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The spatial diffusion of a knowledge base: Laser technology research in West Germany, 1960-2005

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The Spatial Diffusion of a Knowledge Base – Laser Technology Research in West Germany, 1960 – 2005

by

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The Spatial Diffusion of a Knowledge Base—Laser Technology Research in West Germany, 1960–2005

Michael Fritsch

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August 2010

Abstract

We analyze the spatial diffusion of knowledge in laser technology in West Germany from 1960, when this technology began, until 2005. Laser technology research has been nearly exclusively conducted in regions that are home to a university with a physics or electrical engineering department, an indication of the science-based character of the technology. Early adoption of laser knowledge was especially prevalent in large agglomerations. While we cannot detect knowledge spillovers from adjacent regions, geographic proximity to the center of initial laser research was conducive to early adoption of laser research; however, the effect is small. The earlier a region embarked on this type of research, the higher the level of laser research later, indicating the accumulation of knowledge generated in previous periods. Our results highlight the role of a region's absorptive capacity for commencing and conducting research in a new technological field. In the case of laser technology, it was more the level of existing tacit knowledge than an interregional transfer of tacit knowledge that played an important role.

Keywords: Innovation, regional innovation systems,
knowledge, spatial diffusion, laser technology

JEL classification: R11, O33, O52

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1. Knowledge in space¹

It is well recognized that new scientific and technological knowledge does not diffuse evenly in space and that there may be substantial regional differences in the adoption of new technology (Hägerstrand, 1967; Feldman, 1994; Stoneman, 2002). Theoretical explanations for the diffusion pattern highlight certain regional factors, particularly a region's absorptive capacity for the technology and its skill in knowledge production, agglomeration economies, and the mobility of people between regions and between firms, as manifested, e.g., in the formation of spinoffs (Boschma and Wenting, 2007; Klepper, 2009). Understanding the spatial pattern of knowledge diffusion is highly relevant in explaining regional innovation processes and is a basic precondition for designing appropriate policy measures in the event public intervention is deemed desirable.

In this paper, we analyze the emergence and spatial diffusion of knowledge in the field of laser technology in West Germany from the inception of this technology in 1960 until 2005, a period of 45 years. In contrast to other studies on the diffusion of new technologies, such as new farming methods, CNC machine tools, or new vaccines (Nelson, Peterhansl, and Sampat, 2009; Stoneman, 2002), our focus is on the diffusion of *research*, i.e., the generation of new knowledge in a certain technological field, not on applying a given technology. Our goal is to answer three questions. First, where in West Germany did laser research begin and why? Second, what was the general spatial diffusion pattern of

¹ This paper is based on the project "Emergence and Evolution of a Spatial-Sectoral System of Innovation: Laser Technology in Germany, 1960 to Present" sponsored by the German Volkswagen Stiftung and jointly conducted by the Friedrich Schiller University Jena, the Max Planck Institute for Economics, Jena, the Technical University Bergakademie Freiberg, and the University of Kassel. We are particularly indebted to our co-workers in this project, Helmuth Albrecht, Guido Bünstorf, Cornelia Fabian, and Matthias Geissler, for their cooperation. Moreover, Wolfgang Ziegler and Sebastian Schmidt of the patent office of the Friedrich Schiller University Jena provided invaluable help in preparing and processing the data. Our analysis of laser patents considerably benefited from the work of Martin Gehlert and Jana Hofmann, as documented in their diploma theses. All errors are, of course, the responsibility of the authors. We gratefully acknowledge helpful comments by Bo Carlsson, Koen Frenken, Steven Klepper, and Raquel Ortega Argilés on earlier versions of this paper, as well as advice on econometric issues from Florian Noseleit.

laser technology research in West Germany? Third, why did this diffusion pattern occur?

