window, and Van Leeuwen and Moed (2002) suggested a 4–5-year citation window according to various fields. Sombatsompop et al. (2004) suggested using the cited half life of a journal rather than the 2-year citation window. Krell (2012) believed that journal IF is the most common index for assessing scientific output; however, to quantify the performance of authors, adopting the h-index is recommended. Iftikhar et al. (2012) suggested adopting the modified IF to avoid the criticism about not considering the difference in various fields.

Suggestions for modifying the IF citation window proposed by researchers fully reflect the importance of choosing an optimal citation window. Therefore, the Institute for Scientific Information, an institute developing IF, has started providing IF using a 5-year citation window in Journal Citation Reports since 2007 (Campanario 2011; Nierop 2010). How to determine an optimal citation window for research front analysis is also open to discussion. The present study speculates that an appropriate citation window can be identified by comparing the research fronts from different citation windows. An optimal citation window can be determined when the influence of articles in a certain field is fully demonstrated within the chosen time range.

Few studies on research fronts have compared research fronts from dissimilar citation windows. The mainstream is still the single citation window, and a 5-year fixed window is most commonly used for conducting studies on research fronts. Cornelius et al. (2006) divided the research time into three 5-year fixed windows to study the research fronts of enterprise research. Åström (2007) used three 5-year fixed windows to study the research fronts of library and information science. Zhao and Strotmann (2014) used 5-year fixed windows along with an author cocitation analysis and author bibliographic coupling analysis to study the knowledge domains and research fronts of information science. Chang et al. (2015) also used four 5-year fixed windows to track the changes of research subjects in library and information science on the basis of keywords, bibliographical coupling, and cocitation analyses. Furthermore, Boyack and Klavans (2010) used 5-year fixed windows to compare cocitation analysis, bibliographic coupling, direct citation, and a bibliographic coupling-based citation–text hybrid approach for detecting the effectiveness of biomedical research fronts. Persson (1994) used 209 genuine articles of a 5-year fixed window (ranging between 1986 and 1990) to identify the research fronts generalized by *Journal of the American Society for Information Science*. Glänzel (2012) studied emerging topics of scientific disciplines by using two 5-year fixed windows: ranging from 1999 to 2003 and from 2004 to 2008. Apart from the fixed citation window, the sliding window is highly valued by researchers lately. Because articles overlap in the sliding window, researchers can observe the evolution and development of research fronts. Small (2006) used overlapping 6-year sliding windows to study research fronts in 22 disciplines and tracked the development of research fronts by using cocitation clusters over three 6-year sliding windows. Moreover, citing half life can reveal the timeliness of articles and reflect the development speed of a certain technology. However, few researchers have conducted relevant studies; only Chen (2005) used half life for identifying transient research paradigms.

Because few researchers have compared research fronts from different citation windows, the main purpose of the present study was to take organic light-emitting diodes (OLEDs) as an example to conduct a comparative analysis of research fronts from different citation windows by using bibliographic coupling within 10 years (2000–2009). In the information age, display technologies have become increasingly vital as the interfaces between human vision and electronic devices. If liquid crystal display (LCD) technology is viewed as one of the most crucial milestones in the development of flat panel display technology in the twentieth century, then OLED is a newly emerging technology that may surpass flat panel display in the twenty-first century (Chien and Chen 2001). OLEDs have demonstrated the active light-emitting properties and rapid response times of LED devices as well as the energy-saving features and slimness of LCD devices. In addition, OLED displays are easily produced, cheap, and can be used for flexible displays (Chen and Hwang 2007). Because of these advantages, numerous industries have predicted that OLED is highly likely to become a major display technology in the future. This optimistic outlook is shared by the optoelectronics industry, which predicts that the market demand for OLED will grow rapidly and will play a key role in the world economic system in the near future. Because the demand for OLED may increase drastically in the future, detecting OLED research fronts is crucial, especially because Taiwan is one of the leading countries in the OLED field. Therefore, we intend to identify the research fronts of OLED and use these results as a basis for further comparative analysis between different citation windows.

This study examined research fronts by using different citation windows. In addition to adopting a 5-year fixed window, which has been used by numerous researchers, for conducting studies on research fronts, we used overlapping 6-year sliding windows, which were used by Small (2006) to study research fronts in 22 disciplines, for tracking the emergence, development, and decline of OLED research fronts. Moreover, considering the development speed of this technological field, citing half life, which is less mentioned, was adopted. In this study, 'fixed windows' means that the citation time ranges of articles are divided into set lengths of time, namely the two 5-year periods of 2000–2004 and 2005–2009; 'sliding windows' means that the citation time ranges are in overlapping 6-year periods, that is, 2000–2005, 2001–2006, 2002–2007, 2003–2008, and 2004–2009; 'citing half-life' means the median age of highly cited articles in the OLED field, that is, the duration required for the citation time of highly cited articles to reach 50 % of the total citation time. The citing half-life in this study was approximately 4 years. Therefore, we divided the 10-year research time into two citing half-life periods: 2002–2005 and 2006–2009. After the research fronts from these three citation windows were determined, a comparative analysis was conducted to investigate the difference between research fronts from different citation windows and suggest which type of citation window is favorable for studying research fronts.

Research design and implementation

We used the Science Citation Index Expanded (SCIE) database of Web of Science (WOS) to retrieve highly cited OLED-related articles. We also used bibliographic coupling and adopted the UCINET software package to conduct a cluster analysis to detect research fronts from the fixed window, citing half life, and sliding window. The results can facilitate tracking the evolution and development of OLED research fronts from 2000 to 2009 and investigating the differences among research fronts from the three citation windows. The research methodology, design, and subjects are described as follows.

Research methodology

Numerous research methods are used to study research fronts in specific fields, and every method has advantages and disadvantages. Researchers should choose research methods appropriate to their research objects. Previous studies have demonstrated that various styles of citation analysis, including coword, direct citation, bibliographic coupling, and cocitation can be useful approaches for detecting research fronts. Among these approaches, bibliographic coupling and cocitation in particular have already been widely used and have generated extensive research findings. Compared to cocitation, few studies have used bibliographic coupling for detecting research fronts. However, several studies have shown that bibliographic coupling performs better than cocitation in this application (Boyack and Klavans 2010; Huang and Chang 2015; Shibata et al. 2009). Although bibliographic coupling uses the reference lists of papers to form clusters, cocitation relies on future citations of papers to form clusters. We contend that bibliographic coupling can generate more timely and updated research fronts than cocitation can. Therefore, we intended to demonstrate the potential of the bibliographic coupling method and applied this method instead of cocitation, coword, or direct citation to investigate OLED research fronts in three citation windows, namely the fixed citation window, citing half-life, and sliding window; moreover, we compared the effectiveness of these three citation windows in detecting research fronts in the OLED field. Bibliographic coupling is an essential method in bibliometrics. It occurs when two papers cite the same reference, and the "coupling strength" of two specific papers depends on the number of citations they share.

