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Citation network analysis of organic LEDs

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ABSTRACT

The field of organic light-emitting diodes (OLEDs) is an emergent research domain because of both scientific interest in chemistry and condensed matter physics and industrial importance as flat panel displays. In this paper, we analyzed a citation network of OLED papers and used a topological clustering method to investigate the structure of research and to detect emerging research domains. We found that most papers belong to two main clusters: organics and polymers. These two clusters have distinctive differences in subcluster structures and journals where papers are published. Supposing this discrepancy to indicate research progress, organics are in the applied research stage, while polymers are in the basic research stage.

1. Introduction

Scientific knowledge is a critical component of the modern age, and the importance of its creation, dissemination, and application is still increasing. For example, great progress and personalization in computers and the Internet are driven by innovative breakthrough both in fundamental and applied science such as physics, electronics, materials science, computer science, and information science. Modern life benefits enormously from these scientific activities. The semiconductor industry is a typical industry highly dependent upon research and development based on the latest scientific breakthroughs. The speed and scope of development in such an area make it critical for researchers, engineers, and policy makers to be aware of information published across different research domains and different institutions.

Bibliometrics are a powerful tool for overviewing scientific activities in a manner that individuals cannot handle. Bibliometric information, i.e., scientific publications, patents and citations to these publications and patents, constitute an adequate information source for mapping the fields or subfields of scientific and technological fields. There are a number of reports in the semiconductor industry and related scientific research fields based on the bibliometric approach [1–11]. For example, Tsay et al. analyzed the literature on semiconductors by statistical measures such as the number of publications in journals [1], by authors [2], and by citation counts and co-citations [3]. Guan and Ma analyzed publication trends and collaboration patterns of China's semiconductor literature [4]. Bhattacharya and Basu analyzed research topics in related research fields [5].

However, fundamental changes are occurring. For example, the basic components of the semiconductor industry are thin metal and semiconductor films fabricated on silicon substrates. There is an emerging trend from Si-based technology to organics-based technology at least at the stage of academic research. For example, Kajikawa et al. revealed by the citation network analysis that in solar cell research the plastic solar cell is an emerging research area [12]. The role of polymers in the electronics industry is conventionally associated with insulating properties, whether these are for isolating metallic conductors or for use in photoresist technology. But organic materials are expected to be realized as key devices in the electronics industry such as thin film transistors (TFT), liquid–crystal displays (LCDs), and light-emitting devices (LEDs). Organic materials are very promising materials for flexible displays with many advantageous characteristics including transparency, light weight, flexibility, and robustness. They are also

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Table 1
Top 10 papers not included in the maximum connected component.

Rank	First author	Paper title	Journal	Year	TC
1	Felsenfeld G	Chromatin as an essential part of the transcriptional mechanism	Nature	1992	766
2	Bockaert J	Molecular tinkering of G protein-coupled receptors. an evolutionary success	EMBO J.	1999	663
3	Neurath MF	Antibodies to interleukin-12 abrogate established experimental colitis in mice	J. Exp. Med.	1995	624
4	Slade L	Beyond water activity — recent advances based on an alternative approach to the assessment of food quality and safety	Crit. Rev. Food. Sci. Nutr.	1991	623
5	Lingner J	Reverse transcriptase motifs in the catalytic subunit of telomerase	Science	1997	617
6	Wittwer CT	The lightcycler(tm) a microvolume multisample fluorimeter with rapid temperature control	Biotechniques	1997	615
7	Raymo ME	Tectonic forcing of late Cenozoic climate	Nature	1992	570
8	Shenton ME	A review of MRI findings in schizophrenia	Schizophr. Res	2001	563
9	Bryan GW	Bioavailability, accumulation and effects of heavy-metals in sediments with special reference to United-Kingdom estuaries — a review	Environ. Pollut.	1992	472
10	Solomon E	Chromosome-aberrations and cancer	Science	1991	468

some of the least expensive materials and are suitable for mass production via roll-to-roll processes. Therefore, there is an urgent need to understand this emerging and promising research field.