The laser is one of the most important scientific inventions of the 20th century (Bertolotti, 2005), with a great variety of applications that include range finding and transmission and storage of information, material processing, printing, medical technology, and weapons, to name just a few. The term “laser” is an acronym for *light amplification by stimulated emission of radiation*. The term is used to describe a wide range of devices for the amplification of coherent light by stimulated photon emission generated by pumping energy into an adequate medium. A laser device emits a *coherent* light, both in a spatial and in a temporal sense. This coherent light can be generated by using different media, for example, solid crystals and semiconductors. Laser technology is often described as “science based” in that academic (analytical) knowledge played an important role in its development (e.g., Bertolotti, 2005; Bromberg, 1991; Grupp, 2000). Specifically, one of the chief academic inputs needed for its development was an appropriate theory. It was one thing to generate a laser effect, which was initially a rather short flash of light; it was a completely different thing to make this light more durable and control it. In other words, to “tame” the laser, it was necessary to know how it worked—and thus enters theory.

We first discuss hypotheses about the spatial diffusion of laser technology research (Section 2) and describe the underlying data (Section 3). Section 4 lays out the general pattern of spatial diffusion of laser technology research in Germany, with a particular focus on why the initial adoptors became engaged in this field of research. Empirical analyses and tests of our hypotheses are reported in Section 5. Section 6 concludes.

2. Where it should happen first: Expectations about the spatial diffusion of laser technology research

It is now common practice to distinguish between two types of knowledge: codified knowledge, which is well documented in a medium (e.g., written

on paper), and tacit knowledge, which is not codified but embodied in persons (Polanyi, 1966; Nonaka and Takeuchi, 1995). Codified knowledge can be communicated through various mediums, such as scientific publications; the transfer of tacit knowledge, however, requires personal contact between people, in particular, direct face-to face communication.² Particularly in emerging research fields, knowledge will not be completely codified and there will be a significant amount of noncodified, tacit knowledge that is important for accruing the full benefits of the codified part. Different from codified knowledge, which, in principle is widely available, transferring tacit knowledge often requires face-to-face contact, which may lead to an uneven diffusion in space. Transfer of both types of knowledge, however, can only occur in the presence of absorptive capacity, i.e., the receiving unit must be capable of identifying relevant knowledge, absorbing it, and applying it for own purposes (Cohen and Levinthal, 1989; Zahra and George, 2002). Hence, even if knowledge is available, be it codified or tacit, it may fail to be transferred due to lack of absorptive capacity.

We distinguish between two aspects of regional diffusion: the first adoption of laser technology research in a region and the intraregional dissemination of the research. With regard to the first adoption of laser technology research, there are a number of reasons why this type of research should first occur in large agglomerations.³

² This argument corresponds to Mansfield's "epidemic" model of technology diffusion (Mansfield, 1968). To explain the diffusion of a process innovation, Mansfield argues that its adoption is critically dependent on information that is transferred by direct personal contact. Because the share of actors who possess this information increases during the diffusion process, the likelihood of receiving the new information and of adopting the new technology begins to rise. However, after a certain point in the diffusion process, the adoption rate slows and begins to decrease because more and more actors are already "infected" and are using the technology. This type of process leads to the s-shaped diffusion curve that is observed for many different technologies (see Stoneman, 2002).

³ These arguments correspond to a great degree with the reasoning of Torsten Hägerstrand's (1952, 1967) highly influential approach to explaining the spatial diffusion of process innovations. Based on empirical observations, Hägerstrand hypothesized that diffusion of new technology proceeds "down" the spatial hierarchy, i.e., new processes are first implemented in the "center," the large agglomerations, and are then put into practice by actors on the "periphery," i.e., in remote and sparsely populated regions.