Research design

This study applied bibliographic coupling to analyze highly cited OLED articles from the three citation windows to detect the evolution and development of research fronts within 10 years. The research design of this study is explained as follows.

Compiling OLED research front data files

The determination of highly cited articles and bibliographic coupling data files was the foundation in this study. We used the SCIE database of WOS to retrieve highly cited OLED-related articles. When researchers identify highly cited articles, they set different thresholds according to their study design. In the current study, because the number of OLED articles varied substantially on an annual basis during 2000–2009, we chose not to select highly cited articles proportionally or according to a specific number of citations to avoid the disproportionate influence of articles from a particular year. Thus, we defined highly cited articles as the top 20 most-cited papers annually during 2000–2009. Articles with the same number of citations (i.e., tied rankings) were included in this analysis. In this study, the total number of highly cited articles was 210. The chosen highly cited articles formed the basis of bibliographic coupling for identifying OLED research fronts, and the bibliographic coupling data files were coreferenced from these diverse articles.

Determination of citation windows

We compared research fronts from various citation windows and analyzed the effectiveness of these citation windows. No existing studies have compared research fronts from dissimilar citation windows. We thus adopted the 5-year fixed citation window, which is the most frequently used by researchers. In this study, the fixed citation windows comprised two bibliographic coupling data files (i.e., 2000–2004 and 2005–2009). In addition, the overlapping 6-year sliding windows used by Small (2006) were also adopted. The sliding windows comprised five bibliographic coupling data files (i.e., 2000–2005, 2001–2006, 2002–2007, 2003–2008, and 2004–2009). Moreover, we also used citing half-life in this study because it could reflect the speed of technological advancement. Citing half-life was defined as the median age of highly cited articles in the OLED field; that is, the time required for the citation time of highly cited articles to reach 50 % of the total citation time. The citing half-life in this study was approximately 4 years. Therefore, we divided the 10-year research time into two citing half-life periods for bibliographic coupling data files: 2002–2005 and 2006–2009.

Establishment of related thresholds for research fronts

We used bibliographic coupling to generate research fronts from different citation windows and then compared the research results. As mentioned, we defined highly cited articles as the top 20 most-cited papers annually during 2000–2009. Articles with the same number of citations as the article ranked 20th were included in our analysis. We set the threshold of bibliographic coupling frequency to five, which has been used by numerous researchers (Chen and Morris 2003; Morris and Boyack 2005; Morris et al. 2003; Yang et al. 2009), and then conducted a cluster analysis to detect OLED research fronts from the three citation windows.

Cluster analysis

After filtering out articles that did not meet the threshold, we conducted cluster analysis to isolate research fronts in the OLED field. We adopted a hierarchical cluster analysis provided by the UCINET software package. We used Pearson's correlation coefficient to determine the measure similarity and applied the complete-link method to calculate the distance between clusters.

In the process of hierarchical clustering, the selection of the correlation coefficient is also critical, because different levels (i.e., correlation coefficients) lead to different cluster classifications. Specifically, the level selection influences the number of clusters and size of data sets. Currently, no rule governs the level selection; it is executed on the basis of researchers' assessments of how to reach a balanced and optimal solution for clusters (Knoke and Yang 2008).

To ensure optimal results and comparisons, the levels were selected according to the researchers' assessment of the clustering results from the three citation windows. After setting the levels, we found that the distribution of levels across the three citation windows in this study was between 0.350 and 0.450. When clusters were obtained from the analysis, an expert with more than 5 years' experience in OLED research joined this study to verify the titles and keywords in the articles, and assisted in classifying the research fronts represented by these articles. Consulting OLED subject experts during this study improved the credibility of the results.

Comparing the results of the three citation windows

After we identified research fronts from the three citation windows, we compared the results to understand the differences among the research fronts and track the evolution of OLED research fronts. The results can indicate which type of citation window is more effective for detecting research fronts.

Previously, researchers have developed various indices for evaluating the effectiveness of research fronts from different citation windows (Shibata et al. 2008, 2009, 2011; Guo et al. 2011; Fujita et al. 2012, 2014). However, some of these indicators are quite complex and not applicable to the current study. Therefore, this study adopted a relatively simple comparison method; that is, if the specified citation window detected the highest number of research fronts, and if all identified research fronts were considered crucial in that particular research field, then the chosen citation window was regarded as the most effective for detecting research fronts.

Research subjects

In this study, OLED was taken as an example to compare the evolution and development of research fronts from three citation windows. OLED, also called organic electroluminescent devices or organic electro-luminescence (OEL), demonstrate the active light-emitting properties and rapid response time of LED devices as well as the energy-saving features and slimness of LCD devices. In addition, OLED displays are easily produced and cheap and can be used for flexible displays (Chen and Hwang 2007). Because of these advantages, numerous industries predict OLEDs to have a high potential of becoming a major display technology in the future. Because the demand for OLEDs may increase drastically in the future, detecting OLED research fronts is crucial.

However, studies on these research fronts are relatively sparse, and only four main relevant studies have been conducted on these fronts: Kajikawa and Takeda (2009) analyzed OLED knowledge domains and suggested that organics and polymers are the two most crucial domains in the OLED field; Boyack et al. (2009) analyzed articles and patents in solid-state lighting between 1977 and 2004 and proposed that five of nine most debated topics are related to OLED; Huang and Chang (2014) detected OLED research fronts by using bibliographic coupling with a sliding window and identified 18 research fronts matching those predicted by subject experts on OLED materials. Among the 18 research fronts, four were emerging fronts, two were growing fronts, eleven were stable fronts, and one was a shrinking front. In addition, Huang and Chang (2015) employed both bibliographic coupling and cocitation as methods for analyzing the evolution of research fronts in the OLED field, and compared the outcomes to identify the differences between, and assess the effectiveness of, the two methods in detecting such research fronts. Both analytic methods can be employed to track the evolution of research fronts. Compared with cocitation, bibliographic coupling identifies more research fronts and detects their emergence earlier, thus exhibiting higher performance in detecting research fronts. Therefore, our objective in this study was to identify OLED research fronts by using the three citation windows and to compare their effectiveness.

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 a publication data set from 2000 to 2009 and the document type exclusively set as "article." This study investigated OLED research fronts from the cluster analysis of highly cited articles and the evolution of OLED research fronts. Highly cited articles on OLED and some relevant details are explained as follows.

