Business and Economic History On-Line

Vol. 8 2010

Pitfalls of Open Innovation: The Technological Trajectory in Laser Diodes in the United States and Japan

Hiroshi Shimizu

By exploring the technological development of laser diodes in the United States, this study examines how firms began to utilize external research and development resources and how the shift from the vertical integration model to the open innovation paradigm influenced technological development. U.S. firms led development on the technological trajectories until the 1970s. In the 1980s, however, innovation in laser diodes began to depart from the trajectories in the United States. The finding of this study suggests that cumulative features of technological development on the trajectory gradually vanished as a result of surges in entrepreneurial startups and the utilization of external resources and paths to markets in the industry. This implies that development on the technological trajectory will be retarded if firms are not in markets that have a high concentration of rival competitors and if they explore untapped product markets when technology is still in the nascent stage.

By exploring the technological development of laser diodes in the United States, this study examines how firms began utilizing external research and development (R&D) resources and how the shift from the vertical integration model to the "open innovation" paradigm influenced technological development along the technological trajectory.

Large enterprises internalize technological knowledge in their R&D laboratories and place a high priority on knowledge creation in their business strategies. R&D is traditionally an important source of innovation

This research was supported by the Japan Productivity Center, the Telecommunications Advancement Foundation, and the Japan Society for the Promotion of Science, Grants-in-Aid for Young Scientists (B), 21730291, 2009.

Hiroshi Shimizu <shimizu@iir.hit-u.ac.jp> is assistant professor at the Institute of Innovation Research, Hitotsubashi University.

URL: http://www.thebhc.org/publications/BEHonline/2010/shimizu.pdf

and offers firms a competitive advantage.[1] However, as technology has progressed and become more complex, it has become difficult, if not impossible, for a firm to internalize all the resources necessary for in-house R&D.[2] Technological breakthroughs demand a range of intellectual and scientific skills that far exceed the capabilities and resources of any single organization. Utilizing external information, knowledge, and resources gives firms an important competitive advantage.[3] Henry W. Chesbrough coined the term "open innovation" to describe the need of firms to utilize internal and external resources and internal and external paths to market as they strive to advance their technology.[4] The open innovation paradigm is the antithesis of the traditional vertical integration model in which firms internalize R&D resources and develop products internally.

Previous studies have found that U.S. firms began to utilize external resources in R&D earlier and more often than firms in other countries.[5] Large U.S. manufacturing enterprises could no longer source all of their R&D needs internally; they began to utilize external resources not only in manufacturing and distribution but also in R&D. They began to collaborate in R&D with outside organizations such as universities,

---

1 Alfred D. Chandler, Jr., Takashi Hikino, and Andrew Von Nordenflycht, *Inventing the Electronic Century: The Epic Story of the Consumer Electronics and Computer Industries* (New York, 2001); David C. Mowery, "The Relationship between Intrafirm and Contractual Forms of Industrial Research in American Manufacturing, 1900-1940," *Explorations in Economic History* 20 (Oct. 1983): 351-74.

2 Willem P. Burgers, Charles W. L. Hill, and Chan W. Kim, "A Theory of Global Strategic Alliances: The Case of the Global Auto Industry," *Strategic Management Journal* 14 (Sept. 1993): 419-32.

3 Henry William Chesbrough, *Open Innovation: The New Imperative for Creating and Profiting from Technology* (Boston, 2003); Wesley M. Cohen and Daniel A. Levinthal, "Absorptive Capacity: A New Perspective on Learning and Innovation," *Administrative Science Quarterly* 35 (March 1990): 128-52; Ranjay Gulati, "Network Location and Learning: The Influence of Network Resources and Firm Capabilities on Alliance Formation," *Strategic Management Journal* 20 (May 1999): 397-420. Walter W. Powell, Kenneth W. Koput, and Laurel Smith-Doerr, "Interorganizational Collaboration and the Locus of Innovation: Networks of Learning in Biotechnology," *Administrative Science Quarterly* 41 (March 1996): 116-45.

4 Chesbrough, *Open Innovation*; Henry William Chesbrough, Wim Vanhaverbeke, and Joel West, eds., *Open Innovation: Researching a New Paradigm* (New York, 2006).

5 For example, interorganizational collaboration in basic research has developed more in the United States than in Europe and Japan. Hiroshi Shimizu and Takashi Hirao, "Inter-Organizational Collaborative Research Networks in Semiconductor Lasers, 1975-1994," *Social Science Journal* 46 (June 2009): 233-51.

research institutions, and firms. Internal resources began to be taken to market by spinning off from a parent firm to generate additional value as well. Startups in Silicon Valley in California and Route 128 in Massachusetts have been oft-quoted examples.[6] Spilling over from intellectual hubs such as Fairchild Semiconductor and Massachusetts Institute of Technology (MIT), numerous engineers began to establish technology-intensive businesses. Entrepreneurship based on this pattern of startups and knowledge spillovers drives economic and technological development. Universities began to play an important role as well.[7] One of the important institutional changes that promoted the open innovation paradigm was the Bayh-Dole Act adopted in 1980, although David Mowery and Bhaven Sampat have shown that U.S. universities had already commenced increasing patenting prior to the implementation of the Bayh-Dole Act. This suggests that the act did not trigger open innovation, but rather accelerated a pre-existing trend in the United States.[8]

Although the topic of utilization of external resources generates great interest, there have been few studies that consider the impact of open innovation on technological development. It is reasonable to assume that the open innovation paradigm and the vertical integration model have different technological development patterns.

This essay focuses on how the open innovation paradigm influences technological development along the technological trajectory. Following the concept of scientific paradigms, Dosi defines a "technological paradigm" as "an outlook, a set of procedures, a definition of the relevant problems, and of the specific knowledge related to their solution."[9] He defines a "technological trajectory" as "a cluster of possible technological directions whose outer boundaries are defined by the nature of the

---

[6] On the comparison of Silicon Valley with Route 128, see Anna Lee Saxenian, *Regional Advantage: Culture and Competition in Silicon Valley and Route 128* (Cambridge, Mass., 1994).

[7] Wesley M. Cohen, Richard R. Nelson, and John P. Walsh, "Links and Impacts: The Influence of Public Research on Industrial R&D," *Management Science* 48 (Jan. 2002): 1-23; Edwin Mansfield, "Academic Research and Industrial Innovation," *Research Policy* 20 (Dec. 1991): 1-12; Edwin Mansfield, "Academic Research and Industrial Innovation: An Update of Empirical Findings," *Research Policy* 26 (April 1998): 773-76; Brian Rappert, Andrew Webster, and David Charles, "Making Sense of Diversity and Reluctance: Academic-Industrial Relations and Intellectual Property," *Research Policy* 28 (Dec. 1999): 873-90.

