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Analyses of the Key Technologies and Development Trends of Optical Networks from the Perspective of Standard Essential Patents

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Featured Application: In this study, the researchers have constructed a technology network model to explore the development of key technologies in standard essential patents (SEPs) optical networks.

Abstract: Because of the advancement of 5G, mobile devices, and broadband, the development of optical network technologies has received increased research attention. However, studies have mostly focused on the technical or market aspects rather than employing a macroscopic perspective to reveal the technology distribution of optical networks and the development trends in their key fields. Given that technologies disclosed by standard essential patents (SEPs) are the key technologies that determine the standards in relevant industries, we used SEPs optical networks as the basis of analyses and constructed a technology network. Therefore, the contribution of this study lies in bridging the research gap between two studies, using the perspective of SEPs to observe the key technologies in leading industry standard-setting. In addition to the aspects of technologies and markets addressed in existing studies, this study primarily discusses technology distribution and trends in optical networks. The results reveal that transmission of digital information, wireless communication networks and multiple communication are the key technical fields in developing optical networks, with wireless communication devices and digital information transmission being the main focus in recent years. Considering the gradual standardization of future optical network technologies and the fierce competition between manufacturers in SEP applications, relevant industries and universities should cooperate in key technical fields for research and development as well as in talent cultivation to facilitate the development of key technologies and industrial standards in optical networks. The current results may serve as a reference for both industry and academia with regard to research and development resource allocation.

Keywords: optical networks; standard essential patents; patent analysis; network analysis; technical analysis

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1. Introduction

Optical networks are a means of communication that applies signals encoded onto light to transmit information in various telecommunication networks. According to a report by MarketsandMarkets, the optical interconnect market is projected to grow from USD 9.0 billion in 2020 to USD 17.1 billion by 2025; it is expected to grow at a compound average growth rate (CAGR) of 13.7% from 2020 to 2025 [1]. Optical networks have had revolutionary effects on the telecommunication industry and play an essential role in the digital age. They have large transmission capacity and provide excellent confidentiality; optical networks have become the main communication method in cloud computing and 'Internet of things' applications [2–4].

Optical networks have been extensively applied and incorporated in multiple industries, and this technology has progressed considerably. For example, it has been applied in quantum and optical communication [5,6], including quantum optics, a research field that discusses the quantum behavior of light. Photons are used to transmit wave functions to reduce the problem of information distortion caused by environmental interference. Another example is the application of SiO_2 to the field of optical materials [7,8]. The advancement of 5G, mobile devices, and broadband have also promoted the development of optical network technologies. The use of optical networks increases data bandwidth and reduces energy consumption per unit, which limits network latency and the number of disconnections, enables the connection of more networking devices, and improves the interaction and connection between them.

Accordingly, optical networks are widely applied in multiple technical fields, such as optics, communication, semiconductors, materials, artificial intelligence, and computing. However, relevant studies have mostly focused on technical discussions [5–8] or market research concerning optical networks [1,9] rather than on their technology distribution and development trends from a macroscopic perspective. Moreover, few studies have explored the technical trends in optical networks from the aspect of standard essential patents (SEPs). Given that technologies disclosed by SEPs are the foundation and also the key technologies that determine standards in relevant industries, we observed the development trends of these technologies from the perspective of SEPs.

In this study, we focused on the SEPs of optical networks and constructed a technology network of SEPs. Many studies have predicted technology development by using patent data [10,11] and applied them to conduct patent landscape analyses [12,13] because patent data are one of the most direct indicators for observing technology trends. Specifically, SEPs are where standards and patents overlap. The technologies disclosed are the indispensable standards in the industry; they are cited by subsequent technologies and have influence on the industry's technological development. For example, the telecommunications technology standards in optical communication are mostly established by the third generation partnership project (3GPP) members. The standard technologies approved by 3GPP members are submitted to the standard setting organizations (SSOs), which publish them as telecommunications technology standards. As such, we attempted to address two research gaps. First, we examined the key technologies that determined the standards in these industries. Second, unlike the literature that focuses on discussions from a technical or market perspective, we explored technology distribution and trends in optical networks and constructed a technology network of SEPs to more effectively elucidate the key technologies protected by SEPs.

In brief, we analyzed the technology trends and key technologies of optical network patents according to a technology network of SEPs and discussed the key technologies in optical networks as standards in the relevant industries. The current findings may serve as a reference for governments, academia, and relevant professional industries.