- First, large cities are home to relatively many actors and institutions with different types of knowledge so that there should be a relatively high probability that the necessary absorptive capacity is present.
- Second, large agglomerations not only have many actors and institutions, but also contain a relatively highly qualified workforce and a large share of R&D activities, both of which may be particularly relevant for the adoption of new knowledge. Laser technology, given its science-based nature (Bromberg, 1991; Grupp, 2000), may require intensive interaction with academic institutions and may, therefore, be particularly likely to occur in regions with academic research facilities in the appropriate scientific disciplines, namely, physics (including optics) and engineering.⁴ The more scientists there are working in such research facilities, the higher the number of potential adopters should be and, therefore, the higher the likelihood that laser knowledge will be absorbed in the region. Since such research facilities tend to be located in larger cities, we expect first occurrence of laser research in such regions. During the diffusion process, laser technology research is expected to spread to smaller cities. However, given its science-based nature, laser technology research is not expected to occur in regions that do not have academic research facilities in the relevant disciplines.
- Third, large agglomerations tend to have a relatively high share of large firms. To the extent that large firms have an innovative advantage over smaller firms (Cohen and Klepper, 1996), they may adopt research in new technology relatively early.
- Fourth, due to the large number of employment opportunities in large agglomerations, they are more likely to be the sites of labor market mobility and, consequently, attract tacit knowledge from other regions to

⁴ The most relevant fields of engineering for laser technology research are electrical engineering, high frequency engineering, information and communication technology, and mechanical engineering.

a greater degree than would more sparsely populated regions on the periphery.

As laser technology begins to diffuse in space, it is expected that the “second-tier” adopters will be those smaller cities that also have academic research institutions in the required fields. To the degree that transfer of tacit knowledge is important to the spread of this technology, it is plausible to assume that regions located close to the early centers of laser technology research will adopt the technology sooner than more distant locations because the mobility of people is sensitive to geographic distance. The presence of producers of laser technology products in a region can be both a result and a cause of research. On the one hand, the regional manufacture of laser products can be viewed as an attempt to commercialize the results of previous research in the region. On the other hand, producers of laser beam sources may themselves engage in research and may also stimulate research by others located in the same region, e.g., by entering into research cooperation activities with local universities.

With regard to the *intraregional* diffusion of laser technology research, we expect a relatively high speed of diffusion in large cities, for several reasons. First, large agglomerations tend to have more people and organizations with the necessary absorptive capacity. Second, they provide more opportunities for face-to-face contact, as well as for intraregional mobility between organizations, than do small and sparsely populated regions. Since the intraregional diffusion of technology takes time, those regions that adopted laser research relatively early will in later years have a higher level of research activity in this field than will those regions that adopted laser research later.

In summary:

H 1: Laser technology research should be first adopted in large agglomerations.

- H 2: Laser technology research should occur only in regions host to academic research facilities in the fields of physics and engineering.
- H 3: Regions located close to the early centers of laser technology research are more likely to conduct research in this technological field than are regions located farther away.
- H 4: Regions that began research on laser technology relatively early will have more research in this field in later years than will regions that started relatively late.
- H 5: Regions with producers of laser technology will have higher levels of research output than regions without producers of laser technology.

These hypotheses will be tested in our empirical analysis (Section 5).

3. Data and methodology

To describe the diffusion of laser technology research in Germany we use two types of data: information on patent applications and scientific publications related to laser technology. The information on patents in the field of laser technology was obtained from the database DEPATISnet (www.depatisnet.de), which is maintained by the German Patent and Trade Mark Office. From this database we selected all patent applications with priority in West Germany that were assigned to the technological field “devices using stimulated emission” (IPC H01S) as either the main or secondary class. Hence, patents that are related to applications of laser technology, such as printing and measurement, but not to the laser beam source itself, were not considered. Because not all patents, especially the earliest ones, are electronically coded, we consulted secondary sources such as the patent register of the Friedrich Schiller University Jena.⁵ From the patent data we obtained information on the applicant organizations and the inventor’s residence at the time of application. The patent

⁵ These sources are the *Bibliographische Mitteilungen der Universitätsbibliothek Jena, 1960–1971*.

applications are assigned to the region where the inventor resides. Since the focus of this study is on the diffusion of laser knowledge in Germany, inventors living abroad were not considered.