[8] David C. Mowery and Bhaven N. Sampat, "University Patents and Patent Policy Debates in the US, 1925-1980," *Industrial and Corporate Change* 10 (Aug. 2001): 781-814.

[9] Thomas S. Kuhn, *The Structure of Scientific Revolutions* (Chicago, 1970); Giovanni Dosi, "Technological Paradigms and Technological Trajectories: A Suggested Interpretation of the Determinants and Directions of Technical Change," *Research Policy* 11 (Dec. 1982): 147-62.

paradigm itself."[10] In other words, the paradigm defines the direction of technological advances. A single firm does not necessarily create its own technological paradigm and trajectory; rather, they emerge through interaction among several firms. However, it can be reasonably assumed that the ways in which technological trajectories emerge when firms actively utilize external knowledge differ from those when firms rely heavily on in-house R&D and internally developed products. Thus, by exploring the technological development of laser diodes in the United States, this study examines how collaboration under the open innovation paradigm affected the technological trajectory of laser diodes there.

The laser diode is a kind of laser that emits a narrow beam of coherent light. The laser diode was one of the most important technologies underpinning the dramatic changes that occurred in information technology during the latter half of the twentieth century. The United States developed the first laser diode in 1962. U.S. and Japanese firms have led the world in laser diode research.[11] Throughout the 1960s and 1970s, U.S. and Japanese firms followed the same technological trajectory, encountered the same technological problems, and aimed to achieve the same targets. However, as will be described in the following sections, U.S. scientists and engineers began to diverge from this trajectory in the 1980s when U.S. firms began to actively engage in inter-organizational collaborations. We briefly describe the technological development of laser diodes. We then explain how changes in in-house and external resource utilization influenced the technological trajectory in the United States. This study highlights some of the pitfalls of open innovation by illustrating how the shift to the open innovation paradigm can retard technological development along the trajectory.

Laser Diodes and Technological Trajectory

This section briefly describes the technological development of laser diodes. Laser diodes (also known as semiconductor lasers) emit laser beams. Laser was originally an acronym that stands for "light amplification by stimulated emission of radiation." There are currently many varieties of lasers (including CO_2, YAG, He-Ne, ruby, and laser diode). Continuous laser beams have powers ranging from a fraction of a milliwatt to over a megawatt, and laser applications range from commercial applications to specialized military applications. Laser diodes are being used in various areas such as medical use, light for high-speed cameras, material processing, optical sensors, laser pointers, measurement, optical disks, printers, barcode readers, and optical fiber communications. The two biggest applications have been in optical

---

[10] Dosi, "Technological Paradigms and Technological Trajectories."

[11] Stephen R. Forrest et al., *JTEC Panel on Optoelectronics in Japan and the United States Final Report* (Baltimore, Md., 1996).

communication and optical information storage. Long wavelength laser diodes (1.3μm–1.55μm) are used for optical communication appliances. Short wavelength laser diodes (0.47μm–0.85μm) are used for optical information storage and processing such as optical discs and laser printers. The laser diode was one of the most important technologies underpinning the dramatic changes that occurred in information technology during the latter half of the twentieth century. Laser diodes have been the most widely used laser since the 1980s.

In 1960 Theodore H. Maiman in the United States generated the first laser beam using a pink ruby. Four American institutions—General Electric (GE), International Business Machines (IBM), the University of Illinois at Urbana Champaign (UIUC), and MIT—simultaneously but independently developed the first laser diodes in 1962.[12] The development of the laser diode was exciting news for physicists involved in laser-related R&D, because it opened up huge possibilities for lasers. Before the invention of the laser diode, lasers were very bulky and required significant energy input. The invention of the laser diode, which was a very compact laser that would eventually fit on tiny chips and be sufficiently efficient to operate from a small battery, revolutionized the concept of lasers: a laser diode chip was less than one millimeter; the diameter of the packaged laser diode was around five millimeters.

The laser diode was still at a very nascent level, even although physicists recognized its huge potential. The laser diodes developed in 1962 functioned efficiently only at minus 196 degrees Celsius (the temperature of liquid nitrogen). Unless laser diodes could operate at room temperature, their potential would be fairly limited. Therefore, after the invention of the first laser diode, the focus of R&D in this technology turned to developing a laser diode that could operate at room temperature.

It took eight years for engineers to solve this technological problem. In 1970, a Bell Laboratory research team developed the first laser diode that operated at room temperature.[13] They called this new laser diode a double-heterostructure (DH) laser. Although the laser diode developed by Bell was unstable, its development was a turning point that stimulated competition among many firms to develop reliable and stable laser diodes that could operate at room temperature. The newspapers predicted that this newly invented DH laser would revolutionize optical engineering in the same way that the transistor had transformed electronic engineering.[14]

---

[12] On the invention of the four laser diodes, see Russell D. Dupuis, "The Diode Laser: The First 30 Days, 40 Years Ago," *Optics & Photonics News* (April 2004): 30-35.

[13] Morton B. Panish, Izuo. Hayashi, and Stanley Sumski, "Double-Heterostructure Injection Lasers with Room-Temperature Thresholds as Low as 2300 A/cm2," *Applied Physics Letters* 116 (April 1970): 326-27.

[14] *Asahishinbun* (Asahi Newspaper), 1 Sept. 1970, evening edition.

Many U.S. electronic, telecommunication, and electronics enterprises (such as GE, RCA, Bell, and IBM) competed to develop laser diodes that could achieve stable operation with long life times at room temperature. Japanese electronics and telecommunication firms (including Hitachi, Toshiba, Mitsubishi Electric, and Nippon Electric Company [NEC]) became involved in laser diode research from the 1960s as well. Because laser beam amplification was noisy and unstable, and the semiconductor used had short lifetimes in the 1970s, all firms were competing to develop stable and long-life laser diodes that could operate at room temperature.