2. Literature Review

2.1. Current Development of Optical Networks

Because of the rapid development of mobile devices and the Internet of things, users have growing demands for network transmission. Hence, the provision of efficient transmission has become a major concern in network development, where optical networks play an essential role. Optical transmission technology has developed rapidly over the past thirty years through three main technological innovations: time division multiplexing (TDM) technology based on electrical multiplexing, optical amplification technology combined with wavelength division multiplexing (WDM) technology, and digital coherent technology [14]. Literature has used photonic technologies [15,16] and semiconductor optical amplifiers [17,18] to discuss 5G optical communication. However, at present, the technology development of 6G is gradually attracting attention. The development of optical communication technology should not be restricted to photonics or semiconductor optical amplifiers. Currently, the main focus in the development of optical networks is on optical fiber cables, optical devices (including chips), optical communication equipment, and optical modules. Optical fiber cables are the transmission channels for optical communication. Optical devices are the functional devices developed based on photoelectric effects, with functions such as sending and receiving information, WDM, amplifying, switching, and system management. They form the core of optical transmission systems and can be categorized into active optical devices and passive optical devices. Optical communication equipment is composed of optical devices, including an optical terminal transceiver and a switch. Optical modules are crucial devices that perform the conversion between optical signals and electrical signals in optical communication systems and play a major role in data centers and mobile broadband. The production process is as follows: first, optical chips and other components are combined into an optical device, and then the optical device is encapsuled as an optical module (e.g., a light source, an optical detector, or an amplifier).

Optical networks have vast future business potential in various application fields (e.g., 5G, artificial intelligence, data centers, and photonic integrated circuits.) How to combine optical network technologies with the development and application of 5G and artificial intelligence has attracted increasing attention in academia and the professional industry [19,20]. Currently, the focus is on the high transmission rate, low latency, and high bandwidth of 5G wireless communication, which can be applied to popular industries including artificial intelligence and unmanned self-driving automobiles. Furthermore, because of the immense growth of data, data centers are no longer limited to a few computer rooms; instead, they increasingly comprise groups of data center clusters. Such data centers function collaboratively and exchange tremendous amounts of data instantly, which creates a demand for data center interconnect. Data center interconnect equipment has unique requirements such as small size, low power consumption, large capacity, and high speed; optical interconnects have been introduced to provide said characteristics because of their high bandwidth, low power consumption, and reconfigurability [21]. Photonic integrated circuits have the potential to transmit vast amounts of data in a low-cost manner and have had a revolutionary influence on medical technology, photoelectric sensing, solar battery components, far-infrared light source, and light display. Photonic integrated circuit technologies combine optics, complementary metal-oxide-semiconductor technology, and advanced encapsulation techniques. If they are compatible with the semiconductor manufacturing process, the cost of optical integrated circuit chips can be reduced even further. In addition to optical communication, photonic integrated circuits can be widely applied for processor interconnections or the core interconnections of multicore processors [22]. Accordingly, optical networks have been employed in cross-field applications and exhibited output values with high growth. Therefore, in this study, we analyzed the technology development of optical networks and identified the current key technologies from the perspective of SEPs by conducted network analyses. The analysis method is elaborated in the following section.

2.2. Network Analyses of Technologies Licensed with SEPs

SEPs can be regarded as the intersection of standards and patents. The value of SEPs in both technological development and business highlights SEP-protected technologies as essential standards and key methodologies in relevant industries. This study differed from past studies—which only adopted the perspective of patents [23]—in that it adopts SEPs, closer to industry standards and industry technology trends, to observe the development of optical networks. In addition, research indicated that companies with SEPs possess considerable market power because they determine the technology standards in the market [24]. Thus, we conducted technology network analyses from the aspect of SEPs. Past studies have used the co-classification approach to identify key participants in the network, thereby identifying whether a participant is a star or a gatekeeper [25,26]. Considering that a single patent may correlate with multiple technical fields (patent classification numbers), we employed a co-classification approach to define the relationship between these fields [27,28] and established a technology network accordingly. Participants at the center of a technology network provide a key node, or a node that receives much attention. From the perspective of social networks, the value of a network node depends on how centralized the node is in the network. On the basis of the technology network of SEPs, we further conducted centrality analyses to examine the key technologies in optical networks.