The scientific publications on lasers were obtained from two main sources. For the years 1960 to 1970, we looked at the *Physikalische Berichte*, which is an annual register of international scientific publications in natural sciences. This source contains all authors' affiliations. For the period 1971 to 2005, we referred to the INSPEC database, which includes the affiliation of only the first author. Since identification of scientific publications was based on a key word search of both the title and the abstract of papers, the definition of laser technology is considerably wider than that for laser technology patents, which was restricted to inventions related to laser beam sources, and thus the scientific publications may involve applications of the technology.⁶

The information on university departments and institutes whose fields of activity and/or research were close to emerging laser technology was obtained from two main sources. The first of these is the *Vademecum* registers, which contain information on all academic institutions in West Germany. This information includes the scientific discipline, location, and head(s) of each department or institute. The registers are published every four years, and we employed the registries from 1961 to 1992. For the remaining years, 1993 to 2005, data were taken from the German University Statistics of the German Federal Statistical Office. For the purpose of this study, we classified academic institutions as relevant for laser technology if they had departments in physics (including general physics, theoretical physics, experimental physics, applied physics, technical physics, physical chemistry, and optics) or in certain areas of

⁶ The key words included "laser," "lasing," and "lasers." For the search of laser publications in the 1960–1970 period in the *Physikalische Berichte*, a broader concept was used because at that time the term "laser" was not fully established and lasers were frequently referred to as "optical masers." In addition to the terms "laser" and "stimulated photon emission," the search included "microwave frequency doubling in ruby," "parametric amplification and oscillation," and "resonators."

engineering (electronic engineering, high frequency technology, communication technology, mechanical engineering).

The spatial framework of our analysis encompasses the 74 planning regions (*Raumordnungsregionen*) of West Germany. East Germany and the former West Berlin are excluded so as to keep the regional setting constant. Planning regions consist of at least one core city and, in most cases, a surrounding area.⁷ The advantage of planning regions as compared to districts (*Kreise*) as spatial units of analysis is that they can be regarded as functional units, in the sense of travel-to-work areas, and that they account for economic interaction between districts. Planning regions are slightly larger than what is usually defined as a labor market area. In contrast, a district may be a single core city or a part of the surrounding suburban area.⁸ Using planning regions as the spatial framework for the analysis is particularly appropriate since in a number of cases the R&D facilities are located in a larger city while the inventor's place of residence is in a surrounding district that belongs to the same planning region as the R&D facility.

4. Overview of the emergence of laser technology and the diffusion of laser technology research in Germany

4.1 The emergence of laser technology and initial adoption of laser technology research

The theoretical foundations of laser technology date back to 1917, when Albert Einstein rearranged Max Planck's quantum theory into a light quantum theory postulating the possibility of stimulated light emission (Bertolotti, 2005). In 1928, Rudolf Ladenburg and Hans Kopfermann provided the first experimental evidence for stimulated emission, and in the early 1950s, experimental evidence led to speculation about the

⁷ However, for historical reasons, the cities of West-Berlin, Bremen/Bremerhaven, and Hamburg are planning regions without surrounding districts.

⁸ See German Federal Office for Building and Regional Planning (2003) for the definition of planning regions and districts.

possibility of generating microwave amplification by stimulated emission.⁹ In 1960, a research group led by Theodore H. Maiman at the Laboratories of the *Hughes Aircraft Company* in Malibu (California, USA) was the first to succeed in realizing a laser effect, a breakthrough duplicated later that same year by a research group led by Arthur L. Schawlow at *the Bell Telephone Laboratories* (Bertolotti, 2005; Bromberg, 1991). News of this success spread quickly around the world, creating a buzz in the academic community, a flurry of press releases, presentations at conferences, and academic publications (Maiman, 1960a, 1960b; Collins et al., 1960) that became available around the end of that same year, generating a general sense of euphoria among scientists.