This paper analyzes the academic landscape of organic LEDs (OLEDs) to understand the current structure of research by citation network analysis and to detect emerging sub-research-fields within it. In a recent paper, Small and Upham analyzed the citation network of organic TFT [13]. From that starting point, the pioneering work of MacDiarmid, Heeger, and Shirakawa, who won the Nobel prize in chemistry in 2000, inspired chemists and physicists to consider the opportunities of using polymers as conductors. OLEDs are another promising candidate of applications of organic conductors. Light-emitting organic materials under an electric field gained increasing attention in the last decade both for their scientific interest and industrial importance. Products based on active thin-film organic devices are already in the market place, most notably the displays of several mobile electronic appliances. In this paper, we focus on academic publications and analyze the structure of citation networks. In the next section, we present our methodology.

2. Data and methods

2.1. Data

We collected citation data of those publications from the Science Citation Index (SCI) and the Social Sciences Citation Index (SSCI) compiled by the Institute for Scientific Information (ISI), because SCI and SSCI are two of the best sources for citation data. We used Web of Science, which is a Web-based user interface of ISI's citation databases. We searched the papers using the following queries, ((organic* or polymer*) and (electroluminescence* or electro-luminescence* or electro luminescence* or light emitting or LED*)) or OLED*, where * means wildcard.

The above set of queries was determined by the authors to include a wide coverage of papers targeting OLEDs. But it does not mean that the query sufficiently covers relevant papers. The queries, electroluminescence* or electro-luminescence* or electro luminescence* or light emitting or LED*, are necessary, because these are indispensable characteristics of OLEDs. But if we use only this one, the corpus will contain non-relevant papers targeting electroluminescent inorganic materials and be very noisy. Therefore, we must put restrictions to extract papers of OLEDs. One option for such restriction is adding the name of each organic materials as the query. But it is not realistic because there is huge number of varieties in organic materials. Therefore, we simply use organic* or polymer* for that purpose.

Bibliographic records of 33,740 papers were retrieved. The data includes all ISI records, i.e. articles, letters, reviews, editorials, meeting abstracts, and so forth. We extracted the maximum connected component from the retrieved data, and it converted into a non-weighted, non-directed network. In other words, we regarded papers not citing other papers in the component as digressional. The obtained network currently has 16,551 papers (49.05% of the retrieved data). The most cited top 10 papers which are not included in the component are shown in Table 1. These papers are not OLED papers. Therefore, we can eliminate some of the noisy papers retrieved by the query we used.

2.2. Method

Subsequently, the network was divided into clusters using the topological clustering method [14,15]. Traditionally, co-citation has been used to analyze a citation network. However, because co-citation is accompanied by a time lag to create a link, and analysis of direct citation is more relevant in the similarity of pairs of documents [16] and in the detection of research fronts [17] than co-citation, we used direct citation as a link. The clustering algorithm is based on modularity Q, which is defined as follows [14,15]:

$$Q = \sum_{s=1}^{N_m} \left[\frac{l_s}{l} - \left(\frac{d_s}{2l} \right)^2 \right] \quad (1)$$

where N_m is the number of clusters, l_s is the number of links between nodes in cluster s, and d_s is the sum of the degrees of the nodes in cluster s. In other words, Q is the fraction of links that fall within clusters, minus the expected value of the same quantity if the links fall at random without regard for the clustered structure. Since a high value of Q represents a good division, we stopped joining when became minus. A good partition of a network into clusters means there are many within-cluster links and minimal between-cluster links.

After clustering the network, we characterized each cluster by the titles and abstracts of papers that are frequently cited by the other papers in the same cluster. This does not mean that all papers in the cluster study the same topics as covered in these frequently cited papers. In fact, each paper studies its own topics, and each paper has its own unique focus. However, as a first approach, it is reasonable to treat these inter-cited papers as a cluster to investigate the brief structure of a research domain and to consider the frequently cited papers in the cluster as representative of the same. The clustered network is visualized by using a large graph layout (LGL) [18], which is based on a spring layout algorithm where links play the role of spring connecting nodes. Thanks to such layout, papers that cite each other and form a group can be located in closer proximity. We also analyzed the average publication year of papers in each cluster, which is a sign of the speed at which an emerging cluster is developing [19].