Highly cited articles on OLED

The research sample for this study comprised raw and highly cited articles in the OLED field from the WOS SCIE database. 'Raw articles' means article data derived from searching OLED using several terms in the SCIE database. Table 1 lists the annual numbers of OLED raw articles and highly cited articles. During this 10-year period, the total number of raw articles was 12,086 (Table 1). After the titles, keywords, abstracts, and authors were manually verified, the number of related articles derived was 7101 (58.8 % of the raw articles). These related articles were the true OLED-related articles used for analysis in this study. For each year, the top 20 most-cited articles were further selected as "highly cited articles," and articles with same number cited as the article ranked 20th are included in this analysis. Except in 2005 (22 articles), 2007 (22 articles), 2008 (21 articles), and 2009 (25 articles), the number of highly cited articles annually was 20, and the total number of highly cited articles was 210. Among these years, 2000 registered the highest threshold of cited times (every highly cited article was cited at least 152 times to achieve

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

Year	Raw 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	1051	596	56.7	20	101
2005	1340	806	60.1	22	80
2006	1570	937	59.7	20	59
2007	1645	955	58.1	22	38
2008	1857	1075	57.9	21	21
2009	1858	1062	57.2	25	7
Total	12,086	7101	58.8	210	–

Retrieved September 14, 2010

the threshold) and 2009 registered the lowest threshold of cited times (every highly cited article was cited at least seven times). Because articles published in 2009 are fairly recent compared with those from earlier years, a low threshold for "times cited" is reasonable.

OLED knowledge frameworks

Relevant studies by Divayana (2011), Buckley (2013), Mertens (2014), Chen and Hwang (2005, 2007), Hwang and Chen (2004), and Koo (2006, 2008) have revealed that OLED knowledge domains can be divided into three categories: processes, applications, and materials. Processes include vacuum plating and wet coating; applications include OLED displays and lightings; and materials can be divided into eight domains: 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 (Fig. 1). We used three citation windows to detect research fronts and classified them according to the mentioned knowledge domains for further analysis.

Study results

Because of the high thresholds for selecting highly cited articles and bibliographic coupling frequency in this study, the analysis may reveal only 2–3 highly cited articles for each research front. In this study, a cluster with three or more articles did not result in excessive subclusters but demonstrated a highly representative significance. Therefore, only clusters with at least three articles qualified as a basis for identifying research fronts. The following sections present the analysis of research fronts from dissimilar citation windows. The results comprise five parts: research front analysis from fixed citation windows, research front analysis from citing half life, research front analysis from sliding windows, and comparison of research fronts from dissimilar citation windows and that of emerging fronts.

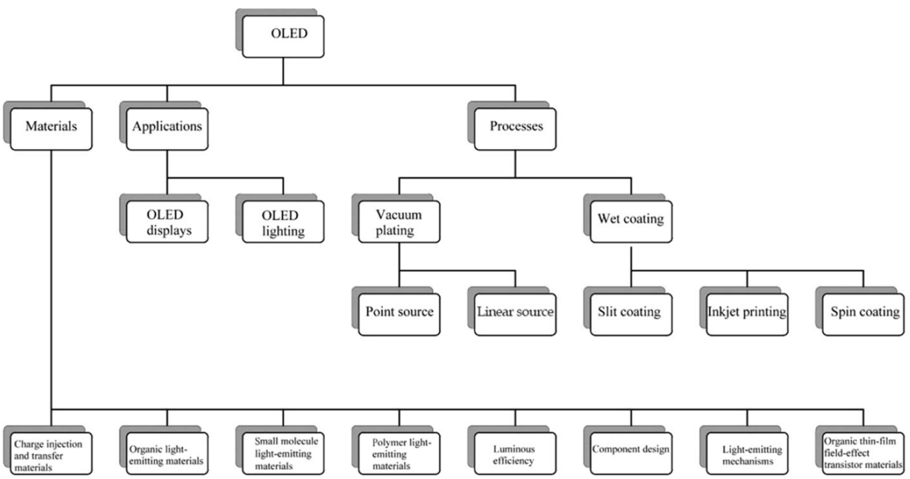

Fig. 1 OLED knowledge domain chart

Research front analysis using fixed citation windows

According to UCINET's hierarchical cluster analysis of highly cited articles during the periods 2000–2004 and 2005–2009, 11 research fronts were separately identified for each of the two periods at the designated levels of 0.3643 and 0.3517, respectively (Fig. 2).

A total of 15 OLED research fronts were identified from the fixed citation windows (Fig. 2). Among these research fronts, seven, namely polyfluorene-based polymer light-emitting diodes, host materials, iridium complexes, blue small-molecular phosphorescent light-emitting diodes, small-molecular phosphorescent materials, energy transfer, and enhance charge injection, were in both the first and second citation windows. Moreover, four of these seven research fronts, namely blue small-molecular phosphorescent light-emitting diodes, small-molecular phosphorescent materials, energy transfer, and enhance charge injection, were associated with increases in the number of articles. According to the research front classification of Upham and Small (2010), these four research fronts were considered growing fronts. The remaining three of the mentioned seven research fronts, namely polyfluorene-based polymer light-emitting diodes, host materials, and iridium complexes, were associated with drops in the number of articles; therefore, these three fronts were considered shrinking fronts. In addition, among all the research fronts, four