In Germany, news about the realization of a laser effect by U.S. research groups induced *Siemens*, a large and highly diversified producer of all kinds of electric and electronic equipment, communications technology, data processing technology, and medical instruments, to dedicate considerable resources to research in laser technology.¹⁰ This strategic decision was made in the summer of 1960, even before publication of the first academic articles describing the successful laser experiments. In late 1960, three *Siemens* labs, two in Munich and one in Erlangen (about 160 km north of Munich), started laser research. The first successful replication of Maiman's experiment occurred in the *Siemens* labs either in late 1960 or early 1961. In February or March of 1961, researchers at *Siemens* in Munich had already considerably improved Maiman's test arrangement. It is remarkable that there is no indication of any research cooperation between *Siemens* and either of the U.S. laser research teams, or any evidence of a transfer of personnel from these teams to *Siemens* at that stage. If *Siemens* received tacit knowledge at

⁹ In 1954, Charles H. Townes, James P. Gordon, and Herbert J. Zeiger presented the ammonia-gas beam oscillator, an important technological breakthrough. Townes coined the term "maser" for this type of amplifier, an acronym for **m**icrowave **a**mplification by **s**timulated **e**mission of **r**

¹⁰ The information on the early adoption of laser technology research by *Siemens* is largely based on Albrecht (1997).

that time, it was mainly through informal contact.¹¹ This clearly suggests that not much transfer of tacit knowledge was needed to reproduce Maiman's experiment. Obviously, scientists with a standard level of absorptive capacity in optics, electrical engineering, and solid state physics who had the necessary equipment available were able to generate the laser effect, as documented in the relevant publications (Maiman, 1960a, 1960b; Collins et al., 1960). Such skills and equipment were available at many universities and the research labs of larger firms at that time.

There are a number of factors that may explain why *Siemens* adopted laser research so early. First, during the late 1950s, *Siemens* had already conducted research in maser technology, the predecessor of the laser. Second, as a large company producing many kinds of electronic equipment, *Siemens* had tacit knowledge in a number of related fields. Third, because of its size and its high degree of diversification, *Siemens* was able not only to mobilize the appropriate resources but also to bear the high risk of early engagement in laser research, which was characterized by extremely high uncertainty about profitable commercial applications. *Siemens* management believed that laser technology was of high relevance for its product portfolio and that early adoption of laser research would eventually pay off. Smaller and less diversified firms would not have been able to mobilize comparable resources for laser research or to bear the high risk of intensive research at this early stage of the technology. The early adoption of laser research by *Siemens* clearly illustrates the role of absorptive capacity. Tacit knowledge inside the organization and the availability of technical equipment as well as a certain laser medium—a ruby of high purity—was sufficient to reproduce the U.S. research results based on available codified knowledge, the publications. This clearly indicates that transfer of tacit knowledge is relatively unimportant if the relevant knowledge base is of an “analytical” character,

¹¹ Albrecht (1997), in his intensive research on early adoption of laser technology by *Siemens*, found no indication of any significant transfer of tacit knowledge at that time.

as is obviously the case in the science-based field of laser beam sources (Asheim and Gertler, 2005).

The importance of internal absorptive capacity may also explain why it took two years longer for the laser effect to be reproduced in the East German GDR (German Democratic Republic). GDR researchers at that time had the same knowledge as did their West German counterparts. They had unhindered access to all the international scientific journals and leading scholars had attended all the main international conferences in physics at which the first realization of a laser effect was an intensely discussed topic. However, in applying their knowledge, the GDR researchers faced two hurdles: they needed permission from the authorities before they could devote resources to this new field of research, and they lacked adequate equipment, most particularly a ruby of high purity (for details, see Albrecht, 2005).

Another important impetus for laser technology research in Germany was that Hermann Haken, a native German who had worked at the Bell Telephone Laboratories and had contact with Arthur L. Schawlow's research group, became Chair of Theoretical Physics at the University of Stuttgart in October 1960. In the following years, Haken was a leading scholar in the development of laser theory. In the summer of 1962, Wolfgang Kaiser, also a native-born German and a friend of Hermann Haken, who had worked at the *Bell Labs* in the *Schawlow* group, realized a laser at the University of Stuttgart where he spent some time as a visiting professor. After moving back from the United States, he became Chair of Experimental Physics at the Technical University of Munich in 1964, where, for the next few decades, he conducted important research in the field of laser technology. Hence, there was a possibly crucial transfer of tacit knowledge via the mobility of leading researchers between the United States and West Germany. However, all these developments occurred *after Siemens* decided to devote substantial resources to research in this new technological field.