In the previous papers, we elucidate the structure of research domains by clustering the citation networks [12,20,21]. By analyzing the publication year of papers in each cluster, we can comprehend the research trend in the domains and detect the emerging research clusters there [12]. Other papers analyze the relationships among clusters using citation count [20], and visualization [21]. By analyzing inter-cluster citation and visualized results, we can judge the interdependency among different research clusters. In this paper, we analyze the distribution of journals in each cluster after clustering. We will demonstrate that information of publication source can be used to monitor the progress of research and evaluate it in different clusters.

3. Results

The citation network of optics can be divided into 129 clusters by topological clustering method, where the number of nodes in each cluster varies from 2 (the smallest clusters) to 6320 (the biggest cluster, #1). Papers in each cluster are strongly coupled with the within-cluster citations. Cluster size, i.e., the number of nodes in each cluster, steeply decreases and after the 4th cluster they become negligible as shown in Fig. 1. Most papers (73.6%) belong to Cluster #1 or #2. Therefore, in the following, we focus on the top 2 clusters, and investigate the detailed structure of those clusters.

Tables 2 and 3 show the top 20 papers in each cluster. Papers are listed in the order of times cited, Tc, in the maximum connected component. The rank of the paper in the cluster, *R*, and that in the component, Rt, are also shown. As we can see in the tables, the research focus of papers in Cluster #1 is organics, and that of Cluster #2 is polymers. The most cited paper in Cluster #1 is the seminal work of Tang and Van Slyke [22] that demonstrated efficient electroluminescence (EL) by using a two layer film comprised of a hole-transporting layer and an emissive layer. These layers are composed of sublimed low molecular weight organics. Although their film has a problem in the short lifetime, their devices operated at quite low voltages of 10 V compared to the existing devices operated at several hundreds of volts. And their later paper reported an improvement of the stability of their films [23]. Other researchers reported an improvement of EL efficiency by using phosphorescent dyes [24,25] and by Al/LiF bilayer [26], and tuning the color in the emissive light [27,28].

The most cited papers in Cluster #2 were published shortly after the paper of Tang and Van Slyke [22] by 1990 the Cambridge group [29]. They observed green–yellow EL by using the conjugated polymer, poly(p-phenylene vinylene) (PPV). As the precursor polymer is soluble and the film is prepared from solution by spin casting, we can expect low cost processing. Brown and Heeger propose that light emission from polymers occurs by tunneling of electrons from the recitifying metal contact into the gap states of the positive polaron majority carriers [30]. Other researchers seek more efficient EL layer and device structures. For example,

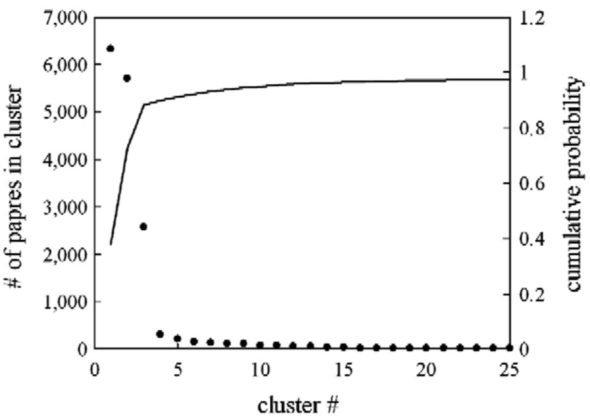

Fig. 1. Distribution of the number of papers in each cluster. Black circles are the number of papers included in each cluster. The line is the cumulative probability of the number of nodes.

Table 2
Top 20 papers in cluster #1.

