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Investigation of technological trends in flexible display fabrication through patent analysis

Pao-Long Chang [a], Chao-Chan Wu [b], Hoang-Jyh Leu [c,*]

[a] Department of Business Administration, Feng Chia University, 100, Wen-Hwa Road, Seatwen, Taichung 40724, Taiwan
[b] Department of Cooperative Economics, Feng Chia University, 100, Wen-Hwa Road, Seatwen, Taichung 40724, Taiwan
[c] Nanotechnology Research Center, Feng Chia University, 100, Wen-Hwa Road, Seatwen, Taichung 40724, Taiwan

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ABSTRACT

This paper uses patent network analysis to investigate technological trends in the field of flexible display fabrication through technology centrality index (TCI) and technology cycle time (TCT) index. The fabrication of electrophoretic display (EPD) was indicated as the key factor in future development of flexible display. Further, the critical technologies were obtained from cluster analysis, and the density index (DI) value of each cluster identified the invention of key materials for electro-optic display as the most important subject, especially in flexible EPD. Finally, recent journal publications and website reports using display key materials as electrophoretic ink could prove that development of EPD device was most important and close to marketing trend. The procedure of this patent network analysis presents significant insights quickly in the field of flexible display fabrication. This fruitful methodology is capable of supporting technological trends effectively for the researchers who are interested in scientific field.

1. Introduction

Display fabrication on a flexible substrate has gained significant interest in the portable photonic products because of its light, convenient and durable characteristics [1,2]. A great deal of attention is being paid to flexible display which represents a new generation of flat panel display [3–5]. The advantages are low cost, less power consumption, short response time, or large area display because it has the potential to be extended to roll-to-roll processes [6–8]. Nevertheless, some technical bottlenecks need to be resolved for the reason of substrate limitation [6,8,9]. In present stage of technological development, it is necessary to realize the key technologies and monitor the technological trends of flexible display fabrication.

Patents represent rich and potentially fruitful sources of data for the study of innovation and technical change [10]. Patent analysis is a useful tool that transfers the patent data into systematic and valuable information about a particular technology. The aim of patent analysis is to evaluate technological development, explore important technologies, monitor technological trends, or make technological plans [11–14]. Traditionally, patent bibliometric analysis is most frequently adopted to perform patent analysis [15]. However, this conventional method is limited to the scope of analysis, the richness of potential information, and the frequency of citations. Instead of the conventional method, patent network analysis is an advanced method of patent analysis suggested by Yoon and Park [16]. Researchers can easily comprehend the overall structure and identify the influential patents in the patent network [12].

The novelty of patent network analysis is to point out the technological trends in scientific research. The important features of this method are organized as follows. Firstly, patent network analysis uses more diverse keywords as research input to construct the relationship of patents and thereby outputs the useful information from internal patent network structure. Secondly, the visualization of patent network enables the researchers to intuitively understand the overview of a set of patents in the field of the technology being studied. Thirdly, this analytical process assists the researchers in finding the relatively important patents quickly without spending time on reading the whole contents of patents. Fourthly, the detailed treatment of this method is uncomplicated in terms of saving time and cost. Finally, this method can easily generate meaningful indexes to identify the critical technologies and analyze the technological trends in research field. The researchers can quickly acquire the effective results in handling lots of patent documents by using patent network analysis for the purpose of scientific management.

Although previous studies focused on using patent bibliometric analysis to implement patent search, this conventional analysis had no capability of considering internal relationship among patents and hence might generate superficial or even misleading

* Corresponding author. Tel.: +886 4 24517250x6865; fax: +886 4 24523485.
E-mail address: hjleu@fcu.edu.tw (H.-J. Leu).

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information. In addition, the conventional analysis is a time-consuming task because it requires an exhaustively searching procedure. In order to solve these problems, patent network analysis provides a convenient and systematic procedure to demonstrate the overall relationship among patents and produce the most important information in a given technology area. This novel method can help the scientific researchers to greatly acquire the cost-effectiveness in processing lots of patent documents and quickly grasp the technological insights in a short period of time. Therefore, this study aims to extract technological trends in the field of flexible display fabrication by using patent network analysis and give a demonstration for patent analysis in scientific research.

2. Methods and calculation

2.1. Data collection

This study adopts a three-stage patent searching procedure to find and collect patent documents related to the main subject of flexible display.

