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# Patent Analysis of the Critical Technology Network of Semiconductor Optical Amplifiers

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**Featured Application: This study explores the development trend of semiconductor optical amplifiers technologies, thereby providing a reference for R&D resource management and the promotion of new technologies.**

**Abstract:** With the development of 5G, mobile communication, and optical communication technologies, semiconductor optical amplifiers (SOAs) have become an important research topic. However, most SOA-related studies have focused on a technical discussion or market research but have failed to indicate the critical SOA technologies and the SOA technology development trends. Therefore, this study analyzes SOA patents and constructs a technology network for SOA patents. The results indicate that the critical SOA technologies are mainly used in lasers, semiconductor lasers, light guides, electromagnetic wave transmission communication other than radio-wave communication, and devices controlling light sources. Among the five critical SOA technologies, lasers (H01S3) account for the highest percentage at 22.21%. Consequently, the critical technologies do not focus on specific technology fields but have characteristics of multiple technology fields. In addition, considerable development has occurred in semiconductor lasers in recent years. Finally, patentee analysis indicates that for SOA technologies, the public sector and academia play relatively weak roles in early technology development or following technology development. However, with the rapid development of mobile communication and optical communication, the government of each country can consider investing additional R&D funds and resources in the future. This study constructs a network model for patent technologies to explore the development tendencies for SOA technologies. This model can be used as a reference for R&D resource management and the promotion of new technologies.

**Keywords:** semiconductor optical amplifiers; semiconductor lasers; patent analysis; patent network; technology analysis

## 1. Introduction

Optical signals have certain levels of attrition when being transmitted along optical fibers, and the transmission distance is limited by the attrition. Therefore, optical signals must be intensified to transmit them over long distances. The traditional method of intensification involves using a regenerator. However, different bit rates and signal formats require different regenerators and each channel requires an individual regenerator, which results in a high network cost. Therefore, a method that does not involve the use of generators is required to intensify optical signals. Optical amplification is a light intensification method that does not require the use of generators. Semiconductor optical amplifiers (SOAs) can support any bit rate and signal format because they simply amplify the received signals. In addition, compared with optical fiber amplifiers, SOAs have smaller structures and are easier to integrate with other components. With the new wave of wearable devices and the development of the Internet of Things economy, small and low-power electronic components are receiving increasing attention. Thus, SOAs are a topic of interest in mainstream studies [1–3].

With the development of light communication technologies, the demand for achieving high speed and large capacity is increasing and SOAs have become a crucial research topic. According to the reports of the market research institution Technovio, the global optical amplifier market size will grow by USD 935.94 million during 2019–2023, Compound annual growth rate (CAGR) of close to 9% during the forecast period [4]. Therefore, the global SOA market will continue to grow [5]. Increasing studies are focusing on the development of SOA technology [1–3]. However, previous studies have mostly focused on the discussion of technical details [6–8] or market research [5,9]. These studies have failed to indicate the critical technologies that drive the development of SOAs. Specifically, SOAs are used in multiple areas, including optical fibers, lasers, optical components, semiconductor manufacturing, and communication components. Because SOAs have infinite future business possibilities, the identification of critical technologies is important. For research universities or businesses, the most critical problem is resource allocation, that is, determining the number of personnel or amount of funds to be invested in different technology fields. This study attempts to solve this problem by using the network analysis method on critical technologies, explaining the statuses and positions of different technology fields in the technology network, and determining the critical technologies.

The focus of this study was the technology network of SOAs, and the SOA technology network model was constructed through patent analysis. Patents are the most direct evidence for measuring innovation output and can be used as indicators to observe technology development tendencies [10–12]. Consequently, investigations of industry–academia technology collaboration outcomes [13,14] or the related studies of the industrial technologies can be conducted using patents [15,16]. Thus, patent information can be used as one of the most direct indicators of technology development. This study examined the SOA technology development tendencies and critical technology fields according to patent information.

Overall, this study is different from previous studies that have discussed the technical and market aspects of SOAs in that it mainly discusses the critical technologies of SOAs. This study focused on the establishment of a technology network model and technology development tendencies. The study results are expected to provide references regarding technology development tendencies to the government, academia, and industry.

The subsequent literature review focuses on research in SOAs and critical technology network analysis. In addition, the research design and empirical evidence of this study for critical technology network analysis are presented before the paper is concluded.