The main application in the early 1970s was long-distance telecommunication. At that time, long-distance telecommunication used electric wires, but the quality was poor. The main problem was energy loss, and it was necessary to use a relay device (called a repeater) every few kilometers. Using too many relay devices produced time lags and background noise and caused lines to be cut off. Engineers believed that laser optical fiber would resolve these problems by reducing energy loss. They estimated that an optical fiber would require one relay device only every 180 kilometers and would enable clear, instant, and stable long-distance telecommunication. They predicted that optical fibers would replace electric wires for long-distance telecommunication if they could develop a practical optical fiber and a reliable laser diode. The Electronic Industries Association of Japan stated that "the laser diode attained continuous amplification at room temperature in 1970. It is projected that it will be used in optical telecommunication and data communication soon."[15]

Scientists and engineers faced two technological problems. One was the short lifespan of laser diodes. The laser diodes that operated at room temperature in 1970 were highly unstable and stopped operating after a few seconds or minutes. High-longevity laser diodes were necessary because it would be very difficult, if not impossible, to replace laser diodes installed in the marine cables for long-distance telecommunication. The second problem concerned the oscillation spectrum. It was indispensable to develop laser diodes that could achieve single-mode oscillation; if the oscillation spectrum was multimode, light transmission in the optical fiber would be significantly disturbed. From the late 1960s, firms competed to develop laser diodes that satisfied these technological targets. Since the wavelength at which laser diodes had minimum energy loss in optical fibers shifted from 0.8 µm to 1.3 µm and 1.55 µm as a result of advances in optical fiber technology, firms competed to develop laser diodes that met these two technological goals at the most appropriate wavelength. If the target wavelength was changed, a different material was required, because the emission wavelength of laser diodes depends on the semiconductor material; this in turn necessitates using a significantly different manu-

[15] Nihon Denshi Kikai Kogyo Kai, *Denshi Kogyo 30 Nenshi* [A 30-Year History of the Electronics Industry] (Tokyo, 1979), 269.

facturing technology. Therefore, the laser diode design and its manufacturing technology depend on the materials that are suitable for the optical communication wavelengths.

Other applications of laser diodes emerged in the mid-1970s. While many firms competed to develop a laser diode for optical communication, Stanford University and Minnesota Mining and Manufacturing (3M) started researching laser technology for data storage on photographic video discs in 1961.[16] In those days, information was stored as analogue signals. The aim was to store data as digital signals, and, although their research attracted little attention at the time, it was the first attempt to use optoelectronic technology for data storage. These efforts failed because laser technology was still at an immature stage. Ten years after Stanford and 3M's attempts, in the early 1970s, some firms began to conduct research on video disc technology, and they developed several video disc systems based on advances in laser technology. Adopting different formats, electronic firms such as Philips, RCA, Mitsubishi Electronics, and Toshiba competed to develop video discs.[17]

As firms committed to laser diode R&D, it became clear that the laser diode would find applications in optical data storage such as video discs, compact discs, and laser discs. Moreover, the expectation was that the potential markets for short-wavelength laser diodes would be huge: they would be utilized in various applications, including barcode readers, laser pointers, and laser printers. By the end of the 1970s, it was obvious that the laser diode had a huge range of future applications. For example, the *Japanese Electronics Industry Year Book of 1979* noted:

> It is expected that electronics products such as POS (point of sales) system and video disc will be widely used in shops and homes. It is projected a huge new market will appear based on the economies of large-scale production, if the laser diode is used in these products. He-Ne laser is currently used in these products. However, firms and research institutions are actively conducting R&D in laser diodes so that it can be used in these products.[18]

Data storage, barcode readers, and laser printers were new product markets for the laser diode. As expectations for those markets grew, more firms (including Xerox, Sony, Sharp, and Panasonic) began to compete to develop laser diodes in both the United States and Japan. In contrast to laser diodes for optical communication applications, it was important to develop semiconductor lasers with shorter wavelengths, because more

---

[16] The photographic video disc utilizes a system in which a signal recorded on the disc is read by the intensity of the light from a mercury lamp. Heitaro Nakajima and Hiroshi Ogawa, *Zukai Konpakuto Disuku Dokuhon* [Handbook of the Compact Disc] (Tokyo, 1982), 55.

[17] Ibid., 57.

[18] Denpa Shinbun Shuppanbu, *Denshi Kogyo Nenkan* [Annual Report on the Electronics Industry] (Tokyo, 1979), 679.

information can be stored with a shorter wavelength laser diode. For instance, the recording density of an optical disc is proportional to the laser beam spot size. Because the beam spot diameter is proportional to the wavelength of light, the recording density is inversely proportional to the square of the wavelength.[19] Consequently, it was necessary to develop laser diodes that emit shorter wavelengths for data storage and processing applications. As mentioned, the wavelengths emitted by a laser diode depend on the semiconductor materials used in the laser diode. In 1982, Sony and Philips released the compact disc, which was the first major consumer electronics product using laser diodes. These first compact discs used GaAlAs laser diodes with an output wavelength of 780 nanometers (nm). In 1985, NEC, Sony, and Toshiba developed barcode readers that used InGaAlAh laser diodes with an emission wavelength of 670 nm. Digital versatile discs (DVD) using semiconductor lasers with an output wavelength of 650 nm were introduced in Japan in 1996, in the United States in 1997, and in Europe in 1998. AlGaInN lasers with an output wavelength of 400 nm were developed in the late 1990s and were released for high-definition optical data storage in 1999.

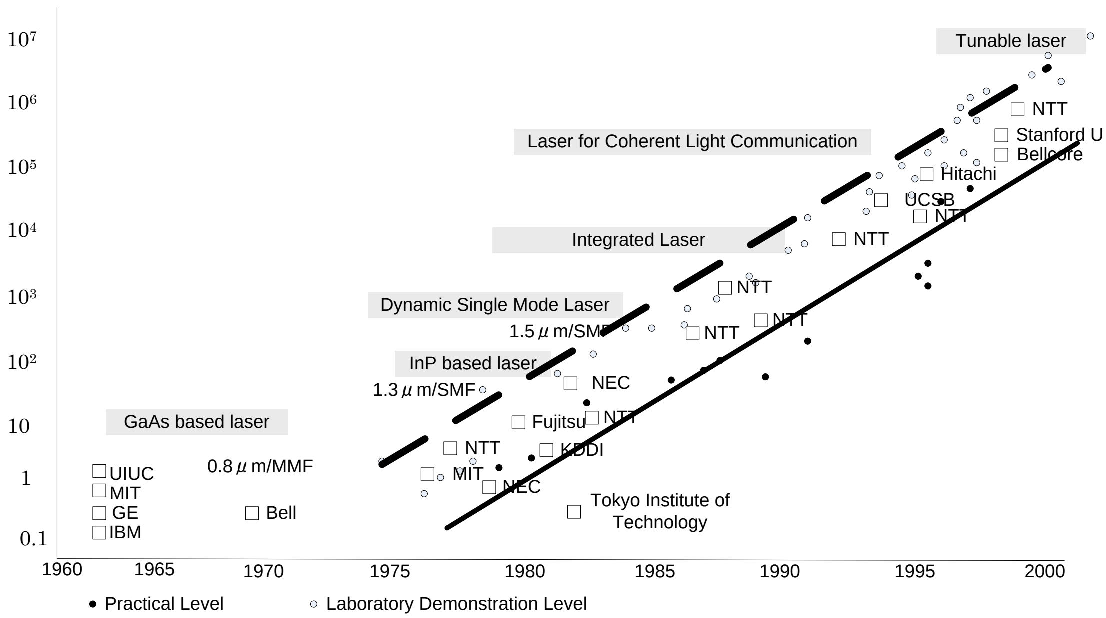
The following figures illustrate the technological trajectories in the main application areas; optical communication and data storage and processing. Figure 1 shows a plot of the transmission capacity and optical communication distance; it illustrates the technological trajectory of optical communications systems and laser diodes. It also indicates the organization that achieved the technological development at each phase. This figure demonstrates the linear progress in the overall technological advances from the 1970s. The transmission capability has increased steadily from the 1960s. This figure also reveals that U.S. organizations took the lead in the trajectory until the 1970s, whereas Japanese organizations dominated after the 1980s.