2.1.1. Stage 1: Patent keyword search

In this stage, a review paper was selected as main reference to take the cross-sectional structure of flexible displays [6]. Then, the essential components of flexible displays were chosen as keywords to find the useful patents from the US Patent and Trademark Office (USPTO).

2.1.2. Stage 2: Patent title selection

The patents searched from stage 1 were selected by scientists in Taiwan who worked in the field of flexible display. These scientists reviewed the titles and abstracts of collected patents to eliminate the irrelevant ones.

2.1.3. Stage 3: Patent content selection

Another group of scientists further reviewed the contents of patents from stage 2 to select the useful patents for database.

2.2. Patent network analysis

After constructing patent database, the patent network analysis was used to examine the overall relationship of patents and to find out the key patents. Two mathematical tools can be used to present the information from patent network, namely graphs and quantitative techniques. Graphs can visually exhibit the structure of relationship among patents by generating a patent network while the quantitative techniques can clearly show the indexes of calculation result from the patent network. This study uses both graphs and quantitative techniques to examine the structure of patent network thoroughly.

The core technique of this method attempts to describe the structure of interactions (edges) between actors (nodes) [17]. Yoon and Park [16] used this concept of network analysis in finding relationship connecting the positions within a system. This method uses the frequency of keywords occurrence in patent documents as the input base to produce a visual patent network. The relationships between patents are represented as edges in the patent network while individual patents are represented as nodes. Patent network analysis can display all the relationships among patents in a visual network and assist the researchers in intuitively understanding the entire structure of patent database. Furthermore, this method is capable of figuring out the internal structure of patent network and thereby produces useful results from following steps.

Step 1: Technical experts select the relevant patent keywords based on the substance and characteristics of the patented technologies.

Step 2: Calculating the frequency of keywords occurrence in patent documents and integrate the data into keyword vectors. The keyword vectors from patent 1 to patent m are as follows:

$$\begin{aligned} &\text{Patent } 1: \quad (k_{11},\ k_{12},\ k_{13},\ \ldots,\ k_{1n}) \\ &\text{Patent } 2: \quad (k_{21},\ k_{22},\ k_{23},\ \ldots,\ k_{2n}) \\ &\qquad\vdots \qquad\qquad\qquad\vdots \\ &\text{Patent } m: \quad k_{m1},\ k_{m2},\ k_{m3},\ \ldots,\ k_{mn}) \end{aligned} \tag{1}$$

For example, in the document of patent 1, the first keyword occur k_{11} times, the second keyword occur k_{12} times and so on as above.

Step 3: Euclidian distance was used to calculate the distance between the patents and to establish the relationship among patents. If keyword vectors of patent i and patent j are defined as $(k_{i1}, k_{i2}, \ldots, k_{in})$ and $(k_{j1}, k_{j2}, \ldots, k_{jn})$ respectively, the Euclidian distance value (E^d_{ij}) between the two vectors is computed as follows:

$$E^d_{ij} = \sqrt{(k_{i1}-k_{j1})^2 + (k_{i2}-k_{j2})^2 + \cdots + (k_{in}-k_{jn})^2} \tag{2}$$

Step 4: Euclidian distance matrix (E^d matrix) consists of all Euclidian distance values among all vectors. The E^d matrix must be dichotomized in order to graph the patent network. It is necessary to transform the real values of E^d matrix into standardized values from 0 and 1 for dichotomizing in the next step:

$$E^s_{ij} = \frac{E^d_{ij}}{\mathrm{Max}\left(E^d_{ij},\quad i=1,\ldots,m;\quad j=1,\ldots,m\right)} \tag{3}$$

The E^s matrix is interpreted as dividing the all values of E^d matrix by the maximum value of E^d matrix. The all values of E^s matrix are from 0 to 1.

Step 5: The cell of the E^s matrix must be a binary transformation, comprising 0s and 1s if it is to exceed the cut-off value p:

$$I_{ij} = \begin{cases} 1, & \text{if } E^s_{ij} < p \\ 0, & \text{if } E^s_{ij} \geqslant p \end{cases} \tag{4}$$

The I matrix includes binary value where I_{ij} equals 1 if patent i is strongly connected with patent j. I_{ij} equals 0 if patent i is weakly connected with patent j or not at all connected. The determination of cut-off value is a task of trial-and-error. The researcher has to select a reasonable cut-off value so that the structure of the network becomes clearly visible. Then, the I matrix can be employed to develop a patent network.