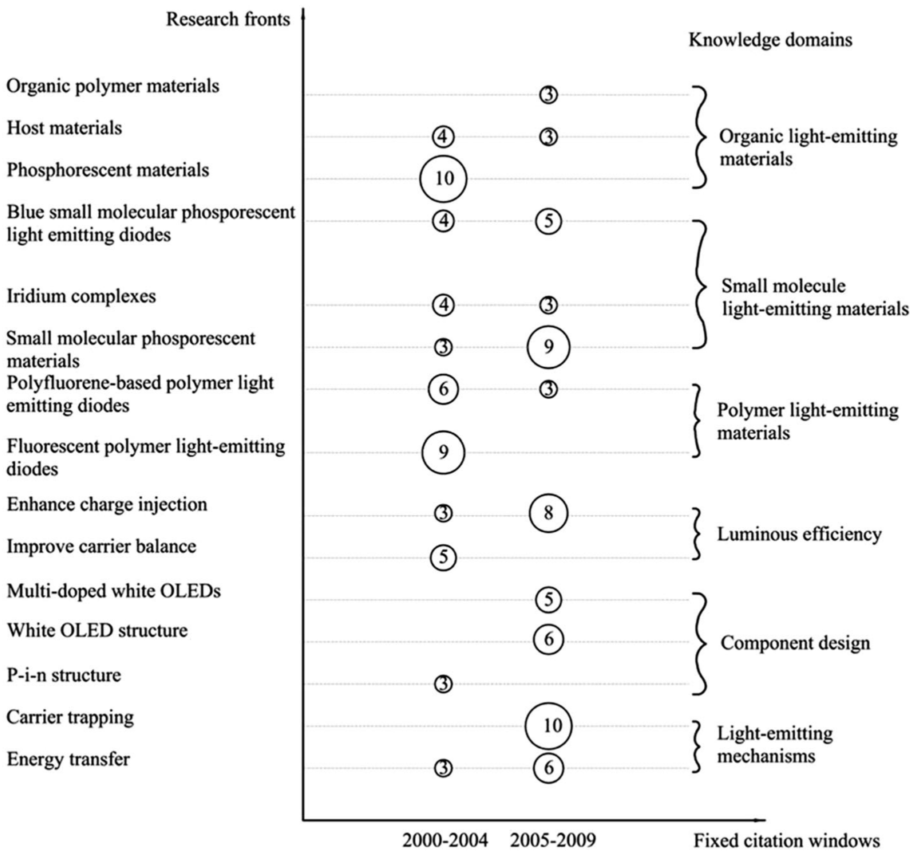

Fig. 2 OLED research front evolution map constructed using fixed citation windows

fronts, namely phosphorescent materials, fluorescent polymer light-emitting diodes, improve carrier balance, and p–i–n structure, which were in the first citation window rather than the second one, were defined as existing fronts. Another four of the research fronts, namely carrier trapping, white OLED structure, multi-doped white OLEDs, and organic polymer materials, which were only in the second citation window, were considered emerging fronts.

A comparison of the knowledge domains associated with the research fronts revealed six knowledge domains in both citation windows. Two of the knowledge domains were growing knowledge domains, namely component design and light-emitting mechanisms; two were stable knowledge domains, namely small-molecule light-emitting materials and luminous efficiency; and two were declining knowledge domains, namely organic light-emitting materials and polymer light-emitting materials.

Research front analysis using citing half life

The citing half life of highly cited articles was identified as 4 years, and the 10-year research period was divided into two citing half-life periods: 2002–2005 and 2006–2009. On the basis of UCINET's hierarchical cluster analysis of highly cited articles during the periods 2002–2005 and 2006–2009, nine and eight research fronts were identified at the designated levels of 0.3674 and 0.3520, respectively (Fig. 3).

A total of 13 research fronts were identified within the citing half life, with four research fronts, namely iridium complexes, multi-doped white OLEDs, small-molecular phosphorescent materials, and blue small-molecular phosphorescent materials, present in both the first and second citation windows (Fig. 3). Among these four research fronts, two fronts, namely iridium complexes and multi-doped white OLEDs, were associated with increases in the number of articles; hence, they were considered growing fronts. By contrast, the other two research fronts, namely small-molecular phosphorescent materials and blue

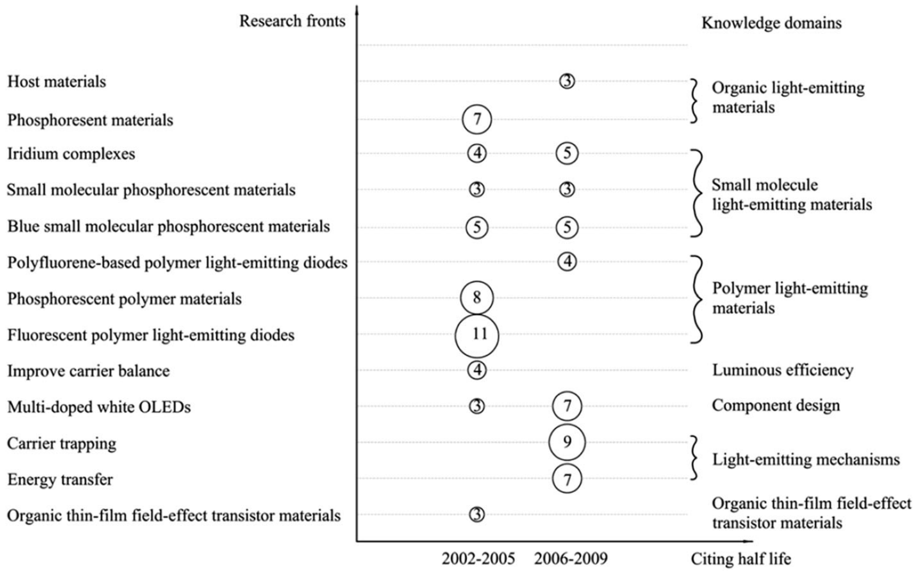

Fig. 3 OLED research front evolution map constructed using citing half life

small-molecular phosphorescent materials, were associated with decreases in the number of articles; hence, they were considered shrinking fronts. Four research fronts, namely host materials, polyfluorene-based polymer light-emitting diodes, carrier trapping, and energy transfer, which were absent from the first citation window, were observed in the second citation window; hence, they were denoted as emerging fronts. Five research fronts, namely phosphorescent materials, phosphorescent polymer materials, fluorescent polymer light-emitting diodes, improve carrier balance, and organic thin-film field-effect transistor materials, were present in the first citation window rather than the second one. Therefore, they were considered existing fronts. Moreover, among all the research fronts, two fronts, namely small-molecular phosphorescent materials and blue small-molecular phosphorescent materials, demonstrated a consistent number of articles in both citation windows. They were thus considered stable fronts.

Four knowledge domains were present in both citation windows. Among all the knowledge domains, two were growing knowledge domains (i.e., small-molecule light-emitting materials and component design), two were shrinking knowledge domains (i.e., polymer light-emitting materials and organic light-emitting materials), two were existing knowledge domains (i.e., luminous efficiency and organic thin-film field-effect transistor materials), and one was an emerging knowledge domain (i.e., light-emitting mechanisms).

Research front analysis using sliding windows

According to UCINET's hierarchical cluster analysis of highly cited articles during the periods 2000–2005, 2001–2006, 2002–2007, 2003–2008, and 2004–2009, a total of 14, 14, 13, 14, and 15 research fronts were identified at the designated levels of 0.3566, 0.3723, 0.3940, 0.3559, and 0.3657, respectively (Fig. 4).

A total of 18 research fronts were identified in five sliding windows by using bibliographic coupling (Fig. 4). Among these research fronts, four, namely fluorescent polymer light emitting diodes, carrier trapping, blue small-molecular phosphorescent materials, and iridium complexes, were present in all the five sliding windows, indicating that these research fronts were still widely discussed. Moreover, 14 research fronts were identified at the first sliding window, two at the second window, one at the third window, and one at the fourth window.