Based on wavelength data from papers published in academic journals, figure 2 illustrates the technological trajectory in laser diodes for optical data storage and processing. Many articles in academic and technical journals that trace the development of the laser diode report that the goal was to develop laser diodes that emit short-wavelength light.[20] The white squares represent pulsed operation of semiconductor lasers, whereas the blue squares signify continuous wave (CW) oscillation at room temperature. Development of pulsed laser diodes generally preceded that of CW semiconductor lasers. However, laser diodes that can produce only

[19] Maria C. Tamargo, *II-VI Semiconductor Materials and Their Applications* (New York, 2002).

[20] Gen-Ichi Hatakoshi, "Visible Semiconductor Lasers," in *Semiconductor Lasers, Past, Present, and Future*, ed. G. P. Agrawal (Woodbury, N.Y., 1995), chap. 6; Tokkyocho, *Korede Wakaru Handotai Reza: Motto Tsukao Motto Ikaso Konna* Gijyutsu [Handbook of Semiconductor Lasers].

Figure 1: Technological Trajectory of Laser Diodes for Optical Communication

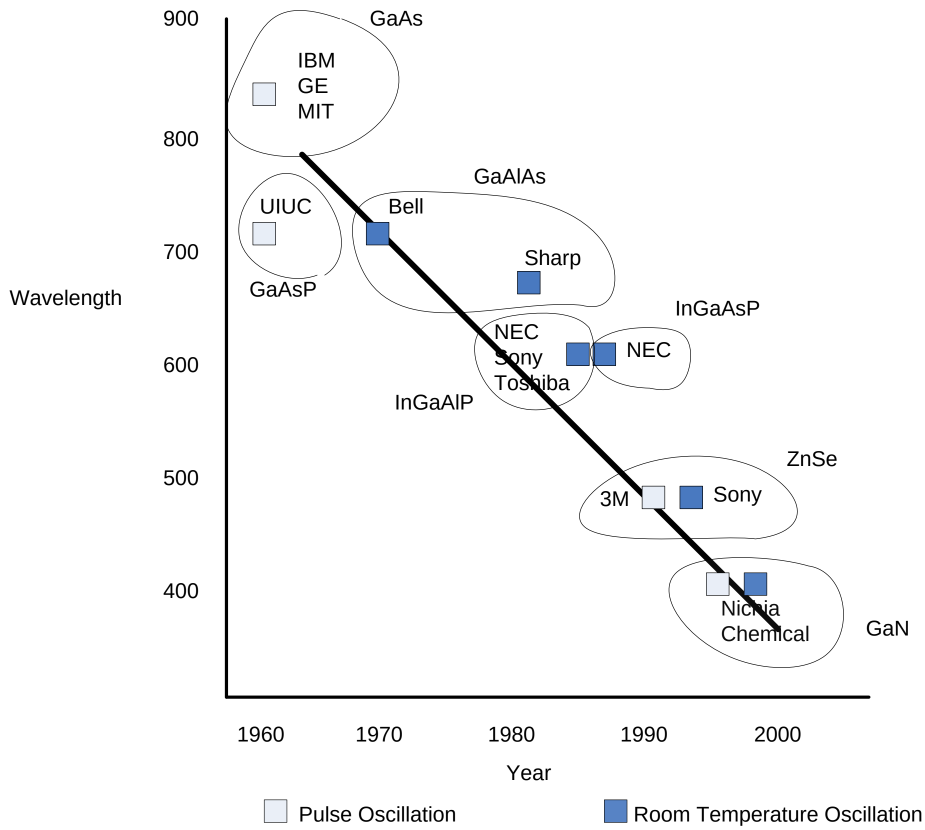


Source: Created by the author based on Yuzo Yoshikuni, "Evolution of the Semiconductor Lasers for Optical Communications: History and Prospects" (in Japanese), *Transactions of the Institute of Electronics, Information and Communication Engineers* CJ92-C(8) (2009): 371-81.

pulsed output will have highly limited applications. Therefore, scientists and engineers tried to develop CW laser diodes at room temperature after developing pulsed laser diodes. As figure 2 illustrates, U.S. organizations such as IBM, GE, MIT, UIUC, and Bell were achieving breakthroughs by 1970. Japanese organizations made no significant breakthroughs in this early phase of laser diode development. From the 1980s, however, Japanese firms began to make breakthroughs with the development of shorter-wavelength laser diodes.

Figures 1 and 2 demonstrate that U.S. firms and universities achieved important developments on the technological trajectories until the 1970s. However, U.S. firms almost disappeared from the trajectories from the 1980s. This shift occurred at about the same time that U.S. firms began to utilize external resourses and external paths to markets. The next section scrutinizes how U.S. firms begun utilizing external resources in laser diode R&D. It also describes how the shift from the vertical integration model to the open innovation paradigm influenced the technological trajectories.

Figure 2: Technological Trajectory of Laser Diodes for Information Storage and Processing



Source: Created by the author based on Gen-ichi Hatakoshi, "Visible Semiconductor Lasers" (in Japanese), *Journal of the Institute of Electronics, Information and Communication Engineers* 80 (July 1997): 692-96.

Inter-organizational Collaborations and Technological Trajectory

In the 1960s and 1970s, large enterprises played an important role in laser diode R&D in both the United States and Japan. Many U.S. electronic, telecommunication, and computing enterprises (such as GE, RCA, Bell, and IBM) competed to develop laser diodes that could operate with longer lifetimes at room temperature. Japanese vertically integrated electronics firms (such as Hitachi, Toshiba, Mitsubishi Electric, NEC, and Fujitsu), and telecommunication firms (such as NTT and KDDI) also became involved in laser diode research from the end of the 1960s. Relying on internal resources, many of them aimed at the same technological targets and conducted R&D in laser diodes in the 1960s and the 1970s. However, U.S. scientists began to utilize external resources and to engage in inter-organizational collaboration from the 1980s.