Moreover, two levels of analysis used in this study are to examine the relationship of patents. At the overall network level, this study uses the whole patent network to examine the overall relationship and to find the key patents. At the cluster level, this study clusters flexible display patents with similar technologies together to form a technology package. By examining the detailed relationship among the patents in each cluster, the characteristics of the clusters and important technologies are identified.

For the quantitative techniques, several indexes can be employed to examine the structure of the patent network at the overall network and/or cluster levels. The first index that finds out the relatively important patents at overall network and cluster levels is technology centrality index (TCI):

$$\mathrm{TCI}_i = \frac{C_i}{n-1} \tag{5}$$

$$C_i = \sum r, r: \text{ ties of patent } i$$

where n denotes the number of patents. It measures the relative importance of a subject patent by calculating the density of its linkage with other patents. The higher TCI value means the greater impact with other patents. For this reason, TCI can be used to identify the influential patents, and the technological implication can also be deduced from this information.

Furthermore, technology cycle time (TCT) index can be used to measure the technological progress by gauging the degree of newness of patents at the overall network. Let T_i be the application date of patent i, and the formula for calculating TCT index of patent i is shown as below:

$$\mathrm{TCT}_i = \underset{j}{\mathrm{Median}}\{|T_i - T_j|\} \tag{6}$$

where patent j and patent i are connected. It is defined as the median value of age gaps between subject patent and other connected patents. Shorter TCT index reflects faster technology progress, and vice versa.

Finally, density index (DI) can be used to realize the characteristic of connection in the network of each cluster:

$$\mathrm{DI} = \frac{T_c}{n_c(n_c - 1)} \tag{7}$$

where T_c denotes the number of ties present in the network of cluster, and n_c denotes the number of patents in the network of cluster. DI measures the degree of connection in the network of each cluster. With the higher density of cluster, the technical concentration was increased, and vice versa.

3. Results and discussion

3.1. Patent selection

The detailed results of three-stage patent searching are shown in Table 1 and 2. In stage 1, the essential components of flexible display from review paper contain "polymer substrate", "anode", "thin-film transistor", "electro-optic material", "cathode", "encapsulation" and "roll-to-roll" during fabrication processes. Therefore, "flexible display" and above seven words were chosen to find the related patents through single word search by looking for above keywords in titles of patent documents from the year 1976 to 2010 (shown as Table 1). The detailed data are listed in column 1. In order to improve the coverage of this search, the intersection search between "flexible display" and above seven words was also carried out in all fields of patent documents during the same period to obtain useful patents into patent database (Table 2). The data were constructed in column 1 for next stage.

In stage 2, the obtained documents searched from stage 1 were selected by scientists who worked in the field of flexible display.

Table 1
The number of patents in the single word search.

Keywords	Stage 1	Stage 2	Stage 3
Flexible display	43	43	42
Polymer substrate	75	7	4
Encapsulation	991[a]	–	–
Cathode	6106[a]	–	–
Electro-optic material	11	3	1
Thin-film transistor	299[a]	–	–
Anode	1908[a]	–	–
Roll-to-roll	19	12	12

[a] It is inapplicable for next section selection due to the large number of these patents, as well as most not in the range of the technology and application of flexible display. Please refer to intersection search for more detail.

Table 2
The number of patents in the intersection search.

Intersection of keywords	Stage 1	Stage 2	Stage 3
Flexible display and polymer substrate	43	26	24
Flexible display and encapsulation	87	23	22
Flexible display and cathode	240	6	6
Flexible display and electro-optic material	21	9	9
Flexible display and thin-film transistor	73	16	16
Flexible display and anode	128	26	25
Flexible display and roll-to-roll	92	16	16

They reviewed the titles and abstracts of collected patents to eliminate the irrelevant ones. Then, the 187 patents were selected for last stage. In stage 3, another group of scientists further reviewed the contents of patents generated through stage 2 to yield 177 relevant patents. However, the 40 patents that repeated the single word search and intersection search were eliminated. Finally, the 137 patents were collected from number 4,347,436 to 7,683,606, which were covering the period from 1982 to 2010. Owing to the too long patent numbers, the patents had been given serial numbers from 1 to 137 according to their application date for further analysis,

3.2. Overall network level

This study uses patent network analysis to analyze the overall structure among patents in the field of flexible display, and the representative keywords with important technical feature were adopted for generating the patent network. A total of 13 keywords were selected including "flexible display", "conducting/conductive", "insulating", "electrophoretic", "transparent", "liquid crystal", "foil", "thin film transistor/TFT", "reflective", "roll", "pixel", "organic light emitting diode/OLED" and "inorganic", and the cut-off value $p = 0.07$ was chosen. The structural features of patent network were described and discussed in depth as follows.