The mentioned research fronts belonged to seven knowledge domains. Among these knowledge domains, organic light-emitting materials and polymer light-emitting materials contained the highest number of research fronts, with each domain containing four research fronts. Another domain, small-molecule light-emitting materials, contained three research fronts. Organic thin-film field-effect transistor materials contained only one research front. To understand the evolution of OLED research fronts from sliding windows, we analyzed the research fronts according to the research front classification of Upham and Small (2010). The results are described as follows.

Emerging fronts represent fronts appearing in later sliding windows. In the present study, two types of emerging fronts were identified: normal emerging fronts, including blue polymer fluorescent materials, and re-emerging fronts, including host materials, improve carrier balance, and enhance charge injection. Growing fronts refer to fronts with a continuously increasing number of articles in later sliding windows, including phosphorescent materials and organic small-molecule materials. Stable fronts represent fronts with a consistent number of articles in later sliding windows, including guest materials, iridium complexes, blue small-molecular phosphorescent light-emitting materials, small-molecule phosphorescent materials, polyfluorene-based polymer light-emitting diodes, white OLED

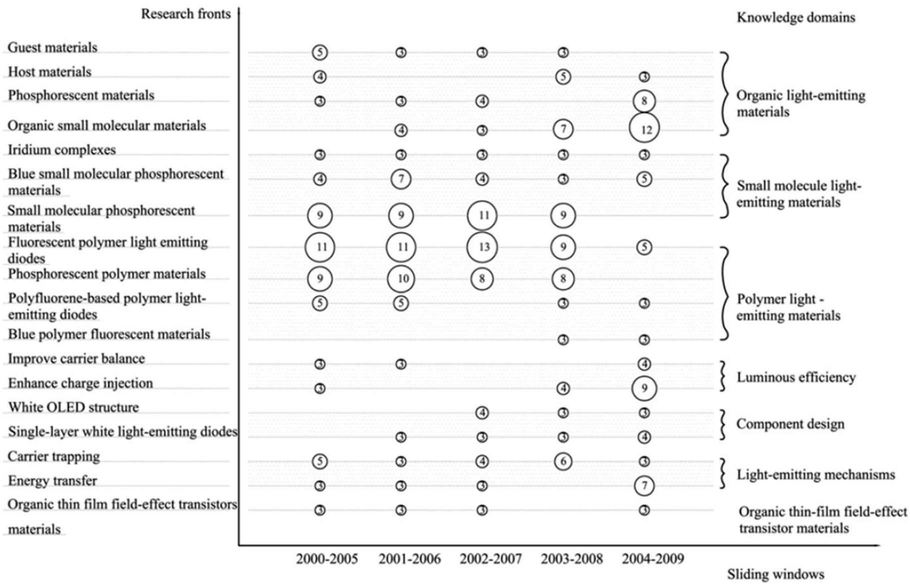

Fig. 4 OLED research front evolution map constructed using sliding windows

structure, single-layer white light-emitting diodes, carrier trapping, energy transfer, and organic thin-film field-effect transistor materials. Shrinking fronts refer to fronts with a constantly decreasing number of articles in later sliding windows, including fluorescent polymer light-emitting diodes. Existing fronts are research fronts that cannot continue developing in later sliding windows. No existing front was identified in this study. This analysis revealed that OLED research fronts comprised four emerging fronts (one normal emerging front and three re-emerging fronts), two growing fronts, eleven stable fronts, and one shrinking front.

Comparison of research fronts from different citation windows

In addition to the aforementioned analysis of research fronts from fixed citation windows, citing half life, and sliding windows, the fronts from these three citation windows were compared (Table 2). A total of 21 OLED research fronts were identified during the 10-year period. The number of times these research fronts appeared in the fixed citation windows (two citation windows), citing half life (two citation windows), and sliding windows (five citation windows) represented their relevance or prominence. A total of nine research fronts, including iridium complexes, blue small-molecular phosphorescent light-emitting diodes, and phosphorescent materials, appearing more than five times in the three citation windows were considered crucial.

Further comparison of research fronts from the various citation windows indicated that the sliding windows registered the highest number of research fronts (18), followed by the fixed citation windows (15), and then the citing half life (13). In total, ten research fronts were identified in all the three citation windows. Among all the knowledge domains, two domains, namely small-molecule light-emitting materials and light-emitting mechanisms, contained 100 % identical research fronts in the three citation windows. In addition, four

Table 2 Research fronts and the number of times they are present in the three citation windows

Knowledge domains	Research fronts	Fixed windows	Citing half life	Sliding windows	Total times
Organic light emitting materials	Phosphorescent materials	★ (1)	★ (1)	★ (4)	6
	Host materials	★ (2)	★ (1)	★ (3)	6
	Organic polymer materials	★ (1)			1
	Organic small molecule materials			★ (4)	4
	Guest materials			★ (4)	4
Small molecule light emitting materials	Iridium complexes	★ (2)	★ (2)	★ (5)	9
	Blue small molecular phosphorescent light emitting diodes	★ (2)	★ (2)	★ (5)	9
	Small molecule phosphorescent materials	★ (2)	★ (2)	★ (4)	8
Polymer light emitting materials	Fluorescent polymer light emitting diodes	★ (1)	★ (1)	★ (5)	7
	Polyfluorene-based polymer light emitting diodes	★ (2)	★ (1)	★ (4)	7
	Phosphorescent polymer materials		★ (1)	★ (4)	5
	Blue polymer fluorescent materials			★ (2)	2
Luminous efficiency	Improve carrier balance	★ (1)	★ (1)	★ (3)	5
	Enhance charge injection	★ (2)		★ (3)	5
Component design	White OLED structure	★ (1)		★ (3)	4
	Multi-doped white OLEDs	★ (1)	★ (2)		3
	Single-layer white OLEDs			★ (4)	4
	p–i–n structure	★ (1)			1
Light emitting mechanisms	Carrier trapping	★ (1)	★ (1)	★ (5)	7
	Energy transfer	★ (2)	★ (1)	★ (4)	7
Organic thin film field-effect transistor materials	Organic thin film field-effect transistor materials		★ (1)	★ (4)	5

★ The research front is present in the citation window, and the number in the parenthesis represents the number of times the research front is present

research fronts, namely organic small-molecule materials, guest materials, blue polymer fluorescent materials, and single-layer white OLEDs, were present in only the sliding windows. After we reviewed related articles (Liu et al. 2006; Segal et al. 2007; Fukagawa et al. 2008; Türker et al. 2009; Lin 2009; Kamtekar et al. 2010; Madhava Rao et al. 2013; Sebastian et al. 2013; Chizu et al. 2014; Sun et al. 2014; Zink et al. 2014) and consulted subject experts in OLED research, we confirmed that these four research fronts were crucial OLED research fronts. Therefore, sliding windows can be used to detect the highest number of and most vital research fronts.