4.2 Laser patents and scientific laser publications in West Germany 1961–2005

According to our data, there were 2,980 patent applications by West German inventors in the field of laser beam sources (IPC H01S) from 1960 to 2005.¹² The number of patent applications reached a peak around the year 2000 (Figure 1). Since then, the yearly number of patent applications has decreased, which may be an indication that the innovation system in the field of laser beam sources has reached a certain stage of maturity. A similar pattern can be found for the number of scientific publications, which were identified by using a broader definition of laser technology that includes applications of the technology (Figure 2). According to our data, there were 22,476 publications by German authors in the field of laser technology during the 1960 to 2005 period.

From 1961 to 1980, there have been very few West German patent applicants in the field of laser beam sources (IPC H01S), never more than 18 different entities in any year. However, from 1961 to 1980, *Siemens* accounted for 387 of all 920 (42 percent) German patent applications in the field of laser beam sources. Over the first 10 years (1961–1970) of our study timeframe, this share was more than half (56.7 percent) of all German patent applications in this technological field;¹³ For the period 1960–1980, 131 of the 530 inventors (25 percent) named in the laser-beam-related patent applications were affiliated with *Siemens*.¹⁴ These figures clearly indicate a high concentration of laser research and laser knowledge in one of Germany's largest firms as well as, not

¹² The number of patent applications and publications is restricted to former West Germany. The Berlin region is excluded because information on this region is not comparable over time due to the change of definition of this region after German Unification in 1990. Since we do not have information about the affiliation of authors of scientific publications listed second, third, etc. for 1971–2005, the number of publications with German co-authors may be underestimated.

¹³ In the first three years (1961–1964), *Siemens'* share of all German patent applications in the field of laser technology amounted to about 72 percent.

¹⁴ This includes 13 “star scientists” who are named on 10 or more patent applications. Dieter Röß is named as an inventor in 95 patent applications, Günter Zeidler in 27, Eberhard Groschwitz in 26, and Karl Gürs in 25; all of them were at that time working for *Siemens* in one of its Munich labs.

inconsequently, a high regional concentration of laser research, particularly in the Munich region.