A well-constructed visual network often transmits an intuitive knowledge of a system's structure [17]. A preliminary visual structure of the overall patent network can be captured by using the graphing approach. Fig. 1 shows the overall patent network in terms of connectivity. This network analysis divides all patents into three sets including high interconnected set, low interconnected set, and non-interconnected set. The interconnection situation represents the figure of patent network, including 65 patents with high relationship and 20 low relationship patents among these 85 patents. However, the other 52 patents in non-interconnected set are not shown in Fig. 1. Obviously, the detailed inventions of these non-connected patents are quite divergent in the field of flexible display, such as electronic manufacture (No. 11), mechanical patterning (No. 33), laser pulse manufacturing method (No. 59), curved display device (No. 95), substrate cleaning (No. 108) and so on. Therefore, these patents are excluded from the patent network through above analytical result. Moreover, the graph with 85 patents and 1190 ties in this patent network was further analyzed through the quantitative techniques of TCI and TCT index.

From Table 3, the front 12 patents with higher TCI values are further classified according to their patent documents. There are 3 patents earlier to 1995 that include patent No. 2, 5 and 9. These patents define the main function, construction and large scale flexible display in earlier stage. This result clearly indicates the flexible feature is important for future growth, and all the researchers in industries, academia, and government R&D institutes may pay more attention in this subject. In addition, another 3 patents, patent No. 38, 56 and 57, focused on the encapsulation of various display devices are also important in recent years. At last, the other 6 patents, patent No. 76, 104, 105, 109, 112 and 118, are described for various applications, such as ATM displays, polymer based

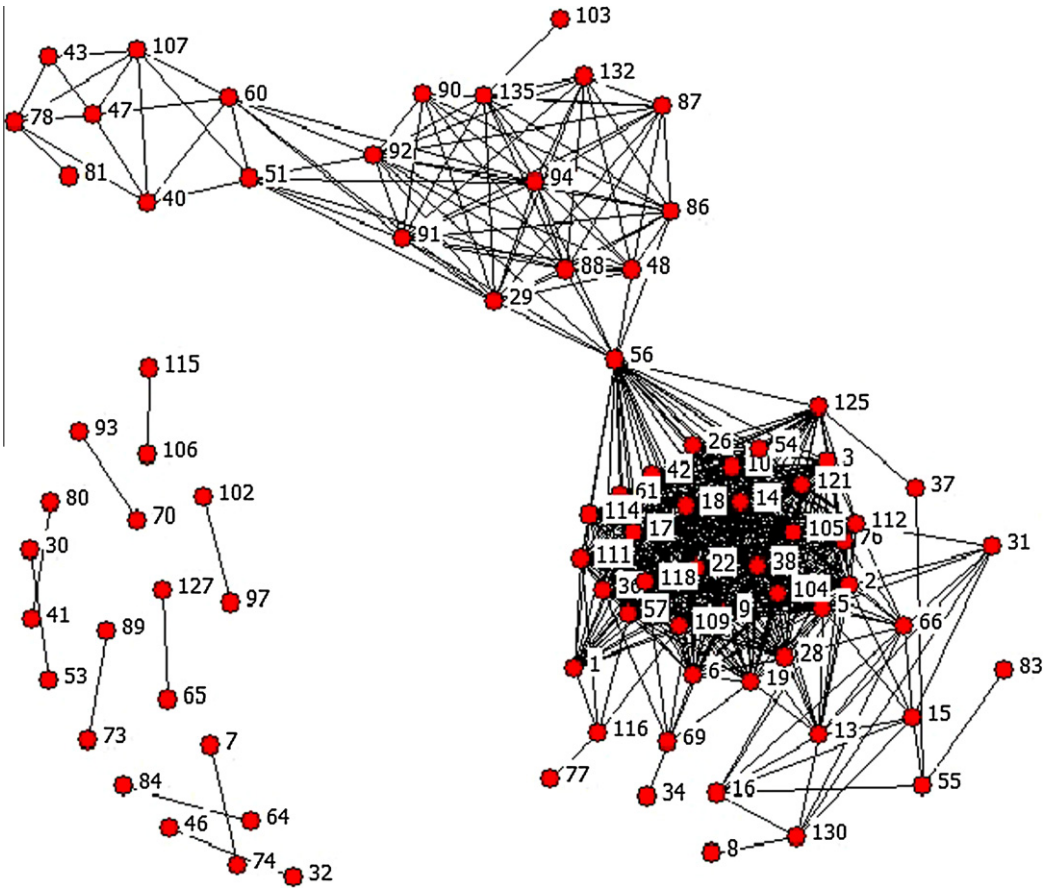


Fig. 1. Patent network in overall network level.

