Available online at www.sciencedirect.com
ScienceDirect
Technovation 29 (2009) 451–464
technovation
www.elsevier.com/locate/technovation

Shedding light on technological development in Brazil

Luciana Pereira*, Guilherme Ary Plonski

Polytechnic School at University of Sao Paulo, Production Engineering Department, Avenida Prof. Almeida Prado, Travessa 2 no. 128—Cidade Universitária, CEP 05508-900 SP Brazil

Abstract

We try to shed some light on the question of why technology-intensive businesses often fail in less-developed countries and under what circumstances they are likely to be a success from the perspective of both domestic and export markets. The answers were drawn from a set of empirical evidences from Brazilian firms applying photonics technologies. Some of the issues faced by them are related to the question of state versus private initiative, entering traditional versus niche market, and technology transfer versus product development management. In overall, we concluded that weakness of the institutions and inadequacy of social and organizational demography play a key role in explaining to a large extent why countries differ in technological development and diffusion. In this context, we point out obstacles, which must be removed in order to make public policies and firm's achievements more efficient.

Keywords: Technological development; Innovation; Photonics; Brazil

1. Introduction

This article discusses possible – positive and negative – firms' responses to different policies concerning technological innovation in less-developed countries. It is a fact that economic activities in technological intensive industries have become increasingly important to explain economic growth and trade performance (Amsden, 2004; NSF, 2004). Consequently, the question of why some countries are more developed than others may be closely related to the question of why some countries have more advanced, or high-tech, industries than others.

For these reasons, a fundamental public and private policy concern in Brazil, as well as in other developing countries, has been how to boost the production of innovative, higher value-added products. Therefore, Brazil has invested in a proactive attitude, combining technological development and industrial applications as a way to foster competitiveness (De Negri and Salerno, 2005; Kannebley et al., 2005; Sotarauta and Srinivas, 2006; Wang and Chien, 2007; Leskovar-Spacapan and Bastic, 2007; Jin and von Zedtwitz, 2008).

Given that, our purpose in this paper is to drawn on a set of empirical evidences from Brazilian companies applying photonics in order to gain insights into the process of emerging technologies in promoting industrial development and market diffusion. Photonics attributes of primary importance to economic outcomes are the fact it can be described as a ''general purpose technology (GPT), able to have multiple vertical and horizontal applications across the industrial spectrum'' (Grupp, 2000). A patent and scientometrics research showed that there are potential niches in photonics to be explored by developing countries because a dominant design has not been defined yet for diverse applications (Frietsch and Grupp, 2006). Although, this research is the first attempt to analyze photonics evolution outside more developed nations such as Canada, Germany, Japan, US, and UK (Miyazaki, 1995; Hassink and Wood, 1998; Hendry et al., 2000; Smy, 2002; Hatakenaka, 2004).

The remainder of the paper is organized as follow: in Section 2, we present a theoretical framework that indicates the necessary elements to build up and strengthen technological capabilities. Section 3 highlights geography and technology as the basis to elaborate research design, followed in Section 4 by a brief explanation of photonics production chain. In Section 5, we summarize the

*Corresponding author. Tel.: +55 11 3091 5363; fax: +55 11 3091 5399.
E-mail address: luciana.pereira@poli.usp.br (L. Pereira).

0166-4972/$ - see front matter © 2008 Elsevier Ltd. All rights reserved.
doi:10.1016/j.technovation.2008.12.001

development of photonics in the US, while Section 6 characterizes the Brazilian experience. In Section 7, we conclude with the discussion of some of the gaps that might continue to obstruct technological and industrial innovation in developing countries.

2. Building technological capacity and capabilities

2.1. Innovation system approach

The important role played by innovation to economic development makes this a rich research field, which has grown since the seminal work of Schumpeter (1942) received renewed attention. Schumpeter had shed light on how new firms, new markets, new products, and new technologies, as well as the figure of entrepreneurs and large corporations, are in the core of capitalism dynamic.

The concept of national system of innovation (NSI), which rests upon evolutionary theory, has been a highly successful product and producer of the arrangement between institutions and organizations (Coriat and Weinstein, 2002). The philosophy behind NSI is that the interaction among firms (private or public, large or small), universities/research institutes, and government, are the building blocks to spur technological development and innovation. These interactions, whose main goal is driving innovative performance of firms, might be technical, social, legal and/or financial (Lundvall, 1992; Nelson, 1993).

One of the main impacts that a system of innovation can have is on skills and on changes in firms' behavior. Evolutionary theory of firm focuses on the dynamic process by which firm behavior and market outcomes are jointly determined over time (Nelson and Winter, 1982). The term "routine" is used to describe the firms' efforts in solving problems, either in a regular and predictable way, or in random events. In this sense, technological change is seen as a gradual modification in routines during natural trajectories.

Consequently, there are clear differences between the structures of industries that respond differently to innovation challenges depending upon the stage of their evolution. Thus, the taxonomy Schumpeter Marks I and II was proposed to define the industrial evolution (Malerba and Orsenigo, 1996). Mark I is characterized by "destructive creation", which is made possible due to the use of a new technology carried out by new and small companies. In this case, the barriers to entry almost do not exist and the pattern of industrial organization is represented by a number of small companies working under conditions of risk and uncertainty. Mark II is represented by incumbents "creative accumulation" that serves as a barrier to entry for new competitors.

The relevance of Schumpeter Marks I and II taxonomy is the fact it links industrial structure to technological regimes, highlighting the implications for building industrial capabilities. This is especially relevant for emerging countries because even though "institutional factors may influence the process of technical change at country level, the properties of innovation processes are, to a significant extent, invariant across countries and specific to technologies or industrial sectors" (Marsilli, 2000). From this point of view, what is different is the type and quality of problem-solving strategies utilized and the amount of resources available in each country (Srinivas and Sutz, 2008).

2.2. Products and processes management and market diffusion

One of the crucial elements within the system of innovation, as well as for firm's growth, is the diffusion of a new product, process, and/or service into the marketplace. In the case of cutting-edge technologies, in addition to the inherent problems associated with product development, there is also the fundamental issue of becoming knowledgeable and skilled in the technology domain.

Therefore, with the specific goal of technological innovation, companies have to overcome two obstacles. One of them involves the key challenge of generation/acquisition of new technologies, while the other deals with the integration of technology into products. Making the bridge between these phases is not a linear process. First of all, companies need to be aware of scientific and technological advancements, while being able to connect them with the company's long-term strategic goals. During the same time, it is necessary to integrate technological and product systems design considering company's market, resources, and competences (Cohen and Levinthal, 1990; Iansiti, 1995). For these reasons, as a means to be successful and competitive, an innovative company needs to improve organizational capabilities, coordinating and communicating external and internal resources, acquiring and maintaining knowledge, and skills across different levels.

3. Technology and geography as a methodological framework

For the purpose of advance an understanding about technological development, we have set forth in this research two dimensions of analysis: technological and geographical. Focus on a specific technology is important for the reason that there are different technologies and each one of them follows its own trajectory, which demands a certain type of knowledge, skill, and infrastructure.

Technological system analytical framework is a methodology that focuses on institutional infrastructure, technology, and network of agents. With this methodological approach we can analyze how such elements are being used to develop and spread a specific technology in order to reach innovation (Carlsson and Stankiewicz, 1991; Carlsson et al., 2002).