R	Rt	Author	Title	Journal	Year	Tc
1	2	Tang & Slykc	Organic electroluminescent diodes	Appl. Phys. Lett.	1987	3498
2	4	Tang et al.	Electroluminescent of doped organic thin-films	J. Appl. Phys.	1989	1337
3	9	Baldo et al.	Highly efficient phosphorescent emission from organic electroluminescent devices	Nature	1998	922
4	10	Parker	Carrier tunneling and device characteristics in polymer light-emitting-diodes	J. Appl. Phys.	1994	768
5	12	Baldo et al	Very high-efficiency green organic light-emitting devices based an electrophosphorescence	Appl. Phys. Lett.	1999	563
6	13	Vanslyke et al.	Organic electroluminescent devices with improve stability	Appl. Phys. Lett.	1996	560
7	14	Hung et al	Enhanced electron injection in organic electroluminescence devices using an Al/LiF electrode	Appl. Phys. Lett.	1997	553
8	15	Sheats et al.	Organic electroluminescent devices	Science	1996	503
9	18	Kido et al.	Multilayer white light-emitting organic electroluminescent device	Science	1995	462
10	26	Adachi et al.	Blue light-emitting organic electroluminescent devices	Appl. Phys. Lett.	1990	416
11	27	Adachi et al.	Nearly 100% internal phosphorescence efficiency in an organic light-emitting device	J. Appl. Phys.	2001	410
12	29	Lamansky et al.	Highly phosphorescent bis-cyclometalated iridium complexes synthesis, photophysical characterization, and use in organic light emitting diodes	J. Am. Chem. Soc.	2001	390
13	30	Burrows et al.	Relationship between electroluminescence and current transport in organic heterojunction light-emitting devices	J. Appl. Phys.	1996	370
14	33	Baldo et al.	High-efficiency fluorescent organic light-emitting devices using a phosphorescent sensitizer	Nature	2000	338
15	34	Adachi et al.	Organic electroluminescent device having a hole conductor as an emitting layer	Appl. Phys. Lett.	1989	332
16	35	Kido et al.	Single-layer white light-emitting organic electroluminescent devices based on dye-dispersed poly(n-vinylcarbazole)	Appl. Phys. Lett.	1995	320
17	37	Tessler et al.	Lasing from conjugated-polymer microcavities	Nature	1996	318
18	43	Shirota et al.	Multilayered organic electroluminescent device using a novel starburst molecule, 4,4′,4″-tris(3-methylphenylphenylamino)triphenylamine, as a hole transport material	Appl. Phys. Lett.	1994	287
19	44	Shirota	Organic materials for electronic and optoelectonic devices	J. Mater. Chem.	2000	284
20	45	Kido et al.	White light-emitting organic electroluminescent devices using the poly(n-vinylcarbazole) emitter layer doped with 3 fluorescent dyes	Appl. Phys. L	1994	282

polyaniline is proposed as the hole-injecting electrode in addition to PPV as the EL layer [31]. And other polymers such as poly (cyanoterephthalylidene) [32], poly(p-phenylene) [33] are also studied.

To investigate the detailed structures of Cluster #1 and #2, we performed recursive clustering. These clusters are divided into subclusters. We call Cluster #1 and Cluster #2 the 1st level cluster and subclusters obtained by recursive clustering of Cluster #1 and #2 the 2nd level subclusters. The basic characteristics of the 1st cluster and 2nd level subclusters are shown in Table 4. Both clusters are mainly divided into these subclusters. Subclusters of Cluster #1 are: #11 electronic properties including 2518 papers whose average publication year (year_{ave}) is 2003.6 (afterwards, we express it as (2516; 2003.6), #12 device performance (2402; 2002.7), and #13 high performance device (1311; 2005.4). Judging from this subcluster structure, Cluster #1, i.e., research on organics is centered on device performance and its improvement. Research on high performance device (#13) is the most active research area whose year_{ave} is 2005.4. Subclusters of Cluster #2 are: #21 PPV and related polymers (2337; 2001.0), #22 polyfluorene and related polymers (1609; 2004.4), #23 theoretical study and other polymers (1383; 2002.4). Research on

Table 3
Top 20 papers in cluster #2.