Table 3
TCI values of the relatively important patents in overall network level.

Patent number (real patent number)	TCI value
5 (US patent no. 4,979,554)	0.2427
2 (US patent no. 4,601,120)	0.2427
56 (US patent no. 7,052,766)	0.2427
104 (US patent no. 7,523,856)	0.2353
38 (US patent no. 6,862,825)	0.2353
112 (US patent no. 7,548,220)	0.2353
9 (US patent no. 5,469,020)	0.2279
109 (US patent no. 7,541,261)	0.2279
105 (US patent no. 7,531,206)	0.2279
76 (US patent no. 7,306,106)	0.2279
118 (US patent no. 7,567,221)	0.2279
57 (US patent no. 7,061,012)	0.2279

displays and e-books in flexible electronics field. Therefore, TCI analysis indicates the key point of flexible display development is not only the manufacturing processes, but also the encapsulation mechanisms and further applications.

Regarding TCT index, the median of age gaps is calculated between each patent and other connected patents in overall patent network. The TCT values are varied from 0 to 24.47 years, which indicates the technological innovation rate is quite different in the field of flexible display. Table 4 shows the representative patents with shorter (less than one year) and longer (more than 10 years) values to evaluate the trend in flexible display fabrication.

In general, most of the patents which have short cycle time are related to the fabrication of electrophoretic display (EPD) device. In patent No. 86, 87, 88, 90, 91, 92 and 94, these documents described their technology progress by introducing various materials to display, and the main EPD medium contained colorant particles charged through the induced electric field. These materials were capable of generating full color images and might be used for various display application including reimageable paper, electronic books, electronic signage, watch, monitor and/or cell phone displays and so on. This also showed that a large proportion of the flexible display researches promoted in industry were of immediate relevance for the inventive activity leading to flexible display fabrication. In addition, there are still 3 patents with short cycle times regarding flexible display fabrication in multi-layer sheets, electro-optic layers, and roll-to-roll processes (No. 34, 132 and 135). This might indicate that flexible display related industries increased fast based on EPD device, and there were still many problems could be overcome or improve in present process. Therefore, the present technological trends can be quickly found in short cycle time patents through TCT analysis.

Furthermore, the patents which have long cycle time are mostly related to the basic components of flexible display and other applications. These patent documents had been found in the early stage of patents such as No. 1, 2, 3, 5, 6, 7 and 8. And there are also some other applications found in this TCT group (No. 74 and 130). Therefore, patents with higher TCT index were focused on constructing the basic process for flexible displays and supported for other industrial applications. From the above result, TCT index can quickly point out the development direction of flexible display and find out the critical technology in device production.

3.3. Cluster level

Cluster analysis is a statistical analysis technique to create categories that help further observation of documents [18]. In this study, the purpose of cluster analysis is to sort all patents within

Table 4
Short and long TCT index values of some patents.

Short TCT group		Long TCT group	
Patent number (real number)	Index value	Patent number (real number)	Index value
86 (US patent no. 7,403,325)	0.00	6 (US patent no. 5,233,773)	10.22
87 (US patent no. 7,417,787)	0.00	130 (US patent no. 7,660,025)	11.39
90 (US patent no. 7,430,073)	0.00	5 (US patent no. 4,979,554)	12.55
34 (US patent no. 6,811,815)	0.38	7 (US patent no. 5,285,908)	13.64
88 (US patent no. 7,426,074)	0.44	74 (US patent no. 7,275,340)	13.65
132 (US patent no. 7,667,886)	0.74	8 (US patent no. 5,383,296)	14.98
91 (US patent no. 7,433,113)	0.88	2 (US patent no. 4,601,120)	16.94
92 (US patent no. 7,440,159)	0.88	3 (US patent no. 4,619,876)	17.12
94 (US patent no. 7,443,570)	0.88	1 (US patent no. 4,347,436)	24.47
135 (US patent no. 7,672,040)	0.88		

patent network into several clusters. These clusters can be viewed as reduced-scale patent network of flexible display. When the linkages are denser among patents, these patents are closer in terms of technological contents. In other words, each patent within a cluster may achieve a similar technological level and generate a technology package. This study further uses cluster analysis to identify important clusters in the patent network, and three different clusters were obtained in flexible display field. Fig. 2 shows the relationship among patents in each cluster, and the details about these three clusters are discussed as follows.