This section provides a brief description of how this study examines R&D collaborations among organizations. Then, by scrutinizing leading scientists who spun off from parent firms, it examines how the open innovation paradigm emerged in laser diode research in the United States and how it influenced the technological trajectories. Referring to academic papers on laser diodes published in *Applied Physics Letters*, this study investigates to what extent firms utilized external resources in R&D.

Both corporate and academic scientists publish their research outcomes in various journals. This study relies on papers published in *Applied Physics Letters* for three reasons. First, it is published every two weeks and thus provides up-to-date reports on new experimental and theoretical findings. Such a brief publication cycle allows more up-to-date monitoring of corporate and academic research than journals that publish full papers such as *Applied Physics*, which usually have longer publishing cycles. Second, since *Applied Physics Letters* has published reports since 1962, it covers a longer time period than other journals that publish letters in applied physics. For example, *Optics Letters* began publishing in the mid-1970s, and *Optics Express* began in the 1990s. Thus, *Applied Physics Letters* permits longitudinal analysis of scientific research. Third, *Applied Physics Letters* has a wide circulation and a strong international reputation as the top journal in semiconductor laser research.[21] *Electronics Letters*, which has offered reports since 1965, is another well-known journal that publishes letters in this area. The present study investigates the number of citations of papers published in *Electronics Letters* and *Applied Physics Letters* based on data from the Web of Science by Thomson Reuters (which monitors citations of over 10,000 of the highest impact journals worldwide). Data obtained in November 2009 indicates that papers on semiconductor lasers in *Applied Physics Letters* have more citations than those in *Electronics Letters*. A total of 3,498 papers were published in *Applied Physics Letters* from 1962 to 2008, and the mean number of citations was 26.81. A total of 2,075 papers were published in *Electronics Letters* from 1965 to 2008, and the mean number of citations was 14.01. Only one paper published in *Electronics Letters* is ranked (10th) in the ten most highly cited papers in both journals.

This study uses co-authored publications as a proxy measure for collaboration among scientists and engineers. Researchers frequently use co-authored publications to identify networks; however, that is not suitable for all purposes.[22] Typically, co-authored publications do not

[21] According to the data from the 2008 Science Edition of Thomson Reuters' *Journal Citation Reports*, *Applied Physics Letters* was the most highly cited journal in Applied Physics.

[22] Diana M. Hicks, Phoebe A. Isard, and Ben R. Martin, "A Morphology of Japanese and European Corporate Research Networks," *Research Policy* 25 (Jan. 1996): 359-78; Maphus Smith, "The Trend Toward Multiple Authorship in Psychology," *American Psychologists* 13 (Oct. 1958): 596-99.

reveal informal collaborative research, which usually does not appear in academic journals. Furthermore, co-authored publications do not measure unsuccessful collaborative research, since published articles are usually the results of successful research. Despite these limitations, this study examines co-authored publications to investigate inter-organizational networking in laser diode technology because co-authored publications provide systematic and consistent data, and they allow longitudinal investigation of long-term trends in collaboration. To explore the results of informal collaborations that are not published in journals and to confirm the collaborations observed in *Applied Physics Letters*, this study also has conducted fifty-four interviews with U.S. and Japanese scientists, engineers, and managers engaged in laser diode R&D.[23]

Table 1 shows the number of papers on laser diodes published in *Applied Physics Letters* by U.S. and Japanese organizations. First, the number of papers increases significantly after the 1970s.[24] Second, the ratio of inter-organizational collaboration increases in the 1990s. This increase in collaboration indicates that U.S. organizations began to rely on external resources much more and much earlier than Japanese organizations did because they could not afford to internalize all their R&D resources.

Table 1: Inter-Organizational Collaborations

		1960s	1970s	1980s	1990s	Total
US	Number of Papers	8	161	806	1058	2033
	Number of Inter-organizational Collaborations	1	17	142	307	467
	Number of International Collaborations	0	5	15	71	91
	Inter-collaboration Ratio	12.5	10.56	17.62	29.02	22.97
JPN	Number of Papers	0	44	223	267	534
	Number of Inter-organizational Collaborations	0	3	15	46	64
	Number of International Collaborations	0	2	6	19	27
	Inter-collaboration Ratio	0	6.82	6.73	17.23	11.99

Source: *Applied Physics Letters*, 1960-2000.

The increase in collaboration in the United States reflects the macroeconomic conditions. In 1973, the U.S. economy experienced the

[23] The interviews were conducted between 9 September 2004 and 5 March 2010. A list of interviewees and interview data are available on request.

[24] This table covers the period from the 1960s to the 1990s. However, the number of papers on laser diodes published in *Applied Physics Letters* decreased in the 2000s. This implies that the amount of basic research and technological advances in laser diodes decreased in the 2000s.

worst recession since the 1930s. By examining U.S. big businesses, especially in the chemical and electronics industries, Alfred Chandler showed how they responded to the economic changes.[25] The increased production costs and the sharp rise in raw material costs reduced the profitability of diversified businesses. Competition against foreign rivals became fiercer in the 1980s. Chandler indicated that the market share of U.S. electronics in the global market dropped from 71 percent in 1960 to 27 percent in 1986.[26] U.S. electronics firms tried to restructure their over-diversified businesses and focus on profit. U.S. electronics, computing, and office equipment firms began to utilize external resources and paths to markets from the 1980s, since they could not afford to internalize all their R&D resources. The existing literature also pointed out that firms tended to shift toward less vertically integrated and to utilize external resources more after large financial loss.[27]

The following describes inter-organizational collaboration in detail. The first inter-organizational collaboration that appeared in *Applied Physics Letters* was between UIUC and Monsanto at the end of 1960s. Dr. Nick Holonyak, Jr., at UIUC was one of the leading scientists in laser diode research. He was one of the physicists who helped develop the first laser diodes in 1962, which demonstrated the potential commercial importance of laser diodes. Holonyak was the first to perceive the importance of visible-wavelength light-emitting diodes (LEDs) and lasers for commercial devices. By collaborating with UIUC in a team led by Holonyak, Monsanto began to develop laser diodes, which were still in a nascent stage.[28] Monsanto was developing LED displays, and Holonyak was seeking a light source for them. UIUC collaborated with Monsanto to develop a LED display that used laser diode technology. The first commercial use of UIUC's red LEDs were in the Hamilton Pulsar watch developed with Monsanto in 1972. UIUC collaborated with Rockwell International at the

---

[25] Alfred D. Chandler, Jr., "The Competitive Performance of U.S. Industrial Enterprises since the Second World War," *Business History Review* 68 (Spring 1994): 1-72; Alfred D. Chandler, Jr., and Herman Daems, *Managerial Hierarchies: Comparative Perspectives on the Rise of the Modern Industrial Enterprise* (Cambridge, Mass., 1980).