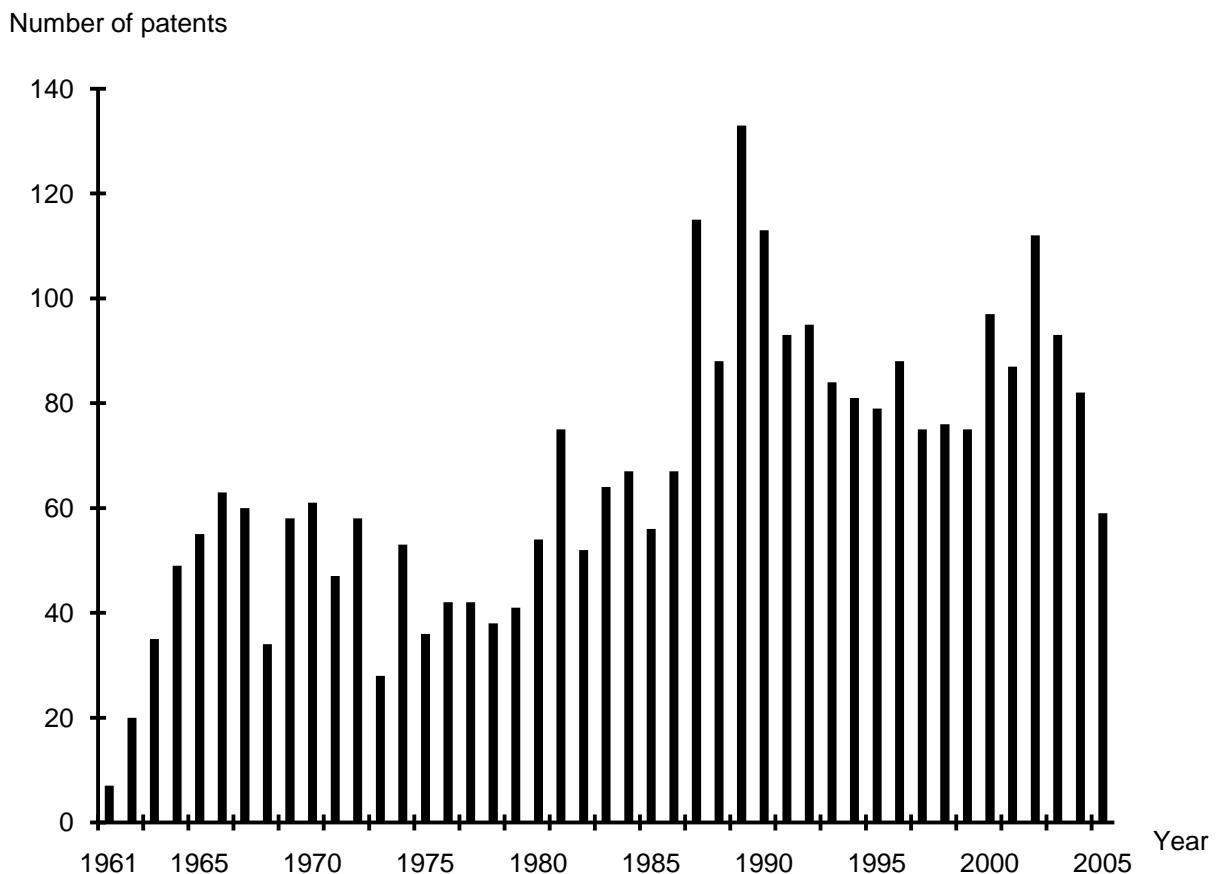


Figure 1: Number of patent application in the field of laser technology (IPC H01S) in West Germany, 1960–2005

The vast majority of inventors named in the patent applications were affiliated with private firms. Patents by university-based inventors were a rare exception. Given the science-based character of laser technology, this dominance of inventors from private-sector firms is surprising.¹⁵ With

¹⁵ Identifying inventors in the patent applications who are affiliated with academic institutions is problematic because, until the year 2002, German professors had the privilege of filing inventions as their own. Hence, patent applications by universities are rather rare in the 1960–2002 period, and many university scientists may be classified as independent inventors. In the case where the invention emerged due to cooperation between a university and a private-sector firm, the university inventors may be assigned to an industry. By matching names of inventors from patent statistics with authors of