Although sliding windows can detect the highest number of and the most vital research fronts, this study found that fixed windows identified two additional research fronts that were not present in either the sliding windows or the citing half-life results, namely organic polymer materials and p–i–n structures. After related articles were reviewed and OLED research experts were consulted, the two identified research fronts were confirmed as crucial OLED research fronts. In addition, this study discovered that using citing half life did not result in any additional research fronts that were not present in either the fixed or sliding windows. The reason may be because the time range used in citing half life was substantially covered by the sliding and fixed windows. Therefore, no additional research fronts were detected using citing half life.

Because using sliding windows for detecting research fronts requires considerable time and effort, we compared research fronts from fixed citation windows and citing half life to identify a simpler and more effective method of detecting the highest number of research fronts. During the 10-year period, a total of 17 research fronts were identified in the fixed citation windows and citing half life, with 15 being identified in the fixed citation windows and 13 being identified in the citing half life. Therefore, two more research fronts were identified in the fixed citation windows than in the citing half life. Eleven research fronts were identified in both the fixed citation windows and citing half life. The results indicated that the fixed citation windows are slightly more effective than the citing half life. Therefore, to understand the development of research fronts by using simpler and more effective methods, applying fixed citation windows first is suggested; however, citing half life can still be used to detect crucial research fronts.

Comparison of emerging fronts

Emerging fronts symbolize the development direction of specific fields and are more valuable than other types of research fronts. In the current study, emerging fronts were denoted as fronts appearing in later citation windows. To thoroughly analyze emerging fronts for tracking the development of the OLED field, emerging fronts from fixed citation windows, citing half life, and sliding windows were examined, as described subsequently (Table 3).

Comparing fixed citation windows with citing half life revealed a total of seven emerging fronts in the fixed citation windows and citing half life: four in the fixed citation windows and four in the citing half life. Except for one emerging front, carrier trapping, which was present in both the citation windows, three emerging fronts were present within each of the citation windows. Therefore, fixed citation windows and citing half life differ slightly in their effectiveness in detecting emerging fronts.

A comparison of the three citation windows revealed four emerging fronts in the fixed citation windows, four in the citing half life, and 11 in the sliding windows, which had the highest number of emerging fronts. A total of 14 emerging fronts were present within these three citation windows. However, these three citation windows did not contain any identical emerging fronts. A possible reason for this divergence may be because the three types of citation windows covered different time periods; in combination with the requirement that emerging fronts were fronts that appeared in later citation windows, few emerging fronts were able to meet all the specified conditions. Therefore, no identical emerging fronts were present within all three types of citation windows in this study.

Furthermore, five emerging fronts were identified in two of the citation windows and nine in only one of the citation windows. Among these nine emerging fronts, seven were present within the sliding windows and two within the fixed citation windows. Therefore, sliding windows can be used to detect the highest number of emerging fronts, which other types of citation windows cannot detect. However, fixed windows alone detected two emerging fronts: organic polymer materials and multi-doped white OLEDs. Because fixed windows were divided into two citation windows, some unique fronts may have emerged

Table 3 Comparison of emerging fronts from the three citation windows

Knowledge domains	Research fronts	Fixed windows	Citing half life	Sliding windows
Organic light emitting materials	Phosphorescent materials			•
	Host materials		•	•
	Organic polymer materials	•		
	Organic small molecule materials			•
Polymer light emitting materials	Polyfluorene-based polymer light emitting diodes		•	•
	Blue polymer fluorescent materials			•
Luminous efficiency	Improve carrier balance			•
	Enhance charge injection			•
Component design	White OLED structure	•		•
	Multi-doped white OLEDs	•		
	Single-layer white OLEDs			•
Light emitting mechanism	Carrier trapping	•	•	
	Energy transfer		•	•
Organic thin film field-effect transistor materials	Organic thin film field-effect transistor materials			•

• The research front is present in the citation window

in the second citation window that were not present in the first window; concurrently, because of the overlapping of articles in the sliding windows, the scale of these fronts may not have been large enough to be identified as emerging fronts using sliding windows. Consequently, two unique emerging fronts were detected solely by using fixed windows. Regarding the citing half life, none of the identified emerging fronts was unique; all fronts were also detected by the other two types of citation windows. This may be because the citation time range used in the citing half life was already substantially covered in the sliding and fixed windows; therefore, no additional emerging fronts were uniquely identified through citing half life.

Conclusion

This study examined research fronts by using three citation windows, namely fixed citation windows, citing half life, and sliding windows, and compared the evolution and development of the research fronts identified using these citation windows. OLED was considered an example for conducting comparative analysis.

This study is the first to compare research fronts identified using different citation windows. Comparing the research fronts from the three citation windows reveals that sliding windows were the most effective. Although sliding windows could detect the highest number of and the most vital research fronts, this study found that two additional research fronts may be uniquely identified by using fixed windows, namely organic polymer materials and p–i–n structures. Therefore, future studies may use an appropriate combination of sliding and fixed windows to gain a more comprehensive picture of the research fronts in a particular field.

Emerging fronts typically symbolize the development direction of specific fields. Hence, they are more valuable than other research fronts. The analysis of emerging fronts from fixed citation windows, citing half life, and sliding windows revealed that a total of 14 emerging fronts appeared in the three citation windows: sliding windows contained the most number of emerging fronts (11), and fixed citation windows and citing half life each contained four emerging fronts. Moreover, no emerging fronts were identified by all three citation windows. Nine emerging fronts were identified within one citation window: seven in sliding windows and two in fixed citation windows. Therefore, sliding windows returned the highest number of emerging fronts, which other types of citation windows did not detect. If researchers plan to detect the most number of emerging fronts to understand the development of specific fields, adopting sliding windows is suggested. However, because two emerging fronts, namely organic polymer materials and multidoped white OLEDs, were uniquely identified by using fixed citation windows, future studies investigating the emerging fronts of a particular field should consider using a combination of sliding and fixed windows, which would present a more comprehensive picture of the emerging fronts in the field.