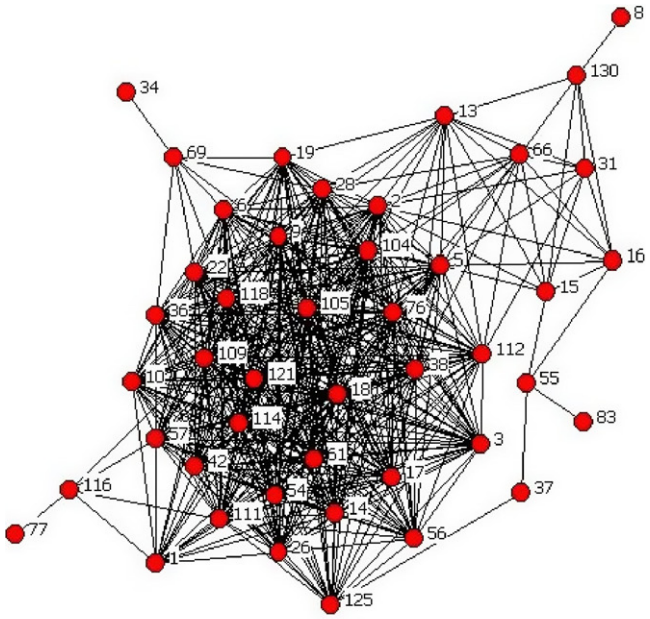
3.3.1. Cluster 1: Device fabrication

This cluster is consisting of 45 patents regarding the fabrication of flexible display with a medium level of connecting DI value (0.505). This result indicates that flexible displays have many useful techniques in their fabrication processes during 1982–2010. The present fabrication processes have been established for production in small scale displays. Therefore, the further processes still need to investigate and identify for a long period of time in constructing large scale devices.

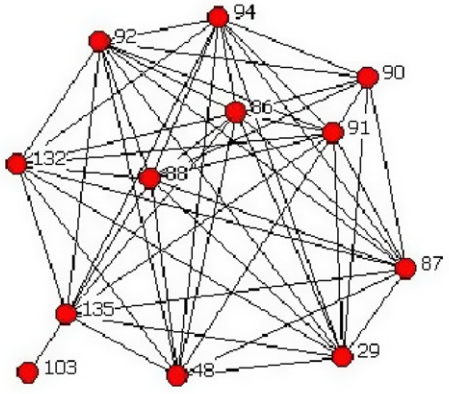
Table 5 shows the TCI values of relatively important patents in this cluster. These 11 patents are all in the central position of network. It reveals that these patents with higher value have more influence than others in this cluster. The patents numbered 5, 38, 57, 105 and 109 are related to make flexible devices by novel processes. The significance of these patents is provided in the fabrication details for flexible display. In addition, the other 6 patents, numbered 2, 9, 76, 104, 112 and 118, indicate the potential applied areas in flexible display, such as electronic book, colored door, and machine display. From the above result, patents in this cluster present the technological trend of flexible display fabrication based on innovative procedure and operation.

3.3.2. Cluster 2: Display key materials

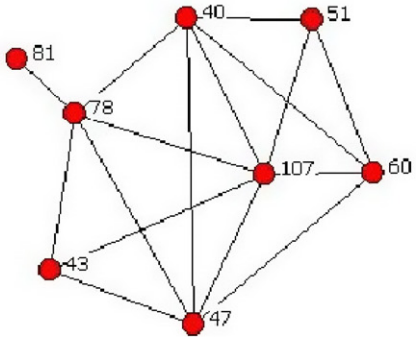
This cluster contains 12 patents that deal with the key materials for flexible display. These patents show the closest mutual linkages, and the DI value is 0.803. This phenomenon indicates that the invention of key materials for imaging use in electro-optic display is most important. There are a lot of key materials that can be used for generating images of EPD device onto reimageable paper, electronic books, electronic signage, watch, monitor, mobile phone, etc.