In this paper, we have chosen to study photonics as our technological system because it deals with applications of fundamental scientific advances, which can be a major factor for socio-economic development. In a broad sense, the definition of photonics relates to the generation, controlling, and detection of photons, or light. The nature of light has been studied by many scientists over centuries, but it was Newton's Optkis (1704) the first work to conceptualize the basic behavior of light. However, it was not until 1865 that Maxwell's equations proved that, in reality, light was an electromagnetic wave. This body of knowledge became known as the classical theory of light or classical optics. At the turn of the 20th century, when everybody was convinced that light was wave, then it came Planck saying that light was a particle as well. Finally, Einstein used Planck's quantum hypothesis to describe photoelectric effect, proving that light behaved not only as a wave, but also as a particle: the photon (Weiss, 1996). These important findings about light phenomena were the beginning of what today is called quantum optics.

Several industrial applications have benefited from scientific and technological advancements carried out both in academic and industrial laboratories. For instance, knowledge in classical optics has led to development of devices such as telescopes, microscopes, cameras, while photonics use have become popular with the advent of lasers, fiber optics, LED, and optoelectronics, among others. The growing importance of photonics occurs because photons have zero mass, which make them travel at the speed of light in a vacuum. Technically, as a result of these characteristics, systems based on photonics have the ability to handle much greater volumes of information, leading to more compact and efficient devices than electronics one. From the point of view of evolutionary economic theory, replacement of electronics by photonics is an example of discontinuities associated with the emergence of new technological paradigms and it is contextual to the industrial structures related with that technology (Dosi, 1982).

Together with technology, we have also determined geography as a dimension of analysis. With the growing flux of international trade and its affects upon the global market, it is important to take into account the structure and trend of international dimension in shaping economic change and technological progress (Carlsson et al., 2002). Brazil was chosen because with other emerging economies such as India, China, Russia, and South Africa, has received a lot of attention as southern engine of global growth. As a control variable, we studied the US since they are a major innovator in all fields of photonics (science, technology, and industry).

3.1. Data collection and analysis

This research, which spanned 2004–2007, involved ethnographic observations, collection, and analysis of data and case study. In order to understand the business applications of photonics, we have to identify who the network of agents are, in which technological context they interact, and what type of institutional infrastructure is required to support them.

First of all, in order to get acquainted with the field of photonics, we have consulted secondary sources from industry and scientific publications such as Laser Focus World (1997–2007a, b), Photonics Spectra, Opto&Laser Europe, Biophotonics, and Nature Photonics. In the Brazilian case, we also have used local newspapers as a source to reconstruct the history of photonics development. The goal was to find information on companies, new technologies, regions, products and processes, mergers and acquisitions, along with public policy and legal issues (intellectual property and environmental legislation). At the same time, we have analyzed several academic papers carried out in countries such as Canada, Germany, Japan, the United States, and the United Kingdom, most of them being concerned with the role of photonics and regional development.

The next step was fieldwork. We have chosen to carry out ethnographic observations at six conferences sites (two in Brazil, one in Argentina, two in the US, and one in Russia). These were scientific meetings, but usually they held products exhibitions as well. Conferences are major field configuring events whereby the participants actively discuss, contest, and negotiate the field's meaning. At these events, participants from communities gather to debate the important players within the field, the role of new technologies and products, and their commercial potential. An important part of these events are networking sessions where participants are able to meet and informally talk about aspects related to technology.

At the Photonics West Meeting, which receives around 1000 exhibitors each year in California, from both the local region and the international optics and photonics community, is the largest commercial exhibition on optics, lasers, biomedical optics, optoelectronic components, and imaging technologies. We used the Photonics West industry database as our major sample selection. After the 2006 meeting, participants were approached by email. The aim was to gather information from decision-makers within the company through primary research that spanned industry interviews and case studies.

The questions addressed the formation, motivation, and the transformation of the business, the role of institutions, and the origin of the capital that would lead us to understanding the company's trajectory. Some questions were especially concerned with management of the various levels of the productive process, from technological acquisition, passing through to product development strategy, to the manufacturing process, and finally to distribution and relationships with clients and suppliers.

The Brazilian sample was not randomly chosen. In fact, it included only national firms whose technology acquisition can be traced back to Brazilian research institutes and universities. Thus, we excluded from this study any company that had its technology obtained outside Brazil. We found 33 firms that fit this requirement, all located in

São Paulo State, with 8 companies in Campinas and 25 in São Carlos, both university towns, traditionally associated to economic and technological development.

4. Industrial value chain

The industrial value chain in photonics technologies covers four main levels. The first of them consisting of the production of advanced materials and process equipment used to manufacture the primary components. When components are combined with other devices they form a set of systems with specific attributes. The last level is composed by enabled products, when systems are integrated to form an equipment unit (see Fig. 1).

We believe that because of the pervasive nature of technology and the complications and costs associated with collection, analysis, and publication of economic statistics, photonics is still not identified as an industry or sector by any of the main international agencies (NAICS—North American Industry Classification System, United Nations ISIC—International Standard of Industrial Classification and NACE—Classification of Economic Activities in the European Community) that classify business establishments by the type of economic activity they are involved with. However, those working with photonics recognize themselves as an industry and they are trying to be accepted as such. In 2007, NAICS Economic Classification Policy Committee (ECPC) received a request to include photonics as a new industry. Even though ECPC recognized technical differences between photonics and other groups, they have decided to group photonics with some of the already existent codes such as 334413 semiconductor and related device manufacturing or 334419, other electronic component manufacturing.

For this reason, in this paper we have used the word photonics technology and applications instead of photonics industry. In addition, in order to select the companies studied here we have used the broadest definition that categorizes companies as photonics-related if "manufacturing or use of photonic-enabled products is a key aspect of their business and when photonic-enabled products are products that would not be possible without their photonic content" (DTI, 2006).

4.1. General characteristics of photonics markets

Basically, the market can be split in components and enabled products. These components have multiple applications, which mean they might be used in diverse manners and for different purposes. Components and systems have been responsible for shaping photonics market structure, creating diverse applications and, consequently, submarkets.

As reported by the Laser and Photonics Marketplace Seminar in 2006 (Fig. 2), the sales of main photonics components – LEDS, fibers and cables, diode lasers, nondiode lasers, image sensors, couplers, modules, connectors and hardware, passives, solar cells, and storage media – were US$ 27 billion in 2004. These components can be used in several applications and markets as diverse as telecommunications, medical devices, microelectronics, semiconductors, and scientific research, among others.

As an example of components and enabled products, we can mention the laser. As a component, lasers have some technical specificities that make them be divided in nondiode and diode lasers. While nondiode lasers use either a gas, a liquid or a crystal to convert electromagnetic radiation into a beam of coherent light, diode lasers use semiconductor technology to do the same. Given that light has many different properties – such as power, wavelength and spectral quality, beam quality, polarization – laser-based applications, and this is also valid for other components, depend on which of these features of light is wanted. In Table 1, we provide a list of applications that use diode laser according to light property that has being manipulated.