R	Rt	Author	Title	Journal	Year	Tc
1	1	Burroughes et al.	Light-emitting-diodes based on conjugated polymers	Nature	1990	4249
2	3	Friend et al.	Electroluminescence in conjugated polymers	Nature	1999	1564
3	5	Braun & Heeger	Visible-light emission from semiconducting polymer diodes	Appl. Phys. Lett.	1991	1281
4	6	Kraft et al.	Electroluminescent conjugated polymers - seeing polymers in a new light	Angew Chem.	1998	1174
5	7	Gustafsson et al.	Flexible light-emitting-diodes made from soluble conducting polymers	Nature	1992	1015
6	8	Greenham et al.	Efficient light-emitting-diodes based on polymers with high electron-affinities	Nature	1993	948
7	11	Grem et al.	Realization of a blue-light-emitting device using poly(para-phenylene)	Adv. Mater.	1992	564
8	16	Mitschke & Bauerle	The electroluminescence of organic materials	J. Mater. Chem.	2000	472
9	17	Brown et al.	Poly(p-phenylenevinylene) light-emitting-diodes — enhanced electroluminescent efficiency through charge earner confinement	Appl. Phys. Lett.	1992	467
10	19	Burn et al.	Chemical tuning of electroluminescent copolymers to improve emission efficiencies and allow patterning	Nature	1992	445
11	20	Berggren et al.	Light-emitting-diodes with variable colors from polymer blends	Nature	1994	441
12	21	Scherf & list	Semiconducting polyfluorenes — towards reliable structure-property relationships	Adv. Mater.	2002	440
13	22	Pei et al.	Polymer light-emitting electrochemical-cells	Science	1995	438
14	23	Bernius et al.	Progress with light-emitting polymers	Adv. Mater.	2000	438
15	24	Ohmori et al.	Blue electroluminescent diodes utilizing poly(alkylfluorene)	Jpn. J. Appl. Phys.	1991	436
16	25	Pei & yang	Efficient photoluminescence and electroluminescence from a soluble polyfluorene	J. Am. Chem. Soc.	1996	418
17	28	Jenekhe & Osaheni	Excimers and exciplexes of conjugated polymers	Science	1994	397
18	31	Cao et al.	Improved quantum efficiency for electroluminescence in semiconducting polymers	Nature	1999	356
19	16	Yang et al.	A soluble blue-light-emitting polymer	Macromolecule	1993	320
20	38	Grice et al.	High brightness and efficiency blue light-emitting polymer diodes	Appl. Phys. Lett.	1998	307

Table 4
1st Clusters and 2nd level subclusters of clusters #1 and #2.

Cluster name (#papers, $year_{ave}$)	Subcluster name (#papers, $year_{ave}$) >1,000 nodes
#0 Organics (6,320; 2003.7)	#11 Electronic properties (2,518; 2003.6)
	#12 Device performance (2,402; 2002.7)
	#13 High performance device (1,311; 2005.4)
#1 Polymers (5,703; 2002.4)	#21 PPV and related polymers (2,337;2001.0)
	#22 Polyfluorene and related polymers (1,609; 2004.4)
	#23 Theoretical study and other polymers (1,383; 2002.4)

polyfluorene and related polymers (#22) is the most active among them. Cluster #2 seems to be divided according to the type of polymer.

Table 5 is the structure of 3rd and 4th level subclusters of Cluster #1. Many efforts are devoted to enhancing electron injection (i.e., Cluster #111) by using SAM (#1111), an aluminum based cathode (#1112), and surface treatment of indium–tin–oxide (#1113). Other studies investigate electronic behaviors (#112) such as electric-field and temperature dependence of the hole mobility (#1121), interface and lifetime (#1122), and transient electroluminescence (#1123). It is clear that enhancement of electron injection efficiency and modifying electronic behaviors can improve device performance. Cluster #113 investigates the device structure and performance itself. Key research topics are surface emission and transparent devices (#1131), nano-patterns and photo crystals to improve efficiency (#1132), microcavity effect (#1133), and low operating voltage and high efficiency diodes (#1134). In addition to EL efficiency (#131) as device performance, reliability (#121) and color of the emission (#123, #132) are also important to realize OLEDs. Although already shown in the above and illustrated in detail later, in polymer research (Cluster #2), we can see many subclusters dedicated to particular types of polymer, and research seeking novel organic molecules (#122) does not occupy a large fraction.

Table 6 is the structure of 3rd and 4th level subclusters of Cluster #2. The large fraction of subclusters focuses on new polymers. PPV is a traditional polymer used by a pioneering group of Cambridge, other polymers such as silole derivatives (#222), fluorene derivatives (#223), and other conjugated polymers (#232), and a mixture of conjugated polymers (#2122) is explored. There are theoretical studies (#231) for science-based polymer design. The effect of side chains (#2121) is a key issue for polymer design. Other research tries to control some specific properties of polymers such as emission wavelength (#2111, #2114) and polarized electroluminescence (#2212).