## 2. Literature Review

### *2.1. Development Status of SOAs*

A SOA is a device that amplifies an optical signal directly, without the need to first convert it to an electrical signal [17]. SOAs are made from semiconductor materials and have the same working principles as semiconductor lasers. In other words, the stimulation phenomenon of jumps between energy levels is used for amplification. SOAs have a small volume, simple structure, low power consumption, long life, and low cost. They can be easily integrated with other optical components and circuits, are suitable for mass production, and can achieve the amplification and switching functions. SOAs are widely emphasized in the applications of optical wavelength conversion and light exchange. SOAs are basically laser diodes which can amplify any optical signal coming from either side of the fiber-end and send the amplified version of the signal out of the fiber attached through the other end. They are constructed in a small package and transmit bidirectional reducing the size of a device. However, it has some limitations which include high coupling loss, dependence of polarization, and a high noise figure. It requires very high quality of anti-reflective coatings [18]. Consequently, a future research direction is to improve these limitations.

Because optical signals are always attenuated during propagation in optical systems, signals cannot be transmitted for hundreds or thousands of kilometers without optical amplifiers. Thus, optical amplifiers are indispensable components in long-range transmission systems. The technologies related to SOAs include optics [2,3], semiconductor [1], material [19], communication [20], and surface treatment [21] technologies. Thus, SOAs constitute an interdisciplinary research topic. In addition, with the development of 5G, mobile communication, and light communication technologies, the governments of different countries currently highly value the development potential of SOAs and believe that adequate resources should be allocated to facilitate the development of this technology [5]. Therefore, this study used SOAs as the main subject of analysis and determined the critical SOA technologies through patent analysis. The exploration of critical technologies was conducted through network analysis, which is explained in detail in the following text.

### *2.2. Network Analysis for Critical Technologies*

Some studies have used network analysis to examine the research trends and development trajectories of certain knowledge fields [22,23] and have determined the knowledge maps, orientation, and technology development in a particular country [24,25]. Network analysis has also been used to explore technology collaboration and the knowledge flow status [26,27]. Network analysis can precisely indicate the transmission paths and evolution of technologies and knowledge. Specifically, the analysis of patent data can provide objective and feasible information regarding technology evolution. This information includes the patent approval year, amount, and technology categories [28]. Consequently, patent data can be used to analyze the development of certain technology. Therefore, this study used network analysis to examine the connectivity and co-occurrence between technology nodes. The method used to classify technology is based on the studies of Mun et al. [29] and Zhang et al. [30]. The existing and mature patent classification structure was also used. Network analysis was used to examine the key players of SOAs to observe the critical SOA technology fields.

## 3. Research Design

### *3.1. Searching Strategy and Data Source*

For patent analysis, this study mainly adopted data from the United States Patent and Trademark Office (USPTO) because the American system has universal representativeness for the analysis of international technologies. In addition, USA is the largest commercial trading market in the world; therefore, researchers generally adopt the USPTO database when measuring global innovative activities [28,31]. The patent data was limited to the American patents declared between January 1990 and December 2019. Moreover, the precise Derwent smart search tool was used for patent searching. The process used in the Derwent smart search tool is equivalent to hundreds of experts reading the entire public data of official patents registered in the database and then translating, rewriting key points and abstracts, debugging, normalizing patentees, and recording the rewritten and normalized data in the database. Derwent smart search is a key word searching method that involves manual reading and arranging. The search criterion was "SSTO/Semiconductor Optical Amplifier," and 990 patents were found. In addition, for the classification of the technology network, the USPTO and the European Patent Office established the Cooperative Patent Classification (CPC) system in early 2013. Therefore, this study adopted the CPC system for classifying patents.

### *3.2. Key Player Analysis*

This study used key player analysis to explore the critical technologies within the technology network. The critical technologies of the patent technology network were determined through technology network analysis. The centralities of each technology field referenced Abraham et al. [32]

for the two methods of key player problem-positive and key player problem-negative to classify the critical technologies in the network.

#### 3.2.1. Key Player Problem-Positive

The key player problem-positive method refers to the ability of a node to connect to other nodes. This ability is mainly based on the closeness centrality and eigenvector centrality. Closeness centrality refers to the reciprocal of the sum of minimal distances between a node and other nodes. The closer a node is to other nodes, the higher the closeness or accessibility of the node is.

$$C_c(n_i) = \left[\sum_{j=1}^{g} d\left(n_i, n_j\right)\right]^{-1} \tag{1}$$

where $d\left(n_i, n_j\right)$ denotes the distance of node $n_i$ to node $n_j$.

The eigenvector centrality reflects whether a node connects with a large number of nodes and whether the nodes connected by the considered node are connected to other nodes simultaneously. If a node is connected to nodes with higher centrality, the node has a high degree of centrality. In other words, the adjacent nodes are not equal [33].

$$C_e(n_i) = \lambda^{-1} \sum_{j=1}^{g} a_{ij} C_e\left(n_j\right) \tag{2}$$

where $C_e(n_i)$ and $C_e\left(n_j\right)$ are the eigenvector centralities of node *i* and node *j*; $a_{ij}$ denotes the node entering the adjacency matrix A; and $\lambda$ is the maximal eigenvector value of the adjacency matrix A and is a constant.