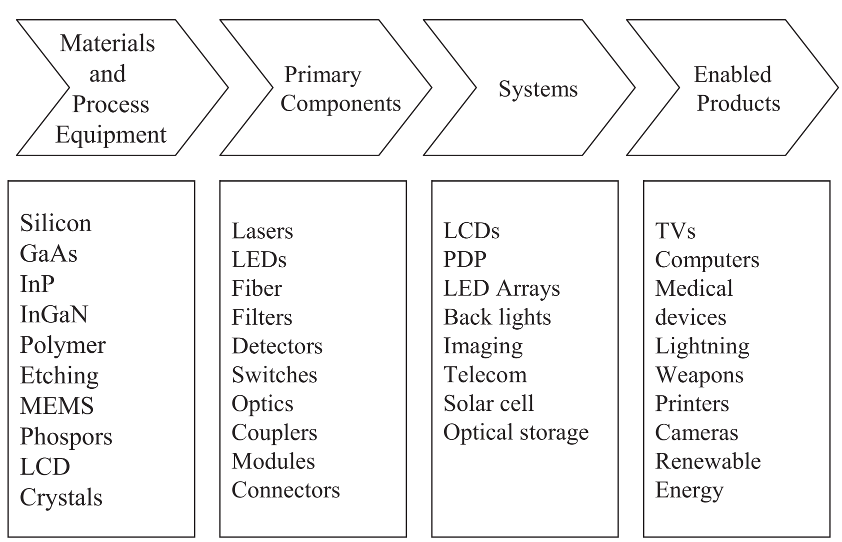

Fig. 1. Photonics value chain. *Source*: Adapted from DTI (2006).

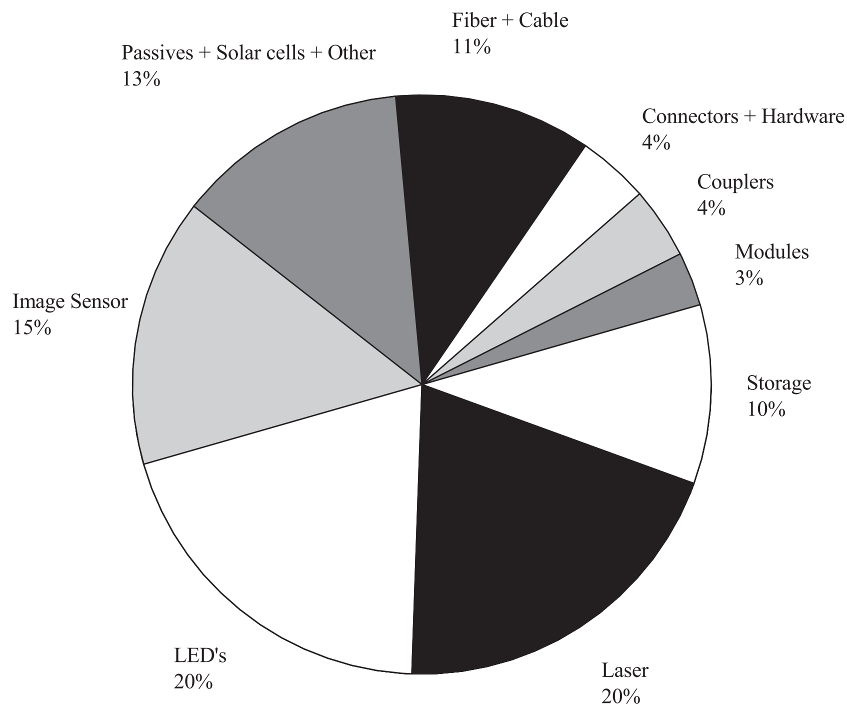

Fig. 2. Photonics component sales in 2004. *Source*: Adapted from Laser & Photonics Marketplace Seminar Proceedings, 2006.

Table 1
A sample of applications that use diode laser according to light property manipulated.

Light property	Applications	
Directed energy of an optical beam	• Laser printers • Bar-code readers • Image scanning • Illuminators • Optical data recording	• Combustion ignition • Laser surgery • Industrial sorting industrial machining • Directed energy weaponry
Narrow spectral properties	• Range-finding • Telecommunication • Infrared countermeasure • Spectroscopic sensing • Photodynamic therapy • Frequency doubling and conversion	• Atomic clock state preparation • Quantum key cryptography • Water purification (in the UV • Generation of radio-frequency or terahertz waves
Coherence of diode-laser-generated light	• Interferometric distance measurement • Holography	• Coherent communications • Coherent control of chemical reactions

Source: Author, adapted from various sources.

Some of these applications are emerging while others are well established. After the prices of components have gone down and diode laser became a mass product, innovative solutions have been found almost every day. In the early 1990s the price of a diode laser was US$100/mW power, while in 2002 this value decreased to US$ 1/mW power.

The point here is that the production of lasers as well as other components has become concentrated in the hands of a few major companies, while the number of enabled products producers has spread among several applications and markets. The result is that market revenue for enabled products is growing year by year at a faster rate than components (Fig. 3). While computing, consumer/entertainment, and communications sectors accounting for the largest share of investments, turnover, and sales, there are still niches to be explored.

4.2. International geographic concentrations

Since photonics is a science-driven application, it is natural that firms have spread around universities and research centers, a common pattern we have observed by taking a look at major producing countries.

A systematic analysis of the Science Citation Index (SCI) and patent applications have showed that Germany is third in the share of papers published in the optics field, as well as occupying the same position in the number of patent applications, behind only the US and Japan (Frietsch and Grupp, 2006). The cities of Jena and Munich concentrate

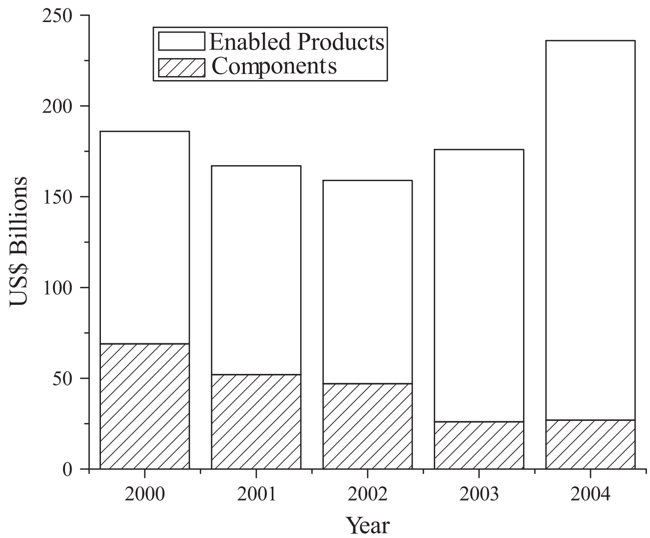

Fig. 3. Total photonics market estimates. *Source*: Adapted from Laser & photonics Marketplace Seminar Proceedings, 2006.

the bulk of companies using photonics. On the one hand, Jena has a long tradition started with Carl Zeiss in 1846, which has been developing and manufacturing microscopes to optical measurement systems, as well as equipments for photography, astronomy, medical, and defense applications. On the other hand, Munich has become a cluster of photonic activities as the result of investments from American and Japanese companies that have chosen the city to distribute their products in Europe (Hassink and Wood, 1998).

In Japan, the Hamamatsu cluster has resulted from the successful experiences of Hamamatsu Photonics (HPK) in the middle 1980s (Hatakenaka, 2004). The advances of Japan in photonics technologies are intricately linked to research and development investments done by large companies operating in consumer electronics, electronic devices, and communication and such as Sony, Hitachi, Fujitsu, Toshiba, Sumitomo, NEC and Sharp that have built internal competencies in photonics in order to apply it to their products (Miyazaki, 1995).

In the UK, the development of firms has spread all over East Anglia and Wales. In spite of Cambridge boom of high-tech companies during the last decade, the concentration of photonics firms in these regions are indeed connected to traditional and established companies. In this case, the new firms have spun off from large corporations, often the fruit of restructuring and downsizing (Hendry et al., 2000). Like in Germany, the Wales cluster has its origin rooted to local institutions/firms, whereas in South Wales where direct foreign investment has played a major role in photonics development.