(1) Cluster 1



(2) Cluster 2



(3) Cluster 3

Fig. 2. Patent network in cluster level.

Table 6 shows the TCI value of relatively significant patents in this cluster. From this result, the importance of all these 8 patents is equal for flexible display fabrications. These patents are all highly related to imaging key materials in EPD device. The EPD devices contain colorant particles capable of field-induced charging and generating full color images. The major advantages of the electrophoretic technology are high reflectivity of the white state, high contrast, high resolution, low energy consumption, and possibility

Table 5
TCI values of the relatively important patents in cluster 1.

Patent number (real patent number)	TCI value
2 (US patent no. 4,601,120)	0.7500
5 (US patent no. 4,979,554)	0.7500
38 (US patent no. 6,862,825)	0.7273
104 (US patent no. 7,523,856)	0.7273
112 (US patent no. 7,548,220)	0.7273
76 (US patent no. 7,306,106)	0.7046
9 (US patent no. 5,469,020)	0.7046
105 (US patent no. 7,531,206)	0.7046
118 (US patent no. 7,567,221)	0.7046
109 (US patent no. 7,541,261)	0.7046
57 (US patent no. 7,061,012)	0.7046

Table 6
TCI values of the relatively important patents in cluster 2.

Patent number (real patent number)	TCI value
29 (US patent no. 6,738,050)	0.9091
92 (US patent no. 7,440,159)	0.9091
86 (US patent no. 7,403,325)	0.9091
87 (US patent no. 7,417,787)	0.9091
88 (US patent no. 7,426,074)	0.9091
135 (US patent no. 7,672,040)	0.9091
91 (US patent no. 7,433,113)	0.9091
94 (US patent no. 7,443,570)	0.9091

Table 7
TCI values of the relatively important patents in cluster 3.

Patent number (real patent number)	TCI value
107 (US patent no. 7,532,389)	0.8571
40 (US patent no. 6,873,452)	0.7143
47 (US patent no. 6,933,098)	0.7143
78 (US patent no. 7,307,778)	0.7143

of thin, mobile and flexible displays. Some recent new applications using electrophoretic ink as advance key material can prove the development of display in EPD device which is an important technological trend and close to marketing trend from journals and websites [2,6,19,20].

3.3.3. Cluster 3: Roll-to-roll manufacturing

This cluster has 8 patents which are chiefly concerned with methods for roll-to-roll manufacturing of flexible display, and its DI value is 0.571. Obviously, the connection of this cluster is close to cluster 1. By considering this result of cluster analysis, this cluster may reflect that roll-to-roll process can be used for flexible display production during these 5 years. Therefore, this subject would still need the improvement in the future.

Table 7 shows the TCI values of relatively important patents in this cluster. These 4 patents contain important fundamental technologies for roll-to-roll production, and they are also highly related to the EPD device. The patents numbered 40, 47 and 78 describe the methods and processes for the manufacture of such displays comprising cells of well-defined shape, size, aspect ratio and cells filled with charged pigment particles dispersed in a solvent. And their processes are included to the roll-to-roll manufacture of an EPD device. Furthermore, patent number 107 describes the important material of colorant for making EPD that can enhance the performance of products by roll-to-roll process. From above analysis, the roll-to-roll process has been used for EPD production in present applications, and the technological trend shows that there is no further requirement in future research.

4. Conclusions

This study uses patent analysis to investigate the technological trends of flexible display. These investigations not only illustrate the trends of technological development in the field of flexible display successfully, but also demonstrate the usefulness of the patent analysis method in technical field. Regarding the technological insights, this analysis can help the researchers to realize the development background of flexible display during recent decades. Even if the users don't work in this field, they can quickly get the key point of device fabrication. Moreover, the visualization of network enables the researchers to intuitively comprehend the overview of selected patents. The critical point of flexible display fabrication is based on device manufacture process, encapsulation material, and further application. In addition, the analytical result indicates that the technological trend particularly focus on fabrication of EPD. Therefore, creating the flexible EPD is the most important feature in future development of flexible display. The device construction, key materials fabrication, and roll-to-roll process are identified as main technologies for EPD production. Among them, the invention of key materials for flexible EPD is taken as the major subject currently based on the recent publications in journals and the website reports. Undoubtedly, this fruitful methodologies applied in this technical field are useful for investigating the technological trends in the field of flexible display.

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