3. Research Design

3.1. Search Strategy and Data Source

In this study, we adopted the IPlytics platform as the data infrastructure for SEPs data. IPlytics connects data on over 90 worldwide million patents, 4 million standards documents and 280k declared standard essential patents and pooled patents [29]. We examined the key technologies according to the SEPs from 2015 to 2019 by using the following search conditions: ((TTL/optical network) or (ABST/optical network) or (ACLM/optical network)), which yielded 465 SEPs. Among them, TTL, ABST, and ACLM, respectively, denote the optical network keywords in title, abstract, and claim in patent documents. We classified the technologies in the technology network by employing the Cooperative Patent Classification (CPC) system implemented by the United States Patent and Trademark Office (USPTO) and the European Patent Office (EPO) in early 2013.

3.2. Centrality Analyses

We searched for the key technologies in the technology network of SEPs by employing centrality analyses. The measurement methods are specified in the following sections.

3.2.1. Closeness Centrality

Closeness centrality is the reciprocal of the distance between a node and all other nodes. A node closer to other ones has a higher degree of closeness.

$$C_c(P_i)^{-1} = \sum_{j=1}^{n} d\left(P_i, P_j\right) \ with \ i \neq j$$

where $d\left(P_i, P_j\right)$ is the distance from Node i to Node j.

3.2.2. Eigenvector Centrality

In eigenvector centrality, the centrality of a node is related to the number of its adjacent nodes and also the centrality of its adjacent nodes. A node has higher centrality when it connects with those with higher centrality; that is, the eigenvector centrality of adjacent nodes is inequivalent.

$$C_e(P_i) = \lambda^{-1} \sum_{j=1}^{n} a_{ij} C_e\left(P_j\right)$$

where $C_e(P_i)$ and $C_e\left(P_j\right)$ are respectively the eigenvector centrality of Node i and Node j; a_{ij} is the node that enters the adjacency matrix A; λ is the maximum eigenvalue (a constant) of the adjacency matrix A.

In this linear function, eigenvector centrality is a linear combination where the centrality of a single node is regarded as that of all other nodes [30].

3.2.3. Fragmentation Centrality

Fragmentation centrality refers to a fragmentated network with reduced cohesion when a node within is removed. After the node is removed, if the proportion of nodes that cannot be connected to each other is small, the network remains stable, which implies that the node has less significance. In this study, we referred to Borgatti [25] and applied distance-weighted fragmentation for measurement.

$$C_f(P_i) = 1 - \frac{2\sum_{i>j} \frac{1}{d\left(P_i, P_j\right)}}{n(n-1)}$$

where $d(P_i, P_j)$ is the distance from Node i to Node j; n is the total number of nodes.

4. Results

4.1. Patent Search Results

With the advancement of optical network technologies and the increased attention to SEPs in various countries, the number of SEPs optical networks has grown yearly. The development trend is depicted in Figure 1.

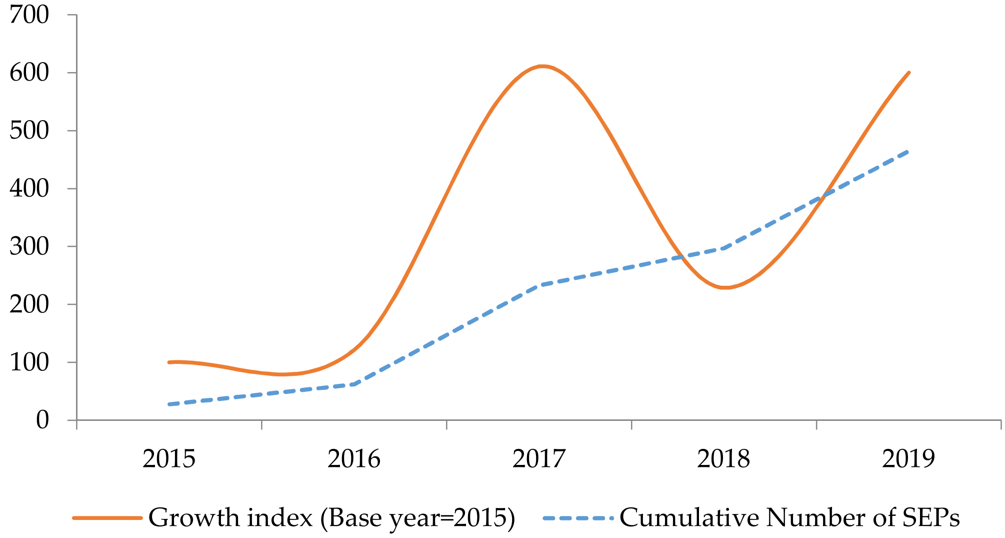

Figure 1. Growth trend of standard essential patents (SEPs) optical networks. Note: One hundred was applied as the number of SEPs in the base year (2015). In subsequent years, the growth index was (the number of SEPs of that year/the number of SEPs in the base year) ×100. Therefore, in 2019, the growth index was nearly 600 which means that it was approximately six times the growth index of 2015, which was 100. The cumulative number of SEPs denotes the accumulated number of SEPs each year.