By focusing on $year_{ave}$, we can extract emerging subclusters among a variety of research topics. For example, in Cluster #1, we can see a number of emerging subclusters such as #1111 enhanced electron injection using SAM (276; 2004.2), #1113 surface treatment of indium–tin–oxide (235; 2004.3) #1131 surface emission and transparent devices (247; 2004.9), #1132 nano-patterns and photo crystals improving efficiency (199; 2004.6), #1134 low operating voltage and high efficiency diodes (135; 2005.2), #1223 novel blue-light-emitting molecule 183; 2004.5), and #1232 red electroluminescence (119; 2004.4). In Cluster #2, PPV and its derivatives (#2112, $year_{ave}$ = 1998.3) are relatively old, and other polymer candidates such as polyfluorene based films (#2211, 2004.5), silole derivatives (#222, 2004.6) and multicomponent conjugated polymers (#2122, 2003.6) are extensively explored.

Table 5
3rd and 4th Level subclusters of the cluster #1.

Cluster name (#papers, $year_{ave}$) >400 nodes	Subcluster name (#papers, $year_{ave}$) >100 nodes
#111 Enhanced electron injection (866; 2004.0)	#1111 Enhanced electron injection using SAM (276; 2004.2)
	#1112 Enhanced electron injection aluminum based cathode structure (260; 2003.7)
	#1113 Surface treatment of indium–tin–oxide (235; 2004.3)
#112 Electronic behaviors (775; 2002.2)	#1121 Electric-field and temperature dependence of the hole mobility (288; 2003.4)
	#1122 Interface and lifetime (229; 2000.8)
	#1123 Transient electroluminescence (192; 2001.7)
#113 Device structure and performance (747; 2004.3)	#1131 Surface emission and transparent devices (247; 2004.9)
	#1132 Nano-patterns and photo crystals improving efficiency (199; 2004.6)
	#1133 Microcavity effect (152; 2002.0)
	#1134 Low operating voltage and high efficiency diodes (135; 2005.2)
#121 Reliability and performance (969; 2002.3)	#1211 Luminescent mechanism (388; 2001.5)
	# 1212 Reliability and degradation (312; 2002.5)
	#1213 Improvement of efficiency and reliability (215; 2003.4)
#122 Novel molecule (775; 2003.7)	#1221 Structural effects on electronic states (275; 2003.1)
	#1222 Novel molecules (266; 2003.2)
	#1223 Novel blue-light-emitting molecule 183; 2004.5)
#123 Emission wavelength (504; 2001.9)	#1231 Multilayer structure and white light emission (181; 2000.1)
	#1232 Red electroluminescence (119; 2004.4)
#131 High efficiency emission (581; 2005.6)	
#132 White-light emission (418; 2005.2)	

Table 6
3rd and 4th Level subclusters of the cluster #2.

Cluster name (#papers, $year_{ave}$) >300 nodes	Subcluster name (#papers, $year_{ave}$) >300 nodes
#211 Polymer design (539; 1999.0)	#2111 Blue-light-emitting polymer (257; 1999.2)
	#2112 Poly(phenylene vinylene) (PPV) derivatives (240; 1998.3)
	#2113 Chemical tuning of the electronic properties (210; 1999.2)
	#2114 Control of emission wavelength (131; 1998.8)
#212 Polymer design (778; 2002.2)	#2121 Effect of side chains (337; 2000.5)
	#2122 Multicomponent conjugated polymers (198; 2003.6)
	#2123 Novel polymers (164; 2003.3)
#213 PPV derivatives (402; 2002.7)	
#221 Polymer design and properties (544; 2004.1)	#2211 Polyfluorene based films (253; 2004.5)
	#2212 Polarized electroluminescence (210; 2003.3)
	#2213 Structure of liquid–crystalline conjugated polymer (78; 2004.7)
#222 Silole derivatives (481; 2004.6)	
#223 Fluorene derivatives (452; 2004.4)	
#231 Theoretical study (365 2001.3)	
#232 Conjugated polymers (452; 2003.1)	

Other subclusters shedding light on different structural aspect and property of polarized electroluminescence (#2212, 2003.3) and structure of liquid–crystalline conjugated polymer (#2213, 2004.7) are also emerging research areas.