Among emergent countries, China has been making investment efforts to develop indigenous capabilities in photonics. In the Plan of Technological Development 863/973, lasers are listed as one of the ten emerging technologies, while a "scientific approach to development" is a key point governing the eleventh five-year development plan (2006–2010). (MOST, 2007). The cities of Wuhan, Shenzhen, and Shanghai are in the national high-tech industry development zone and receive investments in infrastructure in order to become self-sufficient in photonics, as well as to attract foreign companies through fostering innovation and industrial development (Opto&Laser Europe, 2005). Another reason China wants to develop indigenous photonics is related to the fact that US Commerce Department's Bureau of Industry and Security (BIS) has restricted American companies to sell components such as high-power lasers to them claiming the dual character of the technology (Overton, 2008). This policy inflicts any other country working in projects with China. Recently, Brazilian companies working in the Sino-Brazilian satellite project were denied access to American products considered sensitive (Angelo and Garcia, 2007).

5. Photonics made in USA

The United States have thousands of companies using photonics as the main technology. California, Massachusetts, New York, New Jersey, Colorado, and Florida are home to hundreds of organizations and companies that can deliver complete R&D, engineering, and manufacturing capabilities using photonics. These companies consists of a diverse array of large and small companies that serve the aerospace, telecommunications, healthcare, homeland security and defense, testing and measuring, storage, and semiconductor industries.

The region of Silicon Valley concentrates the most technology-intensive industries using photonics such as computers, electronic, communications, equipment of measurement and control, and the aerospace industry. The region of New York is specialized in research and development of products related to image and metrology, while New Jersey's tradition in optical communications dates back to the pioneering work at Bell Labs.

All these places are part of a national system of innovation that was contemplated with investments in education, and partnerships with government and companies that has resulted in a virtuous circle of economic and technological development. The American system of innovation enjoys a diverse industrial base, with strong concentrations of high value-added business. Together with the private sector, governmental agencies annually finance millions of dollars in research carried out in academic, industry and public laboratories, where groups of researchers are involved in multidisciplinary projects sponsored both by industry and government. Whole new companies have sprung up from these efforts.

5.1. Structure and growth

Since photonics technology demands very specific technical knowledge and skills, the barrier to enter this market is very high. In our sample of American companies, we observed two principal patterns of market entry in photonics: the academic spin-off and the corporation model.

In the academic case, researchers (student and/or professors) foresee a commercial application for their lab experiments. As a result, the group starts a company, applying their knowledge to develop a commercial product.

Corporation spin-off occurs when an employee or group of employees decide to leave the company to start their own business, with the support of the former company or not. Sometimes large companies allow their employees to run and test new business unit without supervision. The contrary also can happen. Some employees can start a totally independent business because they have not found support for their ideas inside the company they work for. And, finally they can start a new company just for the sake of entrepreneurial spirit. Usually, these companies start very small, with less than 15 employees, but with a strong technical background and an innovative idea.

To finance the start up at an early stage, many business starters have no other option but to use their own bank accounts, credit cards, and home-equity lines of credit. Seed funding with venture capitalists, or any other type of investor, is not easy to get if the company still needs to prove the technology, develop the product, and get substantiation from the marketplace.

As an alternative to outside investors, some companies take advantage of public contracts to raise capital and find demand for their products. The American government has stimulated photonics by financing special projects through the Small Business Administration agency's special programs, such as Small Business Innovation Research (SBIR) and Small Business Technology Transfer Program (STTR) (see Table 2).

Depending on the technology and product, some companies can also collaborate and receive funds from major industries such as those in automotive, aerospace, and electronics. A major company and/or a government agency as an investor is beneficial in a number of ways: the prestige associated with the name; their contacts and resources; and the fact they might not want a controlling interest in the company.

As the company grows, it may be necessary to raise a more significant amount of capital. In this case, companies may enter a contract with an investment bank to sell its shares to the public, which is called an Initial Public Offering (IPO). The first and greatest challenge with the IPO is that the size of the deal cannot be too small in order to justify the amount of effort the investment bankers will need to make it worthwhile. As a result, the IPO is a viable strategy only for a company raising a few million or more due to the minimum up front costs required.

5.2. Merger and consolidation trends

We have observed a number of merger and acquisitions with companies using photonics. It may happen that one firm's intellectual property complements the other firm's product offerings, thus enabling the enhancement of its product portfolio. It is also very common that American and European's firms combine businesses to offer a comprehensive product range that enable them to address new applications and markets.

Table 2
A sample of US public programs aiming at the development and applications of photonics.

Institution	Programs	
Department of Commerce	• NIST Optoelectronics Division	• NIST Advanced Technology Program
Department of Defense	• Air Force Research Lab • Alliance for Photonic Technology • Army Optics Branch • Defense Advanced Projects Agency (DARPA)	• Naval Research Laboratory • National Technology Transfer Center
Department of Energy	• Lawrence Livermore National Laboratory Laser Programs • Oak Ridge National Laboratories	• Sandia National Laboratories Program in Microelectronics and Photonics
National Aeronautics and Space Administration (NASA)	• Ames Research Center Photonics Group and Vision Group • Goddard Space Flight Center International Laser Ranging Service	• Langley Research Center Lidar in Space • Marshall Space Flight Center
National Institutes of Health (NIH)	• National Institute of Biomedical Imaging	• National Eye Institute
National Science Foundation (NSF)	• The NSF funds optics and photonics research	

Source: Author, adapted from various sources.

6. Brazilian efforts to develop indigenous photonics

Our analysis of the development of photonics technologies in Brazil was based on case studies of firms located in Campinas and São Carlos. Both cities are located in São Paulo state and their economic development was boosted at the end of 19th century by coffee exporters. However, nowadays, they have become university towns that are home of important research centers as well as multinational enterprises and locally grown high-tech companies, from which we have selected a sample to study.

The Center for Research in Optics and Photonics (CEPOF) was conceived in response to the State of São Paulo Research Foundation (FAPESP) recommendations, and also to a perceived need among the leading academic and research institutions in São Paulo. Two centers, one located at University of Campinas (Unicamp), and other, at University of São Paulo at São Carlos campus were commissioned by FAPESP in 1998 by focusing on scientific, technological, educational and industrial outreach efforts toward the rapid and directed development of photonics technology.

There are two submarkets where Brazil has created opportunities for new ventures in exploiting photonics technologies: optical communications with telecom equipments and biophotonics with medical devices. Even though the level of science and technology in Campinas and São Carlos are broadly comparable, as we shall discuss, each city has adopted a different approach toward industrial development. By comparing their similarities and contrasts, we can draw some conclusions about technological development in Brazil.

6.1. Campinas: state import substitution initiative in a traditional market

During the late 1960s and early 1970s, Brazilian government had organized telecommunication services as a monopoly ruled by Telebras, a state-owned company. Being aware of the key role played by the sector, they made investments to expand and integrate the telecom network services as well as foster a private telecom industry, since they had anticipated that services would increase the demand for equipments. In addition, the national telecommunication plan had clear guidelines to support the formation of human resources and knowledge production in strategic areas (Neves, 2002; Oliveira, 2005).

6.1.1. The pillars of optical communications development

6.1.1.1. University of Campinas. With the purpose of providing widespread high education and research around the countryside of São Paulo, a state law of 1962 established the creation of the University of Campinas (Unicamp). As part of the national telecom plan, a group of Brazilian scientists, who have previously worked at Bell Labs, were invited to create the Physics Institute. One of their missions was to provide a research program in optical communications, which is a field that study any form of telecommunication that uses light as the transmission medium.

The Optical Communications Group had two main goals. The first of them was to bring together physicists, engineers, and technicians in order to prepare skilled human resources to work in all stages of the telecom business (services, equipments, and R&D). The second goal was to stay abreast of state of the art knowledge on optical communications and to make significant contributions to building capacity in partner institutions.