In the aforementioned formula, the eigenvector centrality of one node is considered as the linear combination of the centralities of all other nodes; thus, a linear function is obtained from the formula [34].

#### 3.2.2. Key Player Problem-Negative

The key player problem-negative method considers the maintenance of network stability. Thus, removing a node changes the network into a fragmentation network. This method is mainly based on betweenness centrality and reinforced structural holes. Betweenness centrality refers to the fact that some nodes in a network depend on certain nodes (mediators), namely mediums, to connect with other nodes in the network. The connection and flow between different nodes depend on the degree of centrality of the nodes.

$$C_b(n_i) = \sum_{j<k} g_{jk}(n_i) / g_{jk} \tag{3}$$

where $g_{jk}$ denotes the number of shortcuts from node j to node k; $g_{jk}(n_i)$ denotes the number of shortcuts in which node j must go through node i to reach node k.

In addition to the betweenness centrality, another measure of the mediator ability of a node is the number of structural holes. Structure holes describe the characteristics of the node occupying the main routes of network message communication. Burt [35] indicated that the effects of structural holes can be determined through the reinforced structural hole (RSH) value. The RSH value is between 0 and 1, and a higher RSH value indicates superior effects of the structural holes.

$$C_{ij} = \sum\nolimits_K \left(1 - m_{ij}\right) p_{ik} \left(1 - m_{kj}\right) \tag{4}$$

where $C_{ij}$ means to multiply the sum by the extent to which there is an *i*-*j* structural hole for *i* to define a variable RSH that varies from 0 to 1 with the extent to which the network around *i* reinforces an *i*-*j* structural hole; $P_{ik}$ indicates the strength of the connection between $i$ and $k$ (the connection between $j$ and $i$ divided by the sum of $i$'s other connections); $m_{ij}$ indicates the marginal strength of the connection between $i$ and $j$ (the connection between $j$ and $i$ divided by $i$'s maximum connection in $i$'s network); and $m_{kj}$ indicates the marginal strength of the connection between $k$ and $j$.

Where summation is across all of $i$'s contacts $k$, $k \neq i,\ j$. The expression $C_{ij}$ is zero when there is no $i$-$j$ structural hole for $i$ ($m_{ij}$ equals one) or all of $i$'s other contacts are bridges to $j$ (all $m_{kj}$ equal one). The index approaches one to the extent that $j$ is disconnected from $j$, and $i$'s closest contacts are also disconnected from $j$.

## 4. Results

### 4.1. Patent Search Results

Before performing technology network analysis, patent search result analysis was conducted to understand the initial status of SOA technology development. The SOA search involved 117 level-4 CPC classification numbers. Table 1 presents the distribution numbers of the top 10 level-4 CPC classification numbers.

**Table 1.** Distribution numbers of the top 10 level-4 CPC classification

| Ranking | CPC Classification Number | Appearing Number and Frequency | Percentage |
|---|---|---|---|
| 1 | H01S3 | 352 | 22.21% |
| 2 | H01S5 | 296 | 18.68% |
| 3 | H04B10 | 190 | 11.99% |
| 4 | G02B6 | 174 | 10.98% |
| 5 | H04J14 | 99 | 6.25% |
| 6 | G02F1 | 98 | 6.18% |
| 7 | G01B9 | 27 | 1.70% |
| 8 | H01L21 | 27 | 1.70% |
| 9 | H01L29 | 22 | 1.39% |
| 10 | G02F2 | 17 | 1.07% |

Source: compiled in this study.

Table 1 indicates that most of the SOA technologies can be classified under the H01S3, H01S5, H04B10, G02B6, and H04J14 categories; Appendix A displays the definition of each CPC code. Under the CPC International Patent Classification definitions, H01S3 and H01S5 represent lasers and semiconductor lasers, respectively; H04B10 represents transmission systems employing electromagnetic waves other than radio-waves; G02B6 represents light guides; and H04J14 represents optical multiplex systems.

The aforementioned analysis indicates that the SOA patents focused on lasers, semiconductors, transmission systems, light guides, and optical multiplex systems. The top 10 patentees were analyzed, and the results are presented in Table 2. Table 2 indicates that since 1990, the patentees with the longest average terms of patents are Lucent Technologies Inc., Murray Hill, US, Finisar Corporation, Sunnyvale, US, and Alcatel-Lucent Enterprise, Boulogne-Billancourt, FR. These companies have a long development history, and they began developing SOA technologies and filing related patents earlier than other companies did.