In this study, we used the total number of research fronts detected to evaluate the effectiveness of different citation windows. Several studies have effectively evaluated different citation analysis methods, such as comparing the effectiveness of cocitation, bibliographic coupling, and direct citation for detecting research fronts in different fields including gallium nitride, complex network, and carbon nanotube (Shibata et al. 2009; Fujita et al. 2012, 2014). Because the different effectiveness indices developed by various researchers have diverse complexity and are not applicable to all studies, we chose to apply a simpler comparison method in this study; that is, if the specified citation window detects the highest number of research fronts, and if all identified research fronts are considered crucial in that particular research field, then the chosen citation window would be regarded as the most effective for detecting research fronts. However, as technology advances, scientific fields also become increasingly complex. Therefore, developing simpler and generally acceptable indices is both essential and a future trend for evaluating the effectiveness of research fronts identified from different citation windows.

In summary, this study adopted OLED-related literature as an example in conducting a comparative analysis of research fronts from three different citation windows by using bibliographic coupling. Future studies investigating the research fronts of a particular field may be guided by our research results, specifically that sliding windows is the most effective method because it detects the highest number of and the most vital research fronts. Because fixed citation windows can also identify other additional research fronts, sliding windows should be used jointly with fixed windows to gain a more comprehensive picture of the research fronts in a specific field. However, using sliding windows requires considerable time and effort. Therefore, this study also compared the effectiveness of fixed citation windows and citing half life; our results suggest that if researchers aim to only preliminarily understand the research fronts of field, they can adopt fixed citation windows first. Furthermore, regarding investigating the emerging fronts of a particular field, our results indicate that sliding windows is the most effective method because it detects the highest number of and the most vital emerging fronts. However, fixed citation windows can also identify other additional emerging fronts; therefore, sliding windows and fixed windows should be used in combination, which would result in a more comprehensive picture of the emerging fronts in a research field.

Research fronts represent cutting-edge studies in specific fields. Updates on trends in research fronts can improve understanding of current and future development trends in relevant fields. In most countries, scientists, analysts, and policy makers strive to obtain research fronts in a timely manner to maintain current knowledge regarding key technological developments. The results of this study enable us to provide more updated information on the research fronts of OLED, which can be incorporated into developments and investments related to the OLED field and can be used to evaluate national competitiveness. Furthermore, in the process of identifying the research fronts, an expert in the OLED field assisted in the labeling and explanation of relevant issues. When in doubt, he consulted other researchers for recommendations. Therefore, to ensure the accuracy of these findings on research fronts, collaboration with a team of experts in the designated field may facilitate the presentation of more valid results in future studies.

References

Aguillo, I. F. (1996). Increasing the between-year stability of the impact factor in the science citation index. *Scientometrics, 35*(2), 279–282.

Åström, F. (2007). Changes in the LIS research front: Time-sliced cocitation analyses of LIS journal articles, 1990–2004. *Journal of the American Society for Information Science and Technology, 58*(7), 947–957.

Boyack, K. W., & Klavans, R. (2010). Co-citation analysis, bibliographic coupling, and direct citation: Which citation approach represents the research front most accurately? *Journal of the American Society for Information Science and Technology, 61*(12), 2389–2404.

Boyack, K. W., Tsao, J. Y., Miksovic, A., & Huey, M. (2009). A recursive process for mapping and clustering technology literatures: Case study in solid-state lighting. *International Journal of Technology Transfer and Commercialisation, 8*(1), 51–87.

Buckley, A. (2013). *Organic light-emitting diodes (OLEDs): Materials, devices and applications*. Cambridge: Woodhead.

Campanario, J. M. (2011). Empirical study of journal impact factors obtained using the classical two-year citation window versus a five-year citation window. *Scientometrics, 87*(1), 189–204.

Chang, Y. W., Huang, M. H., & Lin, C. W. (2015). Evolution of research subjects in library and information science based on keyword, bibliographical coupling, and co-citation analyses. *Scientometrics, 105*(3), 2071–2087.

Chen, C. (2005). Measuring the movement of a research paradigm. In *Proceedings of the SPIE-IS&T: Visualization and data analysis* (pp. 63–76). San Jose, CA: The International Society for Optical Engineering.

Chen, C. H., & Hwang, S. W. (2005). *Organic electroluminescent materials & devices*. Taipei: Wu-Nan Culture Enterprise.

Chen, C. H., & Hwang, S. W. (2007). *OLED: Materials and devices of dream displays*. Taipei: Wu-Nan Culture Enterprise.

Chen, C., & Morris, S. A. (2003). Visualizing evolving networks: Minimum spanning trees versus pathfinder networks. In *Proceedings of IEEE symposium on information visualization* (pp. 67–74). Seattle, Washington, DC: IEEE Computer Society Press.

Chien, C. H., & Chen, C. H. (2001). OLED flat panel display technology. *Physical Biomonthly, 23*(2), 307–311.

Chizu, S., Yoshiake T., Takeshi, Y., Makoto, K., & Shuji, D. (2014). *Recent progress of high performance polymer OLED and OPV materials for organic printed electronics.* Retrieved September 3, 2014, from http://iopscience.iop.org/1468-6996/15/3/034203/pdf/1468-6996_15_3_034203.pdf.

Cornelius, B., LandstrÖm, H., & Persson, O. (2006). Entrepreneurial studies: The dynamic research front of a developing social science. *Entrepreneurship Theory and Practice, 30*(3), 375–398.

Divayana, Y. (2011). *Electroluminescence in organic light-emitting diodes: Basics, processes, and optimizations*. Saarbrücken: VDM.

Fujita, K., Kajikawa, Y., Mori, J., & Sakata, I. (2012). *Detecting research fronts using different types of combinational citation*. Retrieved September 19, 2014, from http://sticonference.org/Proceedings/vol1/Fujita_Detecting_273.pdf.

Fujita, K., Kajikawa, Y., Mori, J., & Sakata, I. (2014). Detecting research fronts using different types of weighted citation networks. *Journal of Engineering and Technology Management, 123*, 415–423.

Fukagawa, H., Watanabe, K., Tsuzuki, T., & Tokito, S. (2008). Highly efficient, deep-blue phosphorescent organic light emitting diodes with a double-emitting layer structure. *Applied Physics Letters, 93*(13), 133312.

Glänzel, W. (2012). *Bibliometric mothods for detecting and analyzing emerging research topics*. Retrieved August 29, 2014, from http://eprints.rclis.org/16947/1/Bibliometric%20methods.pdf.

Glänzel, W., & Schoepflin, U. (1995). A bibliometric study on aging and reception processes of scientific literature. *Journal of Information Science, 21*, 37–53.

Guo, H., Weingart, S., & Börner, K. (2011). Mixed-indicators model for identifying emerging research areas. *Scientometrics, 89*(1), 421–435.