[26] Chandler, "The Competitive Performance of U.S. Industrial Enterprises since the Second World War," 38.

[27] Chesbrough explained that both IBM and P&G shifted toward a less vertically integrated approach and moved to a more open approach in R&D after they encountered large losses and made major layoffs in R&D. Chesbrough, *Open Innovation.*

[28] For example, Nick Holonyak Jr., et al., "Many-Body Wavelength Shift in a Semiconductor Laser," *Applied Physics Letters* 12 (Feb. 1968): 151-53; Nick Holonyak Jr., et al., "Stimulated Emission Involving the Nitrogen Isoelectronic Trap in $GaAs_{1-x}P_x$," *Applied Physics Letters* 19 (Oct. 1971): 254-56.

end of the 1970s.[29] This collaboration developed mainly through personal networks of UIUC graduates. Dr. Russell D. Dupuis earned a Ph.D. from UIUC in 1972 and joined Rockwell International in 1975. Partly in collaboration with UIUC, Dupuis developed a manufacturing technology for laser diodes, called metal organic chemical vapor deposition (MOCVD), which was a fundamental technology for manufacturing laser diodes for mass markets.

Inter-organizational collaboration did not bloom fully in the United States until the 1980s. U.S. firms rarely relied on external research in the 1960s and 1970s. For instance, Bell Laboratories, one of the leading institutions in laser diode research, relied heavily on in-house R&D resources in the 1960s and 1970s. The first inter-organizational collaboration involving Bell Laboratories that appeared in *Applied Physics Letters* was with University of Berne in 1979.[30] This was the only inter-organizational collaboration of Bell Laboratories in the 1960s and 1970s. UIUC collaborated only with Monsanto and Rockwell International in the 1960s and 1970s.

However, firms began to utilize external R&D resources more from the 1980s in the United States, as Table 1 shows. Plotting the number of inter-organizational co-authored papers, the following figures illustrate the collaborative networks of UIUS and Bell Laboratories scientists. The red circles represent the scientists of those organizations, whereas the open circles signify the scientists of other organizations. The line around the scientists indicates the boundary of the organization. Since these figures focus on scientists' networks in UIUC and Bell Laboratories, they do not cover their partners' networks. Therefore, an organization that has only a few scientists in its circle does not necessarily have few scientists involved in laser diode research. The scientists in the circles indicate only those scientists who were involved in collaborative research with the organizations considered in this study. As these figures demonstrate, both UIUC and Bell Laboratories scientists collaborated with many other organizations. Significantly, almost all the collaborations were developed from the 1980s.

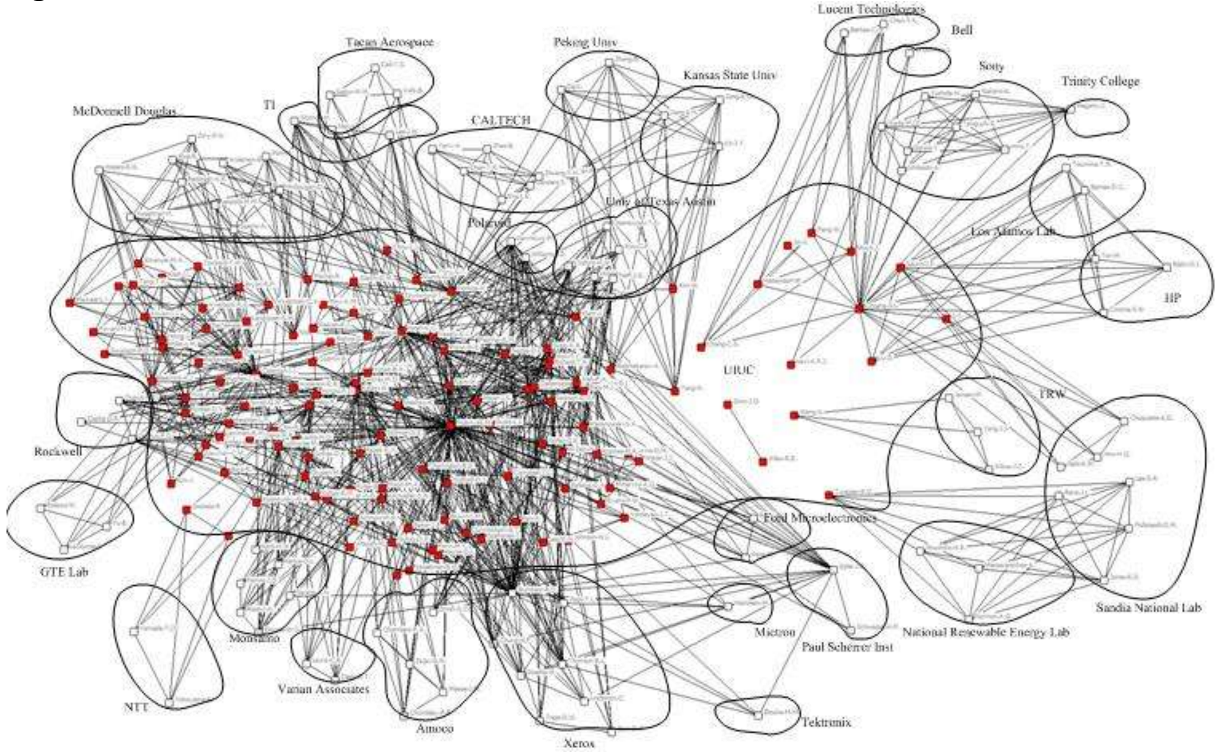
The most significant development behind the increase in collaboration was the surge of entrepreneurial startups. As mentioned above, large U.S. electronics, computing, and office equipment enterprises began seeking smaller, more profitable markets in the mid-1970s, as they lost position in

---

[29] For example, Nick Holonyak Jr., et al., "Low-Threshold Continuous Laser Operation (300-337oK) of Multilayer MO-CVD AlxGa$_{1-x}$As-GaAs Quantum-Well Heterostructures," *Applied Physics Letters* 33 (Oct. 1978): 737-39.