### 4.2. Critical Technology Network Analysis

This study used level-4 CPC as a basis for the critical SOA technology network analysis. The network model results are displayed in Figure 1, and the key CPC results are presented in Table 3. Every patent can belong to multiple CPCs (nodes), and the value of 1 between different CPCs means that the number of appearances in the same patent is 1. The larger the value between two CPCs is, the stronger the technology correlation between the CPCs is. Consequently, the relations between CPCs (nodes) and patent numbers (sides) can be used to construct a technology network, as presented in Figure 1. The participants in the center of the technology network can be considered key nodes, that is, nodes with high attention.

**Table 2.** Number of approved patents for the top 10 patentees

| Ranking | Patentee | Number of Patents | Percentage | Average Age of Patents |
|---|---|---|---|---|
| 1 | Fujitsu Limited, Kawasaki, JP | 76 | 7.62% | 8 |
| 2 | Electronics and Telecommunications Research Institute, Daejeon-city, KR | 40 | 4.01% | 9 |
| 3 | Samsung Electronics Co., Ltd., Suwon Si, KR | 34 | 3.41% | 12 |
| 4 | Finisar Corporation, Sunnyvale, US | 33 | 3.31% | 13 |
| 5 | Alcatel-Lucent Enterprise, Boulogne-Billancourt, FR | 33 | 3.31% | 13 |
| 6 | NEC Corporation, Tokyo, JP | 29 | 2.91% | 12 |
| 7 | Sumitomo Electric Industries, Ltd., Osaka, JP | 28 | 2.81% | 11 |
| 8 | The Furukawa Electric Co., Ltd., Tokyo, JP | 27 | 2.71% | 12 |
| 9 | Lucent Technologies Inc., Murray Hill, US | 20 | 2.01% | 16 |
| 10 | Sumitomo Electric Device Innovations, Inc., Yokohama-shi, JP | 20 | 2.01% | 3 |

Source: compiled in this study.

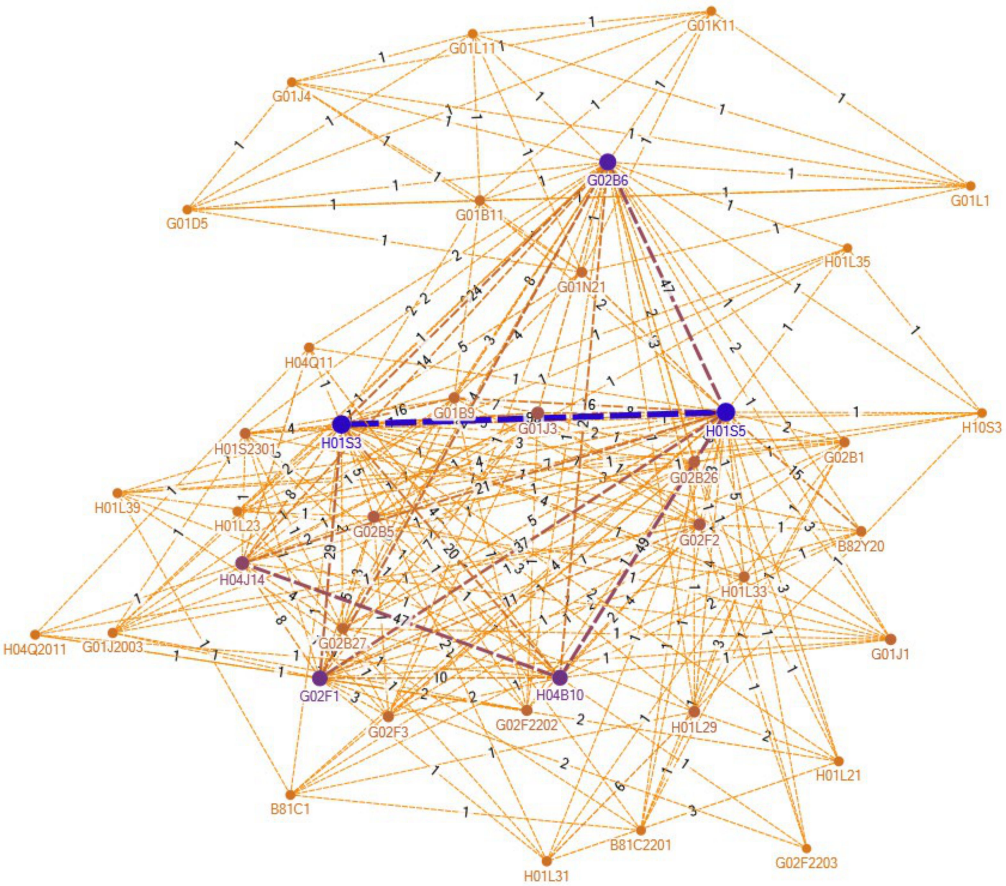


**Figure 1.** level-4 CPC network for SOA technologies. Note: The node size indicates the number of connected nodes, and the arc thickness indicates the connection strength. Only nodes with more than five connected nodes were retained.