Figure 1 illustrates that, compared with the number in 2015, SEPs optical networks have increased approximately six-fold by 2019. We further examined the distribution of the patent offices that granted SEP applications (Table 1).

Table 1. Patent offices that granted SEPs.

Ranking	Patent Office	Frequency	Percentage
1	WIPO	185	39.78%
2	CNIPA	96	20.65%
3	EPO	69	14.84%
4	USPTO	38	8.17%
5	KIPO	27	5.81%

Note: World Intellectual Property Organization (WIPO) patents refer to the patent cooperation treaty patents granted by the International Bureau of the WIPO; CNIPA: China National Intellectual Property Administration, Beijing; EPO: European Patent Office, Munich; USPTO: United States Patent and Trademark Office, Alexandria; KIPO: Korean Intellectual Property Office, Daejeon.

Table 1 demonstrates that approximately 40% of the SEPs were granted by the WIPO. This indicates that most applicants plan to file patent applications in multiple countries. To simplify the application procedures, they only apply to the WIPO rather than to the patent office of each country.

4.2. Technology Network Analysis

Figure 2 depicts the network model of the key technologies, and Table 2 lists the CPC code of each key technology.

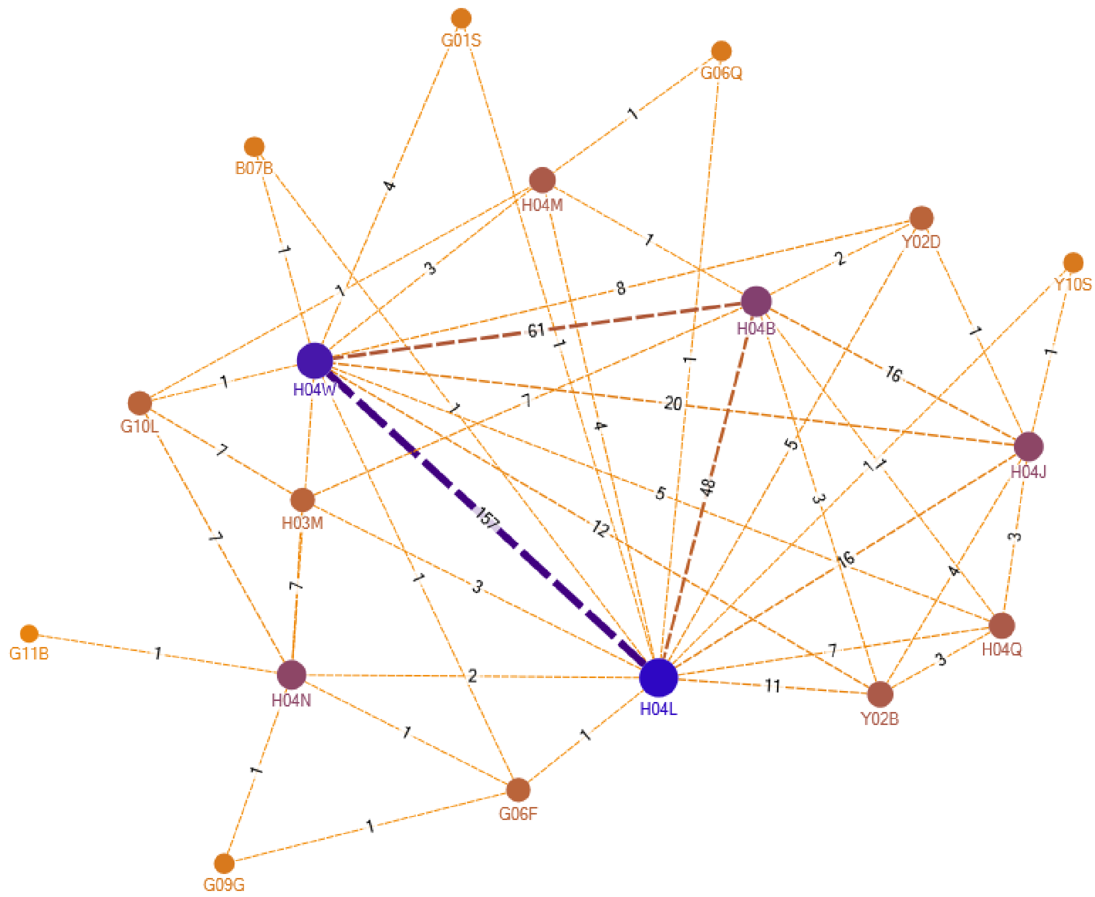

Figure 2. Cooperative Patent Classification (CPC) three-tier network diagram of laser and optical technologies. Note: The size of each node indicates the number of nodes connected to it; the thickness of the arc denotes the strength of the connection.