Huang, M. H., & Chang, C. P. (2014). Detecting research fronts in OLED field using bibliographic coupling with sliding window. *Scientometrics, 98*(3), 1721–1744.

Huang, M. H., & Chang, C. P. (2015). A comparative study on detecting research fronts in the organic light-emitting diode (OLED) field using bibliographic coupling and co-citation. *Scientometrics, 102*(3), 2041–2057.

Hwang, S. W., & Chen, C. H. (2004). *Organic light emitting diode: OLED*. Taipei: National Science Council.

Iftikhar, M., Masood, S., & Song, T. T. (2012). Modified impact factor (MIF) at specialty level: A way forward. *Procedia—Social and Behavioral Sciences, 69*, 631–640.

Jacsó, P. (2009). Five-year impact factor data in the journal citation reports. *Online Information Review, 33*(3), 603.

Kajikawa, Y., & Takeda, Y. (2009). Citation network analysis of organic LEDs. *Technological Forecasting and Social Change, 76*(8), 1115–1123.

Kamtekar, K. T., Mankman, A. P., & Bryce, M. R. (2010). Recent advances in white organic light-emitting materials and devices (WOLEDs). *Advanced Materials, 22*, 572–582.

Knoke, D., & Yang, S. (2008). *Social network analysis* (2nd ed.). Los Angeles: Sage.

Koo, H. S. (2006). *The techniques and applications for OLEDs*. Taipei: New Wun Ching Developmental.

Koo, H. S. (2008). *The techniques and applications for OLEDs* (2nd ed.). Taipei: New Wun Ching Developmental.

Krell, F. T. (2012). *The journal imact factor as a performance indicator*. Retrieved September 5, from http://www.ease.org.uk/sites/default/files/essay_thorsten-krell.pdf.

Lin, J. S. (2009). Technology of white organic light emitting diode. *Chemical Monthly, 78*, 26–35.

Liu, J., Min, C., Zhou, Q., Cheng, Y., Wang, L., Ma, D., et al. (2006). Blue light-emitting polymer with polyfluorene as the host and highly fluorescent 4-dimethylamino-1,8-naphthalimide as the dopant in the sidechain. *Applied Physics Letters, 88*(8), 083505.

Madhava Rao, M. V., Su, Y. K., & Hsu, S. C. (2013). Improving the performance of phosphorescent based white polymer light emitting devices using iridium complexes. *International Journal on Organic Electronic, 2*(1), 19–24.

Mertens, R. (2014). *The OLED handbook: A guide to OLED technology, industry & market*. Herzelia: OLED-Info.

Morris, S. A., & Boyack, K. W. (2005). *Visualizing 60 years of anthrax research*. Retrieved January 11, 2011, from http://www.conceptsymbols.com/web/publications/2005_final_issi_anthrax.pdf.

Morris, S. A., Yen, G., Wu, Z., & Asnake, B. (2003). Time line visualization of research fronts. *Journal of the American Society for Information Science and Technology, 54*(5), 413–422.

Nierop, E. (2010). The introduction of the 5-year impact factor: Does it benefit statistics journals? *Statistica Neerlandica, 64*(1), 71–76.

Persson, O. (1994). The intellectual base and research fronts of JASIS 1986-1990. *Journal of the American Society for Information Science, 45*(1), 31–38.

Sebastian, R., Michael, T., Björn, L., & Karl, L. (2013). *White organic light-emitting diodes: Status and perspective*. Retrieved September 3, 2014, from http://arxiv.org/pdf/1302.3435.pdf.

Segal, M., Singh, M., Rivoire, K., Difley, S., Voorhis, T. V., & Baldo, M. A. (2007). Extrafluorescent electroluminescence in organic light-emitting devices. *Nature Materials, 6*, 374–378.

Shibata, N., Kajikawa, Y., Takeda, Y., & Matsushima, K. (2008). Detecting emerging research fronts based on topological measures in citation networks of scientific publications. *Technovation, 28*, 758–775.

Shibata, N., Kajikawa, Y., Takeda, Y., & Matsushima, K. (2009). Comparative study on methods of detecting research fronts using different types of citation. *Journal of the American Society for Information Science and Technology, 60*(3), 571–580.

Shibata, N., Kajikawa, Y., Takeda, Y., Sakata, I., & Matsushima, K. (2011). Detecting emerging research fronts in regenerative medicine by the citation network analysis of scientific publications. *Technological Forecasting and Social Change, 78*, 274–282.

Small, H. (2006). Tracking and predicting growth areas in science. *Scientometrics, 68*(3), 595–610.

Sombatsompop, N., Markpin, T., & Premkamolnetr, N. (2004). A modified method for calculating the impact factors of journals in ISI journal citation reports: Polymer science category in 1997–2001. *Scientometrics, 60*(2), 217–235.

Sun, J. W., Lee, J. H., Moon, C. K., Kim, K. H., Shin, H., & Kim, J. J. (2014). A fluorescent organic light-emitting diode with 30% external quantum efficiency. *Advanced Materials, 26*(32), 5684–5688.

Türker, L., Tapan, A., & Gümüş, S. (2009). Electroluminescent properties of certain polyaromatic compounds: Part 1—Characteristics of oled devices based on fluorescent polyaromatic dopants. *Polycyclic Aromatic Compounds, 29*(3), 123–138.

Upham, S. P., & Small, H. (2010). Emerging research fronts in science and technology: Patterns of new knowledge development. *Scientometrics, 83*(1), 15–38.

Van Leeuwen, T. N., & Moed, H. F. (2002). Development and application of journal impact factor measures in the Dutch science systems. *Scientometrics, 53*(2), 249–266.

Van Leeuwen, T. N., Moed, H. F., & Reedijk, J. (1999). Critical comments on Institute for scientific information impact factors: A sample of inorganic molecular chemistry journals. *Journal of Information Science, 25*(6), 489–498.

Yang, L., Morris, S. A., & Barden, E. M. (2009). Mapping institutions and their weak ties in a research specialty: A case study of cystic fibrosis body composition research. *Scientometrics, 79*(2), 421–434.

Zhao, D., & Strotmann, A. (2014). The knowledge base and research front of information science 2006–2010: An author cocitation and bibliographic coupling analysis. *Journal of the Association for Information Science and Technology, 65*, 995–1006.

Zink, D. M., Bergmann, L., Ambrosek, D., Wallesch, M., Volz, D., & Mydlak, M. (2014). *Singlet harvesting copper-based emitters: A modular approach towards next-generation OLED technology*. Retrieved September 20, 2014, from http://iopscience.iop.org/2053-1613/1/1/015003/pdf/2053-1613_1_1_015003.pdf.