**Table 3.** Top five CPC codes for SOA technologies.

| KPP-positive | | | | KPP-negative | | | |
|---|---|---|---|---|---|---|---|
| **CPC** | **Closeness Centrality** | **CPC** | **Eigenvector Centrality** | **CPC** | **Betweenness Centrality** | **CPC** | **Reinforced Structural Holes** |
| H01S5 | 67.75 | H01S5 | 0.341 | H01S3 | 1047.512 | H01S3 | 0.871 |
| H01S3 | 67.667 | H01S3 | 0.329 | G02B6 | 851.088 | H01S5 | 0.867 |
| G02B6 | 63.667 | G02B6 | 0.295 | H01S5 | 830.995 | H04B10 | 0.839 |
| H04B10 | 59.75 | G02F1 | 0.265 | H04B10 | 545.99 | G02B6 | 0.837 |
| G02F1 | 59.75 | H04B10 | 0.218 | G02F1 | 438.077 | G02F1 | 0.811 |

Source: compiled in this study.

Table 3 indicates that H01S5, H01S3, G02B6, H04B10, and G02F1 are top five technology fields in both KPP-positive and KPP-negative. Thus, in addition to lasers and semiconductor lasers (H01S3 and H01S5), critical SOA technologies also include light guides (G02B6), electromagnetic wave transmission communication other than radio-wave communication (H04B10), and devices controlling light sources (G02F1). The aforementioned information suggests that the most important SOA technologies mainly include basic electric elements, optical elements, and communication techniques. These technologies and elements are the products of interdisciplinary studies and are indispensable.

### 4.3. Post Analysis: Development Trend of Critical SOA Technologies

This study analyzed the patent changes in the H01S5, H01S3, G02B6, H04B10, and G02F1 critical technologies to understand the trends in SOA technology. The analysis results are displayed in Figure 2. One patent can belong to multiple CPCs. Figure 2 presents the number of patents in each era that belong to the five critical technologies.

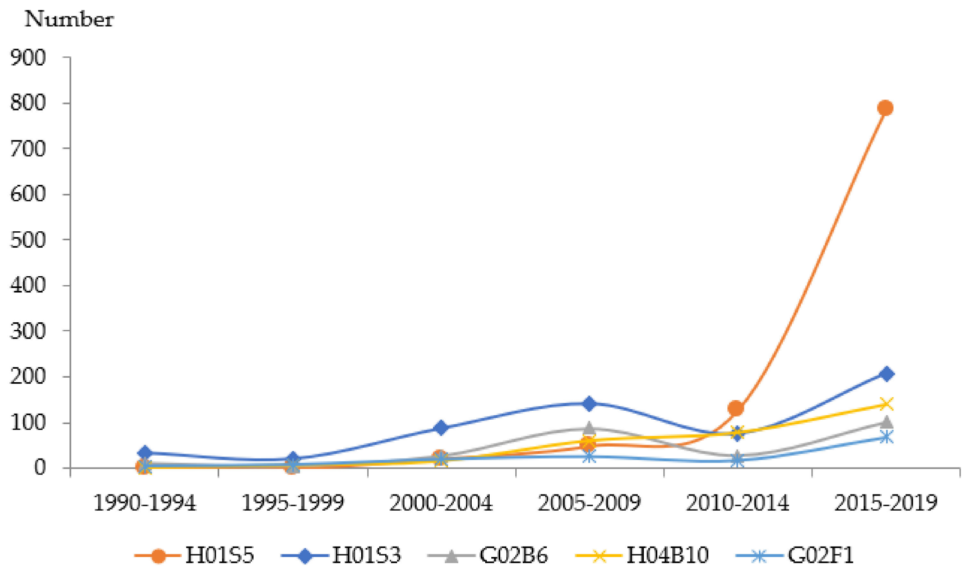


**Figure 2.** Development trend of critical SOA technologies.

Figure 2 indicates that the related technologies of the H01S5 category are receiving increasing interest in recent years. Compared with light guides, semiconductor lasers have been more valued in application and development in recent years.