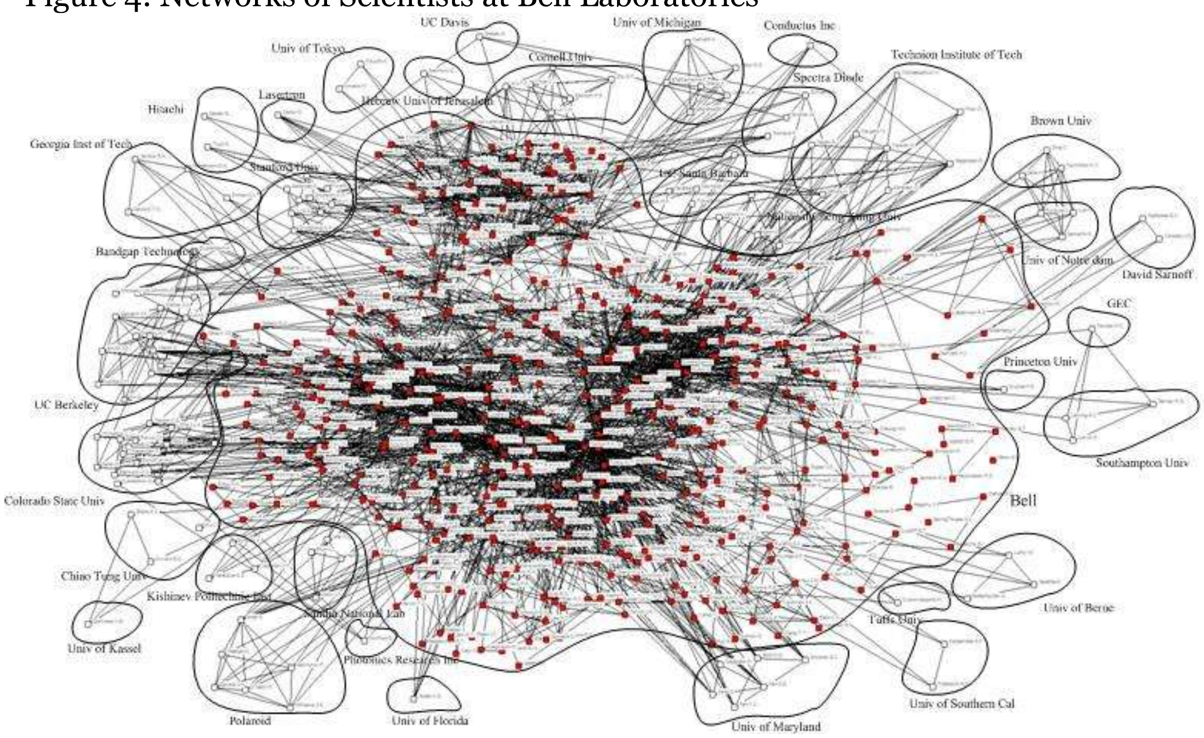
[30] Rene Salathé et al., "Laser-Alloyed Stripe-Geometry DH Lasers," *Applied Physics Letters* 35 (Sept. 1979): 439-41.

Figure 3: Networks of Scientists at UIUC



Source: Applied Physics Letters, 1960-2000.

Figure 4: Networks of Scientists at Bell Laboratories



Source: *Applied Physics Letters*, 1960-2000.

the global market as a result of the fierce competition from new Asian rivals. Many companies decided to exit the race to develop laser diodes for mass markets.

However, scientists and engineers at those organizations did not suddenly disappear from the world of laser diode research. Many leading scientists in the area of laser diode research left large parent organizations to launch new businesses when the large companies withdrew from the R&D race. Consequently, numerous startups emerged in the optoelectronics industry. Because laser technology seemed to have a bright future, venture capital became a major catalyst in bringing risk capital to digital technologies.[31]

The scientists and engineers who had been part of the original, pioneering research played an important role in these venture businesses, providing a vital source of technology transfer and knowledge spillover. For example, Dan Botez, who received a Ph.D. in laser diode manufacturing technology from the University of California, Berkeley, in 1976 and went on to become a highly regarded scientist in laser diode technology, began his career at IBM in 1976.[32] He moved to the RCA David Sarnoff Research Center in 1977, where he was involved in developing novel laser diodes, two of which became commercial products. He was competing to develop laser diodes on the technological trajectories shown in figures 1 and 2 until the mid-1980s. However, in 1984, he left RCA and founded Lytel, Inc., in New Jersey with a scientist from Bell Laboratories. Botez continued his research at TRW, Inc., which he joined in 1986. Twelve years later, in 1998, he founded Alfalight, a company that designed and manufactured high-power laser diodes for industrial, defense, and telecommunication applications.

Leading scientists spun off from Bell Laboratories as well. Dr. John E. Bowers, one of the leading scientists in fiber optics for optical communication, left Bell Laboratories and joined the University of California, Santa Barbara, in 1987. Dr. Won T. Tsang, one of the leading scientists in laser diodes at Bell Laboratories in the 1970s and 1980s, founded Multiplex in 1997. Dr. Don Scifres, who earned a Ph.D. from UIUC, was the one of the leading scientists in laser diode manufacturing technology and high-power lasers at Xerox. He left Xerox in 1983 and joined Spectra Diode, which was founded in that year as a joint Xerox-Spectra Physics venture.

Spinoffs occurred not only from large enterprises, but also from academic institutions. Israel Ury and Nadav Bar-Chaim established Ortel

[31] On finance and venture capital in the optoelectronics and electronics industry, see Henry Kressel and Thomas V. Lento, *Competing for the Future: How Digital Innovations Are Changing the World* (New York, 2007).

[32] The following details of his career are drawn from his CV and interviews conducted by the author.

in 1980 with the assistance of Dr. Ammon Yariv, a professor at the California Institute of Technology. They met at Caltech, where Yariv was working on optics and high-speed laser diodes. Ury and Bar-Chaim were studying Yariv's research at Caltech. In 1994, Ortel became one of the first optoelectronic companies to go public. Dr. Jim Hsieh, who developed the first one-micrometer waveband laser diode in 1976 at the Massachusetts Institute of Technology, founded Lasertron, which manufactured InGaAsP lasers in 1978. Hsieh also founded Sheaumann Laser, which manufactured packaged laser diodes in 2005.

Based on the rich supply of risk capital, the startups targeted niche and custom product markets instead of mass markets. None of the startups founded by the leading scientists targeted mass markets. The JTEC indicates that:

> These small businesses, which generally specialize in the manufacture of photonic components, are rarely positioned to compete head-to-head with the larger, systems-oriented companies; instead, they tend to specialize by filling narrow niches. As companies become established, the niches expand with the manufacture of additional specialized, unique devices produced to fill the needs of particular subsets of customers.[33]

As Chandler indicated, the vertically integrated large enterprises tended to target mass markets because the high fixed costs incurred in building high-throughput facilities demanded high-volume sales.[34] There was no great incentive for these large companies to target small markets, and they therefore. developed laser diodes with general-purpose properties for mass markets. Moreover, many of them internalized both laser diode manufacturing and final product assembly. Those firms had in-house demand for laser diodes. They conducted complex negotiations on the specifications and prices of laser diodes not based on market transactions but through organizational decision making. They could also negotiate the timing and amount of semiconductor lasers supplied through their administrative hierarchy. Furthermore, firms could strategically source laser diodes of their own internally, even if their lasers were slightly less competitive in terms of price or quality than those of their rivals.