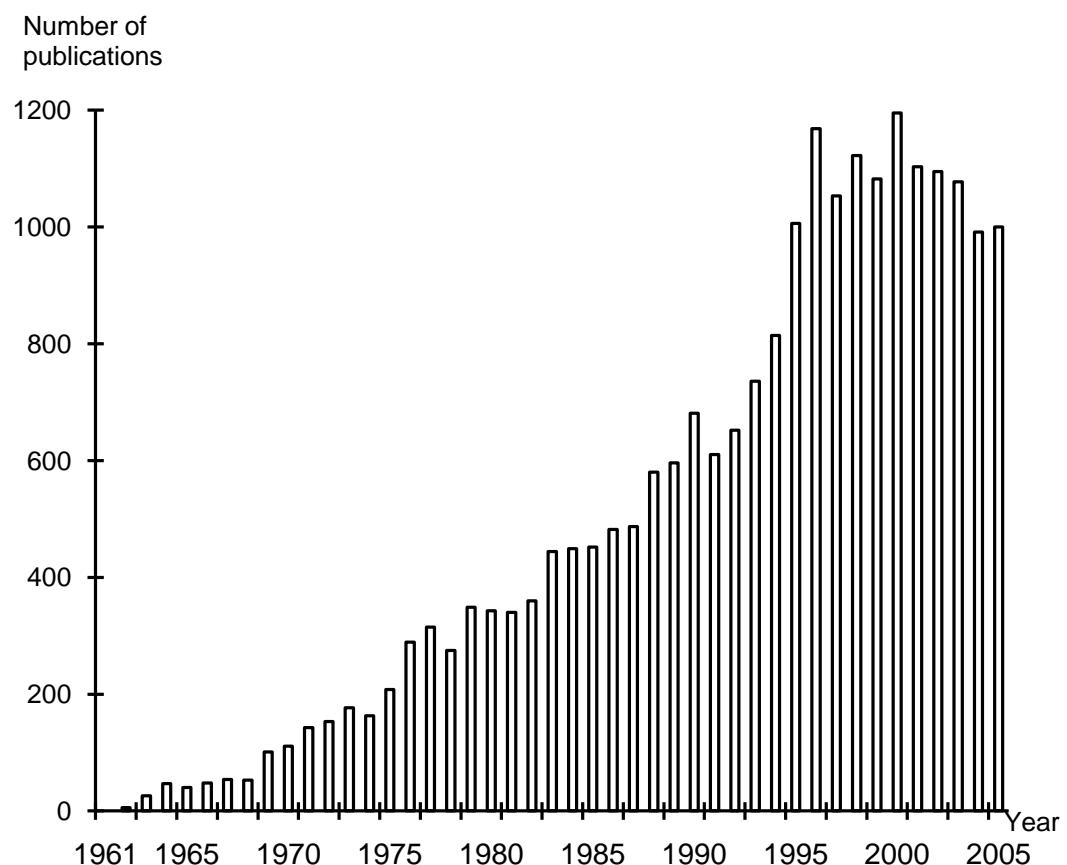


Figure 2: Number of scientific publications in the field of laser technology by West German authors, 1960–2005

regard to scientific publications in the field of laser technology, however, a rather different pattern emerges. For the period 1960 to 1970, the bulk of publications are by authors affiliated with universities (57.62 percent) and public research organizations (14.54 percent). Only 23.58 percent of the publications are by authors working in the private sector, and 1.95 percent are by those with other affiliations, such as the Battelle Institute, a nonprofit organization conducting contract research. This clearly indicates a division of labor where the basic research is mainly conducted by

publications for whom we know their affiliations, we are able to identify patents of inventors working in academic institutions. On the basis of this information, we can assign 2.6 percent of the inventors in the 1961–1970 period to universities. The share of inventors from public research organizations in which university professors were not permitted to patent in their own names is also small (3.25 percent) during that period.

universities and public research organizations, while private-sector firms focus on applied research the results of which can be patented.

4.3 The spatial diffusion of laser technology research in Germany

Where else, other than Munich and Erlangen, where the early Siemens labs were located, and Stuttgart, where research pioneer Hermann Haken worked on laser theory, did research in the field of laser technology begin, and why? Assuming that laser technology research requires academic knowledge in the field of physics, electrical engineering, or communications technology (Albrecht, 1997), we might expect that laser research is conducted only in regions that have academic institutions in these disciplines. In 1960, when news of the first realization of the laser effect spread around the world, 23 of the 74 West German planning regions (31 percent of all planning regions) hosted at least one university with a department or institute of physics or electrical engineering or both. At this time, different organizations and scientists in the regions of Goettingen, Karlsruhe, Braunschweig, and Munich were already involved in research on the predecessor of the laser, the maser (Albrecht, 1997). We may, therefore, expect early adoption of laser technology research particularly in these regions.

In accord with our hypothesis about the presence of academic institutions in physics or electrical engineering being a precondition for conducting research in laser technology, inventors named on applications for laser patents or as authors of publications in the field of laser technology in the year 1965 are almost exclusively found in regions with university departments in these disciplines (Figure 3). Exceptions to this “rule” are probably due to assigning the patent to the inventor’s place of residence instead of the place of work. At that time, the Munich region was clearly in the lead, both in terms of publications and patents, followed by Stuttgart, Darmstadt, and Frankfurt. Figure 3 also shows the earliest recorded industry entry, which occurred in Hamburg, a region where the