## 5. Conclusions

### *5.1. Discussion and Implications*

This study used network analysis to explore critical SOA technologies. The empirical results indicate that the critical technologies are mainly used in basic electric elements, optical elements, and communication technique. Critical technologies do not centralize in specific fields, which indicates that SOA-related research is an interdisciplinary field. In addition, the analysis of major patentees indicates Lucent Technologies Inc., Finisar Corporation, and Alcatel-Lucent Enterprise have long history in SOA technology development. These enterprises started developing SOA-related technologies and patents earlier than other companies did; however, they do not have the highest number of patents. Lucent Technologies Inc. and Alcatel-Lucent Enterprise are businesses that provide telecommunication software and hardware equipment, and Finisar Corporation is a manufacturer of optical communication components. The aforementioned businesses are private businesses. In addition, the top 10 patentees all belong to private businesses, indicating that the private sector plays an important role in the technology development of SOAs. In the future, the government can assist industry by gathering software and hardware manufacturers in the country to collaborate in developing complete solutions toward the development trend of SOAs. In doing so, a consensus can be established, and research resources can be integrated.

In addition, the top 10 patentees are all private businesses, which indicates that the public sector and academia are weaker in the early development phase and following technology development. However, with the rapid development of mobile communication and optical communication technologies, governments of different countries can consider investing additional R&D funds and resources in the public sector and academia to help technology development in the aforementioned fields.

With regard to the technology tendencies, this study discovered that the critical technologies of SOA mainly centralize under the H01S5 category (the centrality indexes of H01S5 include closeness centrality, eigenvector centrality, betweenness centrality, and reinforced structural holes at 67.75, 0.341, 830.995, and 0.867, respectively), which comprises the technologies related to semiconductor lasers and not the more mature technologies of light guides, transmission systems, or devices or arrangements for the control of light arriving from an independent light source. Although these technologies are also critical for developing SOAs and are indispensable, semiconductor lasers have been prioritized after 2000. Semiconductor lasers have the characteristics of small volume, high efficiency, small attrition power, and long lives [36]. These characteristics allow semiconductor lasers to be extensively applied in data processing, optical fiber communication, and precision measurement. Consequently, for the light industry, semiconductor lasers are one of the key elements.

Most prior studies related to SOAs have mainly focused on technical discussions [6–8] and market research [5,9]. However, they have failed to indicate the major technology field focuses, technology development tendencies, and network distribution between technology fields. This study filled this research gap, adopted new viewpoints, and focused on technology fields.

With regard to policy recommendation, this study provides valuable information to countries, research universities, or businesses and proposes the technology map of SOAs. In the technology network, the SOA technology development focus, R&D resource allocation, and information regarding novel technology promotion were analyzed to determine the important critical SOA technologies. This study discovered that the critical SOA technology is semiconductor lasers and not light guides, transmission systems, or light control equipment or techniques. In addition, the technology field of semiconductor lasers has the characteristics of fine manufacturing and high technique level and requires long-term funding and talent cultivation from the government. As a result, the government plays a critical role in the development of this field.

In addition, according to this study's analysis, for research universities, the related technologies of SOAs involve multiple fields in technology. They include basic electric elements, optical elements, and communication technique. Thus, the issue of cultivating interdisciplinary talent in photoelectric technology appears to be relatively important. Research universities can make courses more interdisciplinary or establish platforms for interdisciplinary cooperation between departments. In addition, technology development can be targeted at certain types of demand or products in industry to increase collaboration between talent in different disciplines and the ability of talent to work across disciplines.

Based on this study's analysis, for businesses, semiconductor lasers have recently been a critical technology. Semiconductor materials have a very important position in optical communication, and they will play an even more crucial role in the next few years. Thus, this study aids technology promotion for related manufacturers of SOAs. Manufacturers can analyze recent trends of semiconductor lasers with respect to their competition, capital trades, and technological development to obtain helpful market intelligence and formulate research and development strategies.

### *5.2. Limitations and Future Research Directions*

First, since this study only cover USPTO data base, it may not provide very valuable information to countries which are not filing patents in USPTO data base. In addition, other forms of development patterns and output, such as seminar papers and reports, specific products and industry tendencies, or talent exchanges, should be considered. Many novel technologies in optical communication are being discussed in international working groups, such as the IEEE working group on time sensitive networking. Undoubtedly, these other forms of output could not be considered in this research, which is a major limitation of the present study. Second, due to the limitation of time and the fact that this study is a large-scale overall technology network study of SOAs, only the numbers of approved patents were used as an empirical basis without conducting value or quality judgment for individual patents. Finally, due to personnel and funding limitations, this study only adopted the USPTO database, which is the patent database of the largest commercial trading market in the world, as the patent data source. Although this database is generally adopted for measuring global innovative activities [28,31], researchers are recommended to use additional patent data sources for observation and verification of technology trends. For example, the Patent Cooperation Treaty managed by the International Bureau of the World Intellectual Property Organization can be used for the verification of technology trends to increase the scope of this study