As a means to achieve these objectives, they had financial support from federal and state research agencies such as the National Council for Scientific and Technological Development (CNPq), the Coordination for the Improvement of Higher Education Personnel (CAPES), and The State of São Paulo Research Foundation (FAPESP).

6.1.1.2. Telecom Research and Development Center (CPqD). The Telecom Research and Development Center (CPqD) was created with the specific purpose to do the research and development required to assist the telecom industry with technological solutions. CPqD was supposed to work close with Unicamp, using their outputs to build its own capabilities while searching for technologies that could match the Brazilian telecom market needs. Telebras funded US$24 million in R&D over 7 years (1977–1984). Of this total from 1 percent to 1.5 percent was to fund CPqD (Hobday, 1990).

6.1.1.3. Telecom equipment industry. Policy makers were aware they could not promote Brazilian technological and industrial development in telecom given the market was totally dominated by three multinational subsidiaries (Siemens, NEC, and Ericsson) that locally adapted and assembled the products. At the same time, they long for the end of foreign technology dependency because during pre-regulation years, when the services were decentralized, there were significant technical incompatibilities of telephone systems between cities, making communication difficult.

The solution found to overcome market failure was centralize the services with a state-owned company – Telebras – and stimulate local companies to produce equipments, effectively protecting them from competition, keeping foreign investments out of the Brazilian market during a period of 5 years while state purchase contracts would absorb the supply. In addition, companies could apply for financial support with The Brazilian Development Bank (BNDES), and Research and Projects Funding Agency (FINEP).

6.1.2. From lab to market: fiber optic system

The Brazilian experience with fiber optical systems has become emblematic of the complexity of indigenous efforts to upgrade technological and industrial capabilities.

During early 1970s, Bell Lab conducted basic research with optical fiber, the most common type of channel for the light in optical communications, while defense applications sustained the business market. In 1978, New York telephone system substituted cooper with optic cables after product development had undergone to low cost, high volume, and technical feasibility (Webb, 1996).

In Brazil, research with optical fibers started in 1975 at Unicamp. In early 1980s, CPqD started developing and testing the first prototype of the optical fiber system (fibers, detectors, lasers). After the positive results with the field testing in Rio de Janeiro, the Ministry of Communication (Minicom) opened for bid competition to select the companies eligible for manufacturing and selling the fiber system.

The total of two bids was sent to the competition: Opticabo, a partnership between Bracel and Imbramac, and other consortium formed with X-tal, Condugel, and Marsicano. When it was almost decided that the technology was going to be transferred for the two consortia, Opticabo announced the Italian company Pirelli was joining their efforts as a strategy to compete in international markets.

Under an allegation that the partnership with a foreign company would ruin Brazilian attempt to build technological capabilities, Minicom decided to create a monopoly, choosing the consortium lead by X-tal to manufacture optical fibers, despite the fact it was well known the company was facing some financial difficulty that was solved when the Group ABC, a telephone service provider, acquired X-tal. The initial contract between Telebras and ABC-Xtal had foreseen the production of 2000 km of fiber optics in the first year, which should be delivered 7 months after the contract had been signed.

ABC-Xtal was strategically relocated from Rio de Janeiro to Campinas, next to CPqD. In 1984, a modern and automated plant using laser sensors in assembly systems was inaugurated employing 30 people. They had the market protected until 1989. However, when companies such as Alcatel, Furukawa, Pirelli, and Tectel entered the Brazilian market, this fact has not only led to more players with competitive prices, but also more innovative products. In addition, as we can observe in Table 3, ABC-Xtal lagged far behind its competitors in terms of generations of fiber optics technology development. The world economic crisis that reached the telecom sector in 2000 sealed ABC-Xtal fate.

6.1.3. Misleading the process of technological transfer and product development?

Since the beginning, Telebras had used bid competition as an instrument for selecting companies to receive the technology developed by CPqD. Usually, they elected from two to four Brazilian companies with similar capabilities. However, the strategy of selecting the company when the product was already done created the classic problem of cross-functional integration that occurs during the development of new products.

The problem was that CPqD worked alone during all phases of product development, from concept idea and product planning, to detailed product and process engineering, where the design–build–test cycle was scheduled to occur. Basically, the company that would eventually manufacture the equipment only became part of the process during pilot production and ramp-up. The result was a passive and linear process of collaboration, in which there was little interaction between CPqD and companies.

Another problem was the fact that all the research and development expenses were handled entirely by Telebras. In theory, technology transfer policy included a contract for a period of 5 years during the course of implementing the technology, as well as maintenance and consulting services for improvement after initial product release. Moreover, the contracts stipulated the payment of royalties that varied from 1 percent to 5 percent of the net price of the sale after the manufacturer has been paid by the costumer. Although this was a clause in the contract

Table 3
Commercial development of fiber optic technology.

Generation	Period	Longest wavelength (nm)	Technology
First	1978–1982	900	Gallium arsenide and silicon transmitter (GaAs/Si)
Second	1980–1984	1300	Iridium gallium arsenide phosphide and germanium (InGaAsP/Ge) transmitter ILD (injection laser diode)
Third	1982–1987	1300	InGaAsP PINFET (field effect transistor) LED Single mode fiber
Fourth	1986–1992	1630	InGaAsP Avalanche photo diode (APD) Dispersion shifted fiber
Fifth	1991–1996	1630	Iridium gallium arsenide–iridium phospide (InGaAs–InP) Eridium-doped fiber (EDP)

Source: Webb (1996).

between the CPqD and the companies, the payments lacked a sense of continuity.

In order to correct this problem, Telebras created a plan whose major goal was to fix and solidify the sources to finance R&D by obligating companies to send the royalties generated from the sale of products. They also tried to increase companies' participation during tests cycles. Finally, the solution they settled on was to decrease the levels of product detail.

6.1.4. The outcomes of competing in a traditional market

During the 1990s, following an international trend, the state monopoly in telecom services was transformed into a system with significant participation of international operating companies.

At the technological level, the 1997 General Telecommunications Law made CPqD a not-for-profit private foundation. In order to maintain the existence of CPqD, the law defined certain service concession arrangements. New operating companies were obliged to contract a certain amount of services with CPqD during the first 3 years after deregulation (1999–2001) (Cassiolato et al., 2002).

In pre-deregulation years (1996–97), Minicom increased the amount of investments in telecom to prepare for privatization. This had a positive impact on the equipment industry. During that period, a group of start up companies, mainly composed of CPqD former researchers, entered the market excited by the idea that telecom expansion and information technology popularization could increase demand for their products and services. However, what nobody expected was such rapid advances in technology, resulting in IT and telecom equipment becoming obsolete at an increasingly rapid pace.

In spite of all efforts, today the production and commercialization of telecom equipments in Brazil is dominated by foreign firms. It is therefore not surprising they are the same companies that have been here much before the nationalization policy: Siemens, NEC, and Ericsson. The multinational newcomers entered the market with a structure that relies on global suppliers, competitive costs, volume, and capital. However, they have only assembled and sold products, with no seemingly intentions in a more active role in local R&D. From more than 120 existing companies in the 1980s, when product nationalization reached over 90 percent, little more than 20 still operate (Cassiolato et al., 2002).

Pressure to offer innovative products and to cut costs has lead to the process of deverticalization, attained mostly by parts and components import. Nowadays, another concern for Brazilian producers is the Chinese suppliers Huawei, UT Starcom, and ZTE that were able to become scale producers of telecom equipments, offering competitive prices (Fan, 2006). Faced with so many uncertainties, Brazilian companies are now concentrated on survival strategies.