Table 2. Top 5 CPC codes for optical networks.

CPC	Closeness Centrality	CPC	Eigenvector Centrality	CPC	Fragmentation Centrality
H04L	15.500	H04L	0.448	H04L	0.552
H04W	14.500	H04W	0.419	H04N	0.551
H04B	12.167	H04B	0.340	H04W	0.532
H04N	12.000	H04J	0.304	H04B	0.513
H04J	11.667	H04Q	0.261	H04J	0.510

Table 2 reveals that H04L, H04W, H04B, and H04J are the top five technical fields in terms of closeness centrality, eigenvector centrality, and fragmentation centrality; Appendix A displays the definition of each CPC code. This suggests that transmission of digital information (H04L), wireless communication networks (H04W), transmission (H04B), and multiplex communication (H04J) were the key technologies in optical networks during the period under study.

4.3. Post Analysis: Yearly Changes of the Key Technologies in SEPs Optical Networks

We subsequently inspected the yearly changes in the key technologies in SEPs optical networks to understand the technology trends. The results of the analysis are depicted in Figure 3.

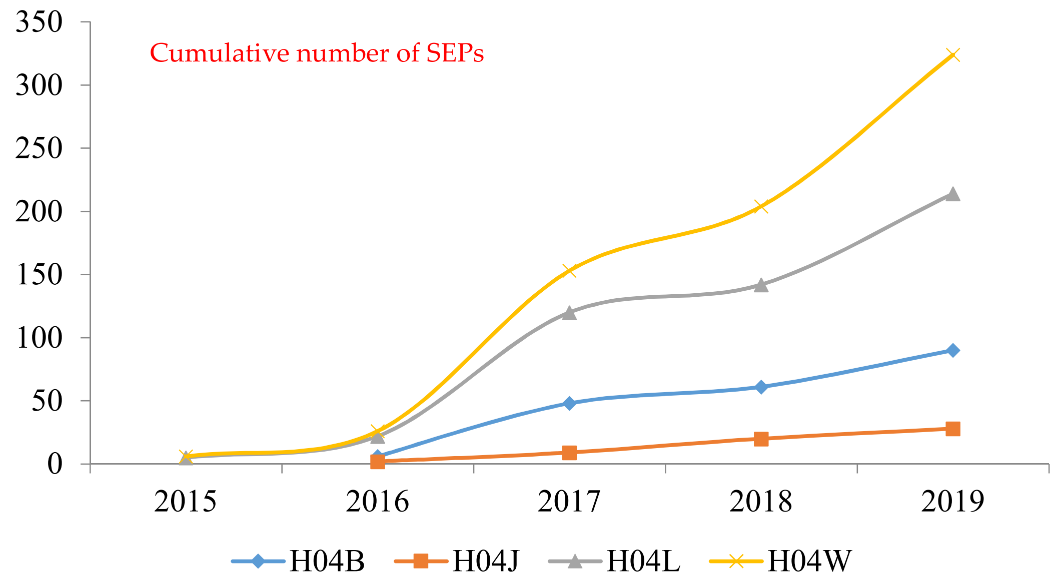

Figure 3. Yearly changes in the key technologies in SEPs optical networks. Note: The cumulative number of SEPs denotes the accumulated number of SEPs each year.

Figure 3 illustrates that H04W and H04L technologies have exhibited high growth in recent years, which signifies that wireless communication devices and digital information transmission have gained attention with the development of 5G and the Internet of things. Looking into the future, we can expect that, as 5G or even 6G develops, the application of communication technologies will become more common in people's lives, such as the Internet of Vehicle. Therefore, many companies co-established the Innovative Optical and Wireless Network, using photonics network and digital twin computing as their core technology. In sum, from Figure 3 and from the industry trend of forming alliances, we can predict that in the future how to integrate optical networks with wireless communication devices and digital information will be a major trend of the industry's technological development.