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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 |
|---|---|
| G01B9 | Instruments as specified in the subgroups and characterized by the use of optical measuring means |
| G02B6 | Light guides |
| G02F1 | Devices or arrangements for the control of the intensity, color, phase, polarization or direction of light arriving from an independent light source, e.g., switching, gating, or modulating; non-linear optics |
| G02F2 | Demodulating light; transferring the modulation of modulated light; frequency-changing of light |
| H01L21 | Processes or apparatus adapted for the manufacture or treatment of semiconductor or solid state devices or of parts thereof |

**Table A1.** *Cont.*

| CPC Categories | Meaning |
|---|---|
| H01L29 | Semiconductor devices adapted for rectifying, amplifying, oscillating or switching, or capacitors or resistors with at least one potential-jump barrier or surface barrier, e.g., PN junction depletion layer or carrier concentration layer; Details of semiconductor bodies or of electrodes thereof |
| H04B10 | Transmission systems employing electromagnetic waves other than radio-waves, e.g., infrared, visible or ultraviolet light, or employing corpuscular radiation, e.g., quantum communication |
| H04J14 | Optical multiplex systems |
| H01S3 | Lasers, i.e., devices using stimulated emission of electromagnetic radiation in the infrared, visible, or ultraviolet wave range |
| H01S5 | Semiconductor lasers |

Source: Espacenet [37].

## References

1. Ahmad, H.; Azmy, N.F.; Azmi, A.N.; Zulkifli, M.Z.; Ismail, M.F. Configurable triple wavelength semiconductor optical amplifier fiber laser using multiple broadband mirrors. *Microw. Opt. Technol. Lett.* **2020**, *62*, 46–52. [CrossRef]
2. Lu, Y.; Wang, F.; Gu, J.; Shi, L.; Pengm, M.; Huang, J.; Kang, W. Photonic generation of broadly tunable radio-frequency signal using a reflective semiconductor optical amplifier. *Opt. Appl.* **2019**, *49*, 27–36.
3. Yang, X.; Lindberg, R.; Margulis, W.; Fröjdh, K.; Laurell, F. Continuously tunable, narrow-linewidth laser based on a semiconductor optical amplifier and a linearly chirped fiber Bragg grating. *Opt. Express* **2019**, *27*, 14213–14220. [CrossRef] [PubMed]
4. Technovio. *Global Optical Amplifier Market 2019–2023*; Technovio: London, UK, 2018.
5. Marketandresearch.biz. *Global Semiconductor Optical Amplifier (SOA) Market Research Report 2019*; Marketandresearch.biz: New York, NY, USA, 2019.
6. Kaur, S.; Shukla, M.K. All-optical parity generator and checker circuit employing semiconductor optical amplifier-based Mach-Zehnder interferometers. *Opt. Appl.* **2017**, *47*, 263–271.
7. Li, Q.; Wang, Z.; Wang, H.; Cui, C.; Wu, C. Artificial neuron based on nonlinear polarization rotation in a semiconductor optical amplifier. *Opt. Commun.* **2019**, *435*, 405–408. [CrossRef]
8. Nosratpour, A.; Razaghi, M.; Darvish, G. Numerical analysis of four wave mixing in photonic crystal semiconductor optical amplifier. *Opt. Commun.* **2019**, *433*, 104–110. [CrossRef]
9. GenMarketInsights. *Global Semiconductor Optical Amplifier (SOA) Market Insights, Forecast to 2025*; GenMarketInsights: Pune, India, 2018.
10. Gui, B.; Ju, Y.; Liu, Y. Mapping technological development using patent citation trees: An analysis of bogie technology. *Technol. Anal. Strateg. Manag.* **2019**, *31*, 213–226. [CrossRef]
11. Lee, C.; Lee, G. Technology opportunity analysis based on recombinant search: Patent landscape analysis for idea generation. *Scientometrics* **2019**, *121*, 603–632. [CrossRef]
12. Woo, H.G.; Yeom, J.; Lee, C. Screening early stage ideas in technology development processes: A text mining and K-nearest neighbours approach using patent information. *Technol. Anal. Strateg. Manag.* **2019**, *31*, 532–545. [CrossRef]
13. Ardito, L. Markets for university inventions: The role of patents' underlying knowledge in university-to-industry technology commercialisation. *Int. J. Technol. Manag.* **2018**, *78*, 9–27. [CrossRef]
14. Azagra-Caro, J.M.; Barberá-Tomás, D.; Edwards-Schachter, M.; Tur, E.M. Dynamic interactions between university-industry knowledge transfer channels: A case study of the most highly cited academic patent. *Res. Policy* **2017**, *46*, 463–674. [CrossRef]
15. Kim, M.; Park, Y.; Yoon, J. Generating patent development maps for technology monitoring using semantic patent-topic analysis. *Comput. Ind. Eng.* **2016**, *98*, 289–299. [CrossRef]
16. Yan, B.; Luo, J. Filtering patent maps for visualization of diversification paths of inventors and organizations. *J. Assoc. Inf. Sci. Technol.* **2017**, *68*, 1551–1563. [CrossRef]