6.2. São Carlos: entrepreneur import substitution initiative in a niche market

The development of photonics technology in São Carlos is also the result of public investments in universities and research centers. However, the origin of a medical device industry applying photonics in São Carlos, differently from Campinas, was a private-led initiative.

6.2.1. The pillars of biophotonics development

6.2.1.1. University of São Paulo in São Carlos. The São Carlos Engineering School was established as part of the University of São Paulo under a state law of 1948. Toward 1971, the University of São Paulo contemplated a plan to found an Institute of Physics and Chemistry aimed at the broad study of natural sciences. However, it was only in 1994 that the Physics Department was reorganized and further expanded into a totally independent institute.

Among the many different groups doing research at the Physics Institute, there was the Optical Group working with experimental atomic physics. As with many scientific fields, atomic physics is often considered in the wider context of atomic, molecular, and optical physics as also known as AMO physics. AMO physics is the study of matter–matter and light–1matter interactions on the scale of single atoms or structures containing a few atoms.

6.2.1.2. Optical design workshop. The essence of certain experimental methods in both natural and life sciences is that they need to use sophisticated and expensive materials, components and equipments. The challenges that developing countries university-based researchers working with experimental design face are very high. First, they have to convince their peers the research proposal is worthwhile to be funded as any other researcher. Second, since most of the tools they need to conduct the experiments have to be imported, they also have to deal with a very bureaucratic process to put a purchase order. Finally, they have to wait for the delivery lead time that can be increased by Brazilian customs operations. Today, with all the improvements brought by internet, the entire process might take months. In the past it was much worse.

As a result, the Optical Group started working on the implementation of an optical design workshop to manufacture and assemble basic optical components, buying equipment and hiring and training technicians in France and Germany. Around 1985, the workshop was doing so well that they became a supplier of components not only for research groups, but some Brazilian companies as well.

6.2.1.3. Medical device industry. Again public investments have not only produced competent human resources and innovative research, but nurtured profit-maximizing entrepreneurial business as well. The transformation of biophotonics in medical devices was the result of the collaboration between research groups working in distinct fields such as physics, medicine, and dentistry, all dealing with problem-solving under scarcity conditions. Sometimes, adverse situations might lead to an optimal solution (Srinivas, 2006; Srinivas and Sutz, 2008). In this case, the solution to overcome the costs of imported medical equipments was to produce their own.

6.2.2. *From lab to market: lasers applications*

The concept of laser was developed in 1958 by Charles Townes and Arthur Schawlow. Two years later, Theodore Maiman made the first working laser at Hughe Labs that was soon commercialized and used for defense proposes (Townes, 1999). Nevertheless, it was only in the middle 1980s that lasers production became cost-effective and boomed in the world. Grupp (2000) used a database of technometrics, patent indicators and bibliometric study of science to trace the market development dynamics for laser beam sources (Fig. 4).

In Brazil, around 1985, the Optical Group scientists had designed a helium–neonium (He–Ne) laser system, which they thought could become a commercial product. With a product in hand and one million dollars loan from FINEP to buy a vacuum coating system to ramp-up production, they set up Opto, a start up company. Despite their technical capabilities, the reality was that there was not demand for He–Ne lasers systems in Brazil. Opto faced the classic entrepreneur puzzle, which is a great technical idea without market viability. In this case, even though Opto entered the laser market in the moment it was boomed in other countries, the Brazilian market was simply not ready for the product.

The initial failure could have been the end of Opto, but it became a lesson when with the support of a venture capitalist, the company started to focus on market and management strategies. Now, instead of manufacturing components, they started to use their knowledge to provide innovative solutions that could find applications in Brazilian market. Opto started to supply industrial markets with laser meter systems and multi-position lasers. Photonics-enabled products gave the company the income they needed to survive and keep the business running as well as the possibility to explore new markets.

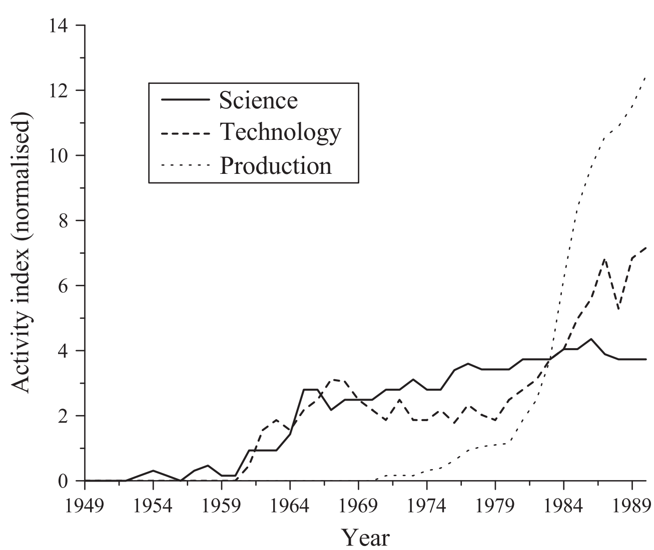

Fig. 4. Market development dynamics for laser beam sources measured in various innovation indicators. *Source*: Adapted from Grupp (2000).

By expanding into new markets, Opto found its way to grow. A medical division was created as a channel of distribution for medical lasers devices. However, the contact with products, suppliers, and clients, gave them enough expertise to manufacture their own devices. Furthermore, collaboration with the Federal University of São Paulo Medical School (Unifesp) has helped them to develop new products. This type of inter-disciplinary collaboration is particularly important for the medical laser submarket since strong scientific foundation is more significant for lasers in medicine than for other medical markets (Grupp, 2000).

Opto trajectory has become an inspiration. Since then, five other companies have been spun off from Opto (DMC, Kondortec, Eyetec, Artec and Optica on-line) while another four companies have been spun off from the Optics Group (MM Optics, CEMAPO, APRAMED, and Calmed). Today these companies have supplied the Brazilian market with light-based devices for eyes surgery, photodynamic therapy, dental applications, and non-invasive diagnostics.

6.2.3. *Efficient technological transfer and product development process?*

The success of the technology transfer that has been occurring between the university's researchers and start up companies is part of a well-managed process of product development. Networks with academic and research institutions have given the access to advanced knowledge to companies producing medical devices.

There are some steps these companies have been following. In the first step, companies carry out the analysis, the access and the capturing of new technologies. Some product's requisites (functional, technical, and commercial) are specified during the concept and experimental studies, while simulated or physical mock-ups are built to evaluate partial or global technical viability. Participation in trade shows and conferences assist them in determining what costumers want and what competitors are doing. At the same time, a company has to assure that the R&D goals match medium and long run strategies.

After research results have being fully understood, technology will be incorporated into a prototype product. Now technology is adjusted to a parameter where it can be reproduced and tested. The project is divided into design, optic, electronic, mechanical, and manufacturing. Although the prototype carries many of the final product elements, its production may be experimental and may not necessarily use the final manufacturing processes.

Safe aspects are exhaustibly evaluated as well as essays to test technical characteristics typical of products applying photonics. Major optic functions such as wavelength, power, and measurement are determined in this phase. In the case of medical products, the homologation with the National Health Surveillance Agency (ANVISA) is initiated simultaneously with product development because they must prove that the results of laboratory, animal, and human clinical testing are safe and effective.