Vertically integrated large enterprises were competing in the same markets (optical communication and data storage and processing); they encountered the same technological problems and adopted the same approaches. A certain technological trajectory emerges when many firms

[33] Forrest et al., *JTEC Panel on Optoelectronics in Japan and the United States Final Report,* xvii.

[34] Alfred D. Chandler, Jr., *The Visible Hand: The Managerial Revolution in American Business* (Cambridge, Mass., 1977); Oliver E. Williamson, "The Economics of Organization: The Transaction Cost Approach," *American Journal of Sociology* 87 (Nov. 1981): 548-77.

share a common definition of relevant problems and tackle those problems with the same approach. Because many vertically integrated large firms competed on the same technological trajectories for the mass markets, cumulative effects of incremental innovations on the trajectories eventually emerged in the 1960s and the 1970s, as figures 1 and 2 demonstrate.

On the other hand, startups tended to focus on untapped small niche or customized markets, because they usually did not have high-throughput manufacturing facilities in-house, and because they expected untapped markets or customized markets to be more profitable if the firm was successful. The risk capital supplied by venture capitalists provides a great incentive to target such markets.

Inter-organizational collaborations play an especially critical role in entrepreneurial startups.[35] A central motivation behind inter-organizational collaboration is to gain complementary knowledge.[36] Because entrepreneurial startups usually have limited capital to internalize R&D resources, it is important for them to utilize network resources. Through inter-organizational collaboration, startups can obtain important information, knowledge, and resources; as a result, they can gain a competitive advantage without incurring the capital investment needed for vertical integration. An organization that has acquired all the knowledge required for in-house R&D has little incentive to engage in inter-organizational collaboration.

The emergence of new specialized startups in the optoelectronics industry led to expansion of the open innovation paradigm; such networks provide an important means of accessing complementary knowledge and resources from outside. The monthly report of the Industrial Bank of Japan reported that: "Aside from a few large-scale telecommunications companies and optical fiber manufacturers, it was small and medium-sized business ventures that were to play the central role in the US optoelectronics industry."[37] The Japan Technology Evaluation Center, a U.S. research institute, reported that, "due to the vibrant entrepreneurial industry base that is an integral part of the US economy and which is apparently nearly absent in Japan, numerous small companies have spun-off from their larger, parent photonics companies."[38]

---

[35] Andrea Larson, "Network Dyads in Entrepreneurial Settings: A Study of the Governance of Exchange Relationships," *Administrative Science Quarterly* 37 (March 1992): 76-104.

[36] Sanford V. Berg, Jerome Duncan, and Philip Friedman, *Joint Venture Strategies and Corporate Innovation* (Cambridge, Mass., 1982).

[37] Nihon Kogyo-Ginko, "Hikari Sangyo no Shorai Tenbo [The Prospects for the Optoelectronics Industry]," *Kogin Chosa* 250 (Dec. 1990): 77.

[38] Forrest et al., *JTEC Panel on Optoelectronics in Japan and the United States Final Report*.

These entrepreneurial startups became the basis of the open innovation paradigm in the United States. They significantly influenced development along the technological trajectories. As many leading scientists left big companies and launched startups that tended to target niche and customized markets, their R&D efforts were scattered into small segmented markets. Cumulative technological developments on the technological trajectories vanished in the United States, as scientists began to seek to differentiate their R&D targets by utilizing external complementary knowledge and their startups were spun off from parent large enterprises or universities.

Conclusions

By exploring the technological development of laser diodes in the United States, this essay has discussed how firms began to utilize external R&D resources and how that influenced the technological trajectories. The findings imply that the way in which R&D is organized significantly influences the technological trajectory. Technological development of a certain device is likely to occur on the technological trajectory if vertically integrated firms compete in the market, because they usually have in-house demand for the device. However, when external resources are heavily utilized and in-house R&D is focused on a small market, technological developments were likely to occur off the technological trajectory. Giovanni Dosi indicates that "progress" on the technological trajectory is likely to retain some cumulative features.[39] The cumulative effect of numerous small improvements gradually increase productivity.[40] The finding of this study implies that cumulative features of technological development on the trajectory gradually disappeared as a result of the surge in entrepreneurial startups in the industry in the United States.

Technological trajectory plays an important role when the level of technological development is still in the nascent stage. If we assume that technological development follows an S curve, cumulative development plays an important role in technological development until the exponential curve becomes flat. In other words, R&D competition on the technological trajectory contributed to the technological development until the curve became flat. The technological trajectory will vanish if many firms exit R&D competition on the technological trajectory and target different small markets with different technological approaches. Technological developments will then lie off the technological trajectory. In other words, technological development will be retarded if firms target untapped product markets (called "blue oceans") when the technology is still in the

39 Dosi, "Technological Paradigms and Technological Trajectories."

40 William J. Abernathy, *The Productivity Dilemma: Roadblock to Innovation in the Automobile Industry* (Baltimore, Md., 1978).

nascent stage.[41] The open innovation paradigm offers opportunities to target small niche or customized markets that vertically integrated firms do not usually target by utilizing external resources and paths to market. Open innovation could hinder technological development when the technology still has ample room for development, because the cumulative effects of incremental innovations on the technological trajectories could vanish if many firms begin to target different markets. Of course, severe price competition will result if firms continue to compete on the same technological trajectory even when the S curve becomes flat. This occurred in the laser diode industry of Japan, where firms targeted the same mass markets and competed on the same technological trajectories; this eventually boosted the technological development of laser diodes. Therefore, it is important for firms to shift laterally to utilize technology in new markets to exploit the technological trajectory after technological development on the trajectory has been fully achieved.

As Paul Robertson and Richard Langlois indicated, the dichotomy between the vertical integration model and the open innovation paradigm is not very useful for exploring how innovation occurs through markets.[42] Various alternative structures exist in markets. The central aim of this study is not to evaluate the U.S. laser diode industry as an example of the open innovation paradigm. Instead, it aims to explore how the shift from the vertical integration model to the open innovation paradigm influenced technological development.

---

41 Chan W. Kim and Renee Mauborgne, *Blue Ocean Strategy: How to Create Uncontested Market Space and Make the Competition Irrelevant* (Boston, 2005).

42 Paul L. Robertson and Richard N. Langlois, "Innovation, Networks, and Vertical Integration," *Research Policy* 24 (July 1995): 543-62.