17. Imran, M.; Collier, M.; Landais, P. Performance analysis of semiconductor optical amplifier as a gate switch. *Aip Conf. Proc.* **2019**, *2146*, 020016.
18. Transparency Market Research. *Optical Amplifiers Market—Global Industry Analysis, Size, Share, Growth, Trends and Forecast 2015–2023*; Transparency Market Research: Albany, NY, USA, 2020.
19. Wang, W.; Allaart, K.; Lenstra, D. Semiconductor optical amplifier gain anisotropy: Confinement factor against material gain. *Electron. Lett.* **2004**, *40*, 1602–1603. [CrossRef]
20. Yang, S.; Zhang, Y.; Li, Q.; Zhu, X.; Bergman, K.; Magill, P.; Baehr-Jones, T.; Hochberg, M. Quantum dot semiconductor optical amplifier/silicon external cavity laser for O-band high-speed optical communications. *Opt. Eng.* **2015**, *54*, 1–5. [CrossRef]
21. Soto, H.; García, E.; Marquez, H.; Valles, N. A simple experimental technique to obtain an optimum antireflection coating in semiconductor optical amplifiers. *Microw. Opt. Technol. Lett.* **2000**, *27*, 223–225. [CrossRef]
22. Chen, K.; Zhang, Y.; Fu, X. International research collaboration: An emerging domain of innovation studies? *Res. Policy* **2019**, *48*, 149–168. [CrossRef]
23. Silva, J.T.M.; Ablanedo-Rosas, J.H.; Rossetto, D.E. A longitudinal literature network review of contributions made to the academy over the past 55 years of the IJPR. *Int. J. Prod. Res.* **2019**, *57*, 4627–4653. [CrossRef]
24. De Paulo, A.F.; Porto, G.S. Solar energy technologies and open innovation: A study based on bibliometric and social network analysis. *Energy Policy* **2017**, *108*, 228–238. [CrossRef]
25. Shen, F.; Ma, T.A. methodology to position nations' efforts in a technology domain with a patent network analysis: Case of the electric vehicle domain. *Technol. Anal. Strateg. Manag.* **2018**, *30*, 1084–1104. [CrossRef]
26. Ho, Y.; Chiu, H. A social network analysis of leading semiconductor companies' knowledge flow network. *Asia Pac. J. Manag.* **2013**, *30*, 1265–1283. [CrossRef]
27. Jewell, J.; Vetier, M.; Garcia-Cabrera, D. The international technological nuclear cooperation landscape: A new dataset and network analysis. *Energy Policy* **2019**, *128*, 838–852. [CrossRef]
28. Graham, S.J.H.; Marco, A.C.; Myers, A.F. Patent transactions in the marketplace: Lessons from the USPTO patent assignment dataset. *J. Econ. Manag. Strategy* **2018**, *27*, 343–371. [CrossRef]
29. Mun, C.; Yoon, S.; Park, H. Structural decomposition of technological domain using patent co-classification and classification hierarchy. *Scientometrics* **2019**, *121*, 633–652. [CrossRef]
30. Zhang, T.; Chen, J.; Jia, X. Identification of the key fields and their key technical points of oncology by patent analysis. *PLoS ONE* **2015**, *10*, 1–18. [CrossRef]
31. Zahringer, K.; Kolympiris, C.; Kalaitzandonakes, N. Time to patent at the USPTO: The case of emerging entrepreneurial firms. *J. Technol. Transf.* **2018**, *43*, 923–952. [CrossRef]
32. Abraham, A.; Hassanien, A.E.; Snášel, V. *Computational Social Network Analysis: Trends, Tools and Research Advances*; Springer: London, UK, 2010.
33. Batool, K.; Niazi, M.A. Towards a methodology for validation of centrality measures in complex networks. *PLoS ONE* **2014**, *9*, 1–14. [CrossRef]
34. Borgatti, S.P.; Everett, M.G. A Graph-theoretic perspective on centrality. *Soc. Netw.* **2006**, *28*, 466–484. [CrossRef]
35. Burt, R.S. Reinforced structural holes. *Soc. Netw.* **2015**, *43*, 149–161. [CrossRef]
36. Sharma, K.; Baul, S. *Global Semiconductor Lasers Market: Opportunity Analysis and Industry Forecast, 2014–2022*; Allied Market Research: London, UK, 2017.
37. Espacenet. CPC Scheme and CPC Definitions. Available online: https://www.cooperativepatentclassification.org/cpcSchemeAndDefinitions/table (accessed on 12 February 2020).