A third phase is product manufacturing when it is necessary to choose the best tools for the production processes. Due to product diversification and market increases in participation, manufacturing integration is becoming less vertical. Optic components and devices design are a core competence; consequently, they are manufactured in-house as well as modules and final integration. The scarcity of resources to invest in capital equipments might be solved using the creativity of engineers and technicians. Moreover, through this incremental process of innovation, it is more difficult that competitors can copy the process.

Pre-market evaluation is then performed through internal presentations for customers, conferences, and trade shows. These demonstrations is also a strategy of product marketing while official launching is organized at events with specific media, interviews, and the presence of targeted costumers.

Customer assistance and after-sales support is perceived to be a fundamental part of product development. Firstly, innovative products allow the company to establish a bond with its customer, since they need to be prepared to use the new technology. During the customer training, a company can teach them how to extract the best results from that product. Secondly, the company can follow product performance during its life cycle in order to find the product's strengths and weaknesses. The user–producer relationship does not mean only the company knows about customer opinions and needs concerning a specific product, but it is also a source of innovation and may thus strengthen customer loyalty and retention.

6.2.4. The outcomes of competing in a niche market

A natural market protection has helped the process of development of Brazilian companies entering the biophotonics market for medical device. This time is the American, Japanese, and German companies that cannot compete in Brazil with the high-prices of their products.

Meanwhile, Brazilian companies have used this market barrier not only to learn and catch up, but to surpass the competition in their own territory. Opto for instance has registered products with Food and Drug Administration (FDA) and European Union Medical Devices Directive (MDD 93/42) in order to enter American and European markets.

7. Discussion and conclusion

As we have just reported, photonics applications contain much of the elements that puzzle academics, policy analysts, and companies dealing with technological and industrial development. We identified two key areas that seem to be able to explain to a large extent why countries differ in technological development and diffusion: (i) weakness of institutions that affect the incentives to innovate, and (ii) inadequacy of social and organizational demography to carry out innovation activities.

We will start by discussing the weakness of the institutions, in special on the legal and financial systems and their connections. Legal institutions arrangements are necessary to establish incentives and standards to innovation. They enable efficiency and transparency of the public administration and of the corporate governance. The perception that the legal system is predictable and effective enhances confidence that contracts enforcement and property rights will be respected. For example, according to Sérgio Paulino from the National Institute of Industrial Property (INPI), the Brazilian patent system is characterized by unfairness and lack of neutrality. This means that the application of the intellectual property law is influenced by the position of the economic agents, such as business sector, technology involved, origin of capital, and technological capabilities and scientific competence of the researchers involved. Some idiosyncrasies faced by developing countries' IP regime are better explained by Sarkissian (2008).

Solid legal institutions also provide financial markets the protection investors need to promote business. In developed economies, potential businesses have relied on a variety of financial sources (angel investors, venture capitalists, equity markets, and alliance partners) instead of traditional lenders (banks) and personal sources (family and friends). In Brazil, FINEP has taken actions to strengthen a broader set of financial tools, combining public, and private capital. The new financial framework includes instruments that increase the availability of risk capital, equity financing, and loan guarantees to encourage public–private R&D partnerships and interactions among government, universities, and business ventures.

In fleshing out this new initiative, Brazilian policymakers have targeted companies that need capital to expand their operations to consolidate their product lines and market positions. However, a challenge for them is in deciding whether and how to provide access to early-stage capital, during pre-seed and seed stages, when start ups are being created and conceiving a high-tech product.

As we have mentioned, the inadequacy of social and organizational demography also play an important role on innovation activities. The composition of social, organizational, and physical infrastructure must exist and be constantly upgraded to ensure the process of innovation (Albuquerque, 2007). Within this context we shall discuss the role of education, organization of industrial production and infrastructure and support services.

Education is one component inside social infrastructure that assists in the process of innovation. However, while school attendance in Brazil has increased since 1990s, the quality of most part of the educational system is considered incapable of prepare workers with the skills the private sector needs.

In addition to provide skilled workers, education system through universities and R&D labs can also drive industrial competitiveness, spreading their research capabilities into new spin-off companies and/or products and services (Kroll and Liefner, 2008). Although spin-offs of strategic R&D programs and collaboration between firms and universities have long existed in Brazil, they have not been occurring in the proportion the country needs.

Further, lack of continuity and long-term commitment due to political and economical issues are one of the main obstacles the country has to face to sustain industrial development. Despite new incentives, it is well known that there are still constraints on academic professionals starting their own firms, barriers to movement from academia/research institutions to industry and back, and inadequate infrastructure for product development and testing.

It is certain that the dynamism and diversification of the industrial output depends on the composition of firms' population. In a complete innovation system, we observe that the industrial base is composed by a set of firms characterized by different sectors, sizes, and ages. These characteristics together with their organizational strategies and technical capabilities determine the type of relationship firms will have with each other (cooperation, complementarity or competition) to get benefits in the market.

Innovative Brazilian firms have had their operations restricted because of the dependence on foreign suppliers that result in more costs and lead times. Although there are several firms in Brazil, there is not enough critical mass of dynamic firms that could form the bedrock of a strong technological capability. The result is that while American companies may operate on an international basis at start up, Brazilians have first to develop domestic market, and only later, a few of them may have accumulated enough resources and experience to compete in international markets.

Slow development of physical infrastructures threatens to reduce the pace of economic development in general and the evolution of the innovation system in particular. Infrastructure focused on transportation issues presently one of the main bottlenecks holding up economic development in Brazil. The relentless and rapid urbanization, not properly managed, have caused public transport inadequacy, traffic congestion, and environmental degradation (pollution, flooding). Additionally, they have also exacerbated urban poverty and violence, with proliferation of slums and joblessness, thus deterring investments.

As a result, all these variables should be built and strengthen simultaneously if the intention is to achieve high levels of technological and industrial innovation and socio-economic development. Otherwise, isolated initiatives, though worth pursuing, will reach only modest and partial results.

An interesting subject for future work is to compare the evolution of photonics – and also other technologies – with other emerging countries. As pointed out by Cetindamar et al. (2008), studies that take into account the reality of developing countries may open up new ways to understand and think the literature of technological management as well as open up new avenues for cooperation among them.

Acknowledgements

The authors would like to thank Alice Amsden and gratefully acknowledge her support during research at MIT. Thanks are also due to Smita Srinivas comments during MIT Industrial Performance Center seminaries. We are especially indebted to the referees, who provided useful and relevant criticisms. This research was financially supported by the National Council for Scientific and Technological Development (CNPq no. 140497/2004-8) and the Coordination for the Improvement of Higher Education Personnel (CAPES no. BEX1197/05-3). The usual disclaimer holds.

References

Albuquerque, E.M., 2007. Inadequacy of technology and innovation systems at the periphery. Cambridge Journal of Economics 31 (5), 669–690.

Amsden, A.H., 2004. Import substitution in high-tech industries: Prebisch lives in Asia. Cepal Review 82, 75–89.

Angelo, C., Garcia, R., 2007. EUA barram satélite do Brasil com a China. Folha de São Paulo. Caderno Ciência 〈http://www1.folha.uol.com.br/fsp/ciencia/fe2210200701.htm〉.

Carlsson, B., Jacobsson, S., Holmén, M., Rickne, A., 2002. Innovation systems: analytical and methodological issues. Research Policy 31 (2), 233–245.

Carlsson, B., Stankiewicz, R., 1991. On the nature, function, and composition of technological systems. Journal of Evolutionary Economics 1 (2), 93–118.

Cassiolato, J.E., Szapiro, M.H.S., Lastres, H.M.M., 2002. Local system of innovation under strain: the impacts of structural change in the telecommunications cluster of Campinas, Brazil. International Journal of Technology Management 24 (7–8).