4. Discussion

In this paper, we performed topological clustering of the citation network of OLED research to investigate the structure of research, and found that most OLED papers (73.6%) belong to the largest cluster (Cluster #1) or the second largest cluster (Cluster #2). We also found emerging research domains in those clusters by the recursive clustering method. Cluster #1 and #2 focus on the research of organics and polymers, respectively. And there is a fundamental difference in the structure of subclusters in those clusters. Cluster #1 can be divided by the type of methodology to enhance device performance, while Cluster #2 can be divided by the type of polymer used in it. Reflecting this difference, we can also see the different distribution of journals in which papers in each cluster are published (Table 7). Table 7 shows the top 20 journals in the order of the number of OLED papers. A large fraction of papers in Cluster #1 is published in the journals of applied physics field such as *Applied Physics Letters*, *Journal of Applied Physics*, and *Japanese Journal of Applied Physics*, while papers in Cluster #2 are in the journals of chemistry and materials science such as *Synthetic Metals*, *Macromolecules*, *Advanced Materials*, *Chemistry of Materials*. One plausible explanation for this discrepancy in journal distribution is that it reflects the nature of organics research (Cluster #1) and polymer research (Cluster #2). But it might not be valid for our case. Fig. 2 shows the publication trend of each cluster. As shown in Fig. 2, even in cluster 2, there are papers published in the journals of applied physics field until 1999, and the number of papers of Cluster #2 published in these journals is almost equivalent to that of Cluster #1. But there is a strong difference in the publication trend between Cluster #1 and #2. While the fraction of papers of Cluster #1 published in these journals is increasing, that of Cluster #2 is saturated or decreasing. As researchers first test the feasibility of their molecules or polymers for OLED devices by measuring their EL properties, and then

Table 7
Number of papers in the top 20 journals.

Journal	Total	Cluster #1	Cluster #2
Appl. Phys. Lett.	1470	986	162
Synth. Met.	1417	476	699
Macromolecule	705	24	523
J. Appl. Phys.	629	413	89
Jpn. J. Appl. Phys.	516	315	88
Adv. Mater.	502	177	192
Thin Solid Films	470	254	108
Chem. Mater.	355	103	178
J. Polym. Sci. A-Polym. Chem.	351	24	270
J. Phys. Chem. B	337	73	181
J. Mater. Chem.	289	97	120
J. Am. Chem. Soc.	277	77	114
Phys. Rev. B	263	92	129
Mol. Cryst. Liq. Cryst.	249	116	86
Adv. Funct. Mater.	236	116	73
Chem. Phys. Lett.	221	112	79
Polymer	213	14	141
Org. Electron.	174	123	21
J. Phys. D	145	102	15
J. Lumin.	137	69	30

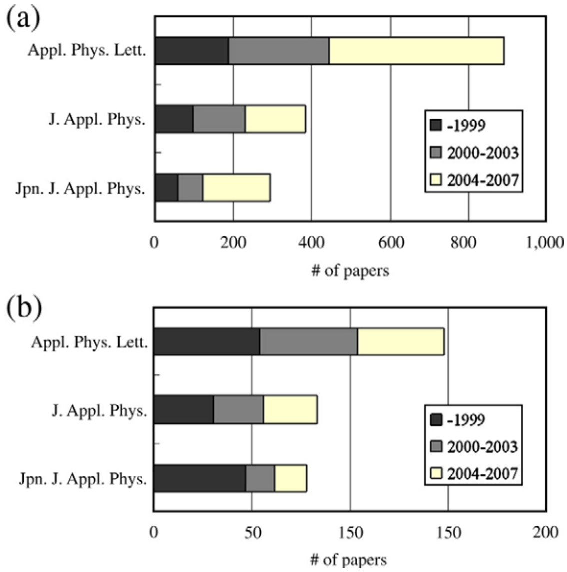

Fig. 2. Number of publications in the representative journals in the area of applied physics. (a) Cluster #1, and (b) Cluster #2.

design and improve the total structure of OLED devices, we can suppose that the journals where their outcomes are published differ from the development stage of their research. In the initial stage, it is plausible that a large fraction of their submission is to the journals related to chemistry and materials science, and in the later stage, it shifts to the journals related to applied physics. Therefore, we can evaluate a research domain by tracking the journals and their categories and by comparing them with those in the competitive research domains.