5. Conclusions

5.1. Discussion and Implications

In this study, we conducted network analyses to explore the key technologies in SEPs optical networks. The empirical results revealed that transmission of digital information, wireless communication networks, transmission, and multiplex communication are the key technologies in optical networks. Relevant professional industries have noted the increase in data volume and the demand for transmission speed and have thus emphasized the strengthening of digital information transmission. The number of hyperscale datacenters is increasing worldwide. These datacenters mainly provide services such as cloud computing, social media, software or platform services, and content transmission. Modules in optical networks that are capable of rapidly processing large amounts of information are thus crucial in such datacenters. At present, 100 G single channel has become the norm in the market, and the recent research and development of 400 G single channel is also promising [31,32].

In terms of transmission and multiplex communication, optical multiplexing is a perennial research focus [33,34]. Wavelengths used for optical multiplexing are specified in channel spacing grids issued by the International Organization for Standardization (ISO) and the International Telecommunication Union. This signifies that technologies in optical networks are highly valued by the ISO. In 2020, the European Telecommunications Standards Institute of the Industry Specification Group established the Fifth Generation Fixed Network (F5G) and proposed an industry prospect, Fiber to Everywhere, which defines the five work items, namely F5G use cases, landscape of F5G technology and standards, definition of fixed network generations, architecture of F5G, and F5G quality of experience [35]. Accordingly, optical network technologies are gradually being standardized, and the competition between manufacturers of SEPs is becoming fiercer.

In terms of theoretical contribution, research on optical networks have mostly focused on technical [5–8] or market [1,9] aspects rather than employing a macroscopic perspective to reveal technology distribution of optical networks and the development trends in their key fields. Additionally, few studies have explored the technology trends of optical networks from the perspective of SEPs. However, observing the technology distribution of optical networks from the aspect of SEPs has become increasingly relevant because such technologies are gradually being standardized. Therefore, we adopted SEPs as the research focus in expectation of addressing this research gap.

Furthermore, we introduced a technical map for optical networks to provide relevant industries and universities with valuable information. We analyzed the focus of technology development in a technology network of SEPs and disseminated information on research and development resource allocation and talent cultivation to industries and universities, respectively. With the development of optical networks, relevant industries should recruit technical talent in key technical fields and also cooperate with academia to increase relevant research and further cultivate technicians. The results of this study revealed that transmission of digital information, wireless communication networks, transmission, and multiplex communication are they key fields in optical networks. Relevant industries and universities can cooperate to enhance the development of optical networks and advance the key technologies that contribute to industrial standards.

5.2. Limitations and Future Research Directions

We examined the key technologies in optical networks from the perspective of SEPs. However, SEP applications proceed slowly; therefore, they only reveal the indispensable standard technologies but not the latest ones in the market, which is a considerable limitation of this study. We adopted the more mature CPC classification code to categorize the technical fields. The classification code only indicated the fields that require long-term funding and talent cultivation but neglected the detailed development process of the fields (e.g., the latest development trend of dense wavelength-division-multiplexed passive-optical-network, orthogonal frequency division multiplexing, and space division multiplexing). Hence, follow-up studies may conduct content analyses on individual patents to increase the depth of the research. Second, this study adopted the perspective of SEPs to discuss the focus of optical networks in the industry's standard stetting. Through the observations of this study, we can see that optical networks have had substantial growth in the industry standard setting. In recent years, there have been 465 SEPs. Regarding standard stetting, the number of SEPs on wireless communication devices and digital information transmission increased most quickly. However, future studies should investigate more detailed sub-topics and focus on expanding the key sub-topics reported by this study, such as wireless communication devices, digital information transmission, and multiplex communication, thereby integrating them into bigger categories. Consequently, the identification of the trend and need for talent development will attract the interest of a wider community. Moreover, we explored the global key technologies protected by SEPs from a macro-level perspective. Nevertheless, the motivation and necessity of filing SEP applications vary because technologies have different attributes and are developed under different industrial environments (e.g., electrical machinery, apparatus and energy have fewer SEPs [36]). We have only analyzed the technical fields disclosed by standard-setting organizations and SEPs. Future studies may employ data from other patent offices (e.g., the USPTO or EPO) to more precisely predict the development trends of novel technologies in optical networks.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Definition of CPC categories.

CPC Categories	Meaning
H04B	Transmission
H04J	Multiplex communication
H04L	Transmission of digital information, e.g., telegraphic communication
H04N	Pictorial communication, e.g., television
H04Q	Selecting
H04W	Wireless communication networks

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