Cetindamar, D., Wasti, S.N., Ansal, H., Beyhan, B., 2008. Does technology management research diverge or converge in developing and developed countries? Technovation.

Cohen, W.M., Levinthal, D.A., 1990. Absorptive capacity: a new perspective on learning and innovation. Administrative Science Quarterly 35 (1), 128–133.

Coriat, B., Weinstein, O., 2002. Organizations, firms and institutions in the generation of innovation. Research Policy 31 (2), 273–290.

De Negri, J., Salerno, M.S. (Ed.), 2005. Inovações, padrões tecnológicos e desempenho das firmas industriais brasileiras.IPEA.Brasília. Access online on 〈http://www.ipea.gov.br/sites/000/2/livros/Inovacao_Padroes_tecnologicos_e_desempenho.pdf〉.

Dosi, G., 1982. Technological paradigms and technological trajectories: a suggested interpretation of the determinants and directions of technical change. Research Policy 11 (3), 147–162.

DTI, 2006. Photonics: a UK strategy for success: Painting a bright future. Department of Business Enterprise and Regulatory Reform Report 〈http://www.dti.gov.uk/files/file30415.pdf〉 (17.08.2006).

Fan, P., 2006. Catching up through developing innovation capability: evidence from China's telecom equipment industry. Technovation 26 (3), 359–368.

Frietsch, R., Grupp, H., 2006. There's a new man in town: the paradigm shift in optical technology. Technovation 26 (1), 13–29.

Grupp, H., 2000. Learning in a science-driven market: the case of lasers. Industrial and Corporate Change 9 (1), 143–172.
Hassink, R., Wood, M., 1998. Geographic 'clustering' in the German opto-electronics industry: its impact on R&D collaboration and innovation. Entrepreneurship and Regional Development 10 (4), 277–296.
Hatakenaka, S., 2004. Optoelectronics in Hamamatsu: in search of a photon valley. MIT Industrial Performance Center. Working paper, pp. 1–40 ⟨http://web.mit.edu/ipc/www/pubs/articles/IPC04-003.pdf⟩.
Hendry, C., Brown, J., Defillippi, R., 2000. Regional clustering of high technology-based firms: opto-elelectronics in three countries. Regional Studies 34 (2), 129–144.
Hobday, M., 1990. Telecommunications in Developing Countries. The Challenge from Brazil. Routledge, London.
Iansiti, M., 1995. Shooting the rapids: managing product development in turbulent environments. California Management Review 38 (1), 37–58.
Jin, J., von Zedtwitz, M., 2008. Technological capability development in China's mobile phone industry. Technovation 28 (6), 327–334.
Kannebley Jr., S., Porto, G.S., Pazzello, E.T., 2005. Characteristics of Brazilian innovative firms: an empirical analysis. Research Policy 34 (7), 872–893.
Kroll, H., Liefner, I., 2008. Spin-off enterprises as a means of technology commercialisation in a transforming economy—evidence from three universities in China. Technovation 28 (5), 298–313.
Laser& Photonics Marketplace Seminar Proceedings, 2006 ⟨http://lms07.events.pennnet.com/fl/home.cfm?Language=⟩.
Laser Focus World, 1997–2007a. Review and Forecast of the Laser Markets: Part I. Nondiode Lasers, vol. 1, January.
Laser Focus World, 1997–2007b. Review and Forecast of the Laser Markets: Part II. Diode Lasers, vol. 2, February.
Leskovar-Spacapan, G., Bastic, M., 2007. Differences in organizations' innovation capability in transition economy: internal aspect of the organizations' strategic orientation. Technovation 27 (9), 533–546.
Lundvall, B.A., 1992. National Systems of Innovation: Toward as Theory of Innovation and Interactive Learning. Pinter, London.
Malerba, F., Orsenigo, L., 1996. Schumpeterian patterns of innovation are technology-specific. Research Policy 25 (3), 451–478.
Marsilli, O., 2000. Technological regimes: theory and evidence. DYNACOM Working Paper Series, St. Anna School of Advanced Studies.
Ministry of Science and Technology of People's Republic of China-MOST, 2007 ⟨http://www.most.gov.cn/eng/programmes1/index.htm⟩.
Miyazaki, K., 1995. Building Competences in the Firm: Lessons from Japanese and European Optoelectronics. Macmillan, New York.
NAICS Economic Classification Policy Committee (ECPC), 2007 ⟨http://www.census.gov/epcd/naics07/NAICS07docketPage68.html⟩.
National Science Foundantion (NSF), 2004. Science and Engineering indicators. Industry, Technology, and the Global Marketplace.
Nelson, R., Winter, S., 1982. An Evolutionary Theory of Economic Change. The Belknap Press of Harvard University Press, Cambridge, MA.
Nelson, R. (Ed.), 1993. National Innovation Systems. A Comparative Analysis. Oxford University Press, New York/Oxford.
Neves, M.S., 2002. O Setor de Telecomunicações. In: Elizabeth Maria de São Paulo; Jorge Kalache Filho. (Org.), BNDES 50 Anos-Histórias Setoriais, vol. 1, 1 ed. DBA Artes Gráficas, São Paulo, pp. 297–319.
Newton, I., 1704. Opticks: or, a Treatise of the Reflections, Refractions, Inflections and Colours of Light. Based on the fourth ed., London 1730. Courier Dover Publications, 1979.
Oliveira, E.Q., 2005. Euclides Quandt de Oliveira (depoimento). 2005. Rio de Janeiro, CPDOC/Empresa Brasileira de Correios e Telégrafos (ECT).
Opto&Laser Europe, 2005. China turns its eyes to photonics to fuel growth. January, pp. 35–43.
Overton, G., 2008. Confronting photonics: are controls on exports of high-power lasers hurting US manufacturers? Laser Focus World 4 (6), 59–61.
Sarkissian, A., 2008. Intellectual property rights for developing countries: lessons from Iran. Technovation 28 (11), 786–798.
Schumpeter, J.A., 1942. Capitalismo, socialismo e democracia. Zahar Editores, Rio de Janeiro.
Smy, T., 2002. Photonics in Canada: An Outline of Current Research and Industrial Capability. Carleton University, Ottawa February.
Sotarauta, M., Srinivas, S., 2006. Co-evolutionary policy processes: understanding innovative economies and future resilience. Futures 38 (3), 312–336.
Srinivas, S., 2006. Industrial development and innovation: some lessons from vaccine procurement. World Development (10), 1742–1764.
Srinivas, S., Sutz, J., 2008. Developing countries and innovation: searching for a new analytical approach. Technology in Society 30 (2), 129–140.
Townes, C.H., 1999. How the Laser Happened. Adventures of a Scientist New York. Oxford University Press, Oxford.
Wang, T.Y., Chien, S.C., 2007. The influences of technology development on economic performance—the example of ASEAN countries. Technovation 27 (8), 471–488.
Webb, G.K., 1996. Product development and price trends for fiber optic components. Technovation 16 (31), 133–141.
Weiss, R.J., 1996. A Brief History of Light and Those That Lit the Way World. Scientific Publishing Company.

Luciana Pereira is an associate researcher with the Technological Change Laboratory (TCLab) at Columbia University. Dr. Pereira received the Ph.D. and M.S. in Engineering (Labor, Technology, and Organization Program) from Polytechnic School at University of São Paulo and a B.A. in Economics from São Paulo State University (UNESP).

Guilherme Ary Plonski Guilherme Ary Plonski, Full Professor of University of São Paulo (USP), is the Scientific Coordinator of the University's Center for Technology Policy and Management (PGT/USP).