Before concluding this work, it is worth noting a limitation of the bibliographic approach. One of the difficulties in evaluating a research domain lies in the definition of a research domain by a set of scientific publications extracted from a database. To construct the corpus to analyze, we must retrieve papers by using queries, and the selection of relevant query for collecting necessary and sufficient papers is not an easy task.

In this paper, we collected papers by the query described in the section of data. But such an approach often results in the inclusion of noisy data. A word has more than one connotation, and can be used in a different meaning, and we sometimes experience difficulty in expressing a scientific concept by a couple of words. Our work also has the same problem. Our retrieved corpus includes noisy papers whose contents do not directly relate to OLED. Some papers were eliminated because we focus on the maximum connected component, while other are included in the component.

But visualization of a citation network can solve this problem. For example, we examined the research topics in papers of Cluster #4 and #5, but Cluster #4 (polymerization) and Cluster #5 (LED light curing biomaterials) are not directly related to OLEDs. Papers in #4 seem to be collected because they include terms related to OLED in keyword plus assigned by ISI but do not include those terms in their titles and abstracts. Papers in #5 focus on the reaction of organic materials on the surface of biomaterials under light irradiation using

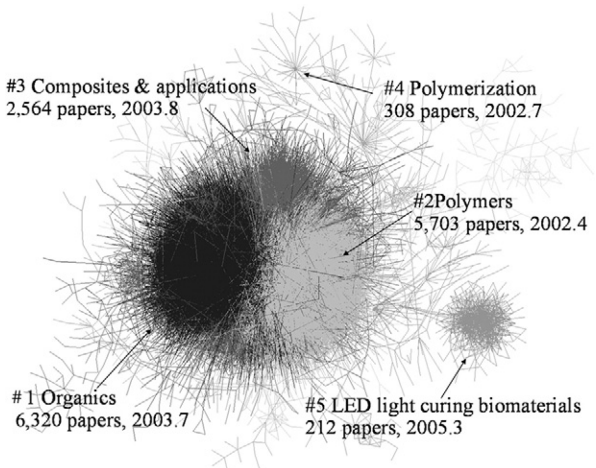

Fig. 3. Visualization of the citation networks.

LEDs. These papers were collected because we used a set of simple queries in retrieval. But this discrepancy is also illustrated by the result of visualization, where these two clusters locate apart from the other clusters (Fig. 3). Therefore, our visualized results illustrate that these clusters are outside the focus of OLED research. Analyzing the citation network and visualizing can detect noisy data in the corpus before evaluating a research domain. Therefore, the implication and recommendation to eliminate noisy papers obtained by this work is to extract the maximum connected component and then to eliminate clusters locating in greatly differing position in visualized results. The latter approach can be supported by some algorithms which quantitatively express the distance of the cluster form the other clusters. These cleansing processes are essential because if the performance of the cleansing algorithm is sufficiently high, we can use iterative process of query expansion and cleansing. The development of this corpus construction approach to define research domain by a necessary and sufficient set of papers are needed and must be solved in future research.

5. Conclusion

In this paper, we analyze the citation network of OLED research, which is an emergent research domain in chemistry and condensed matter physics, because of the industrial importance as flat panel displays. We performed clustering recursively to investigate the structure of research and to detect emerging research domains. We found that most papers belong to two main clusters: organics and polymers, and detected emerging subclusters in these clusters. These two clusters have distinctive differences in subcluster structures; research in organics is divided according to the methodology for improving device performance, while research in polymers is divided according to the type of polymers they used. We also see a discrepancy in the distribution of journals where papers in each cluster are published. Supposing this discrepancy to indicate research progress, organics are in the applied research stage, while polymers are in the basic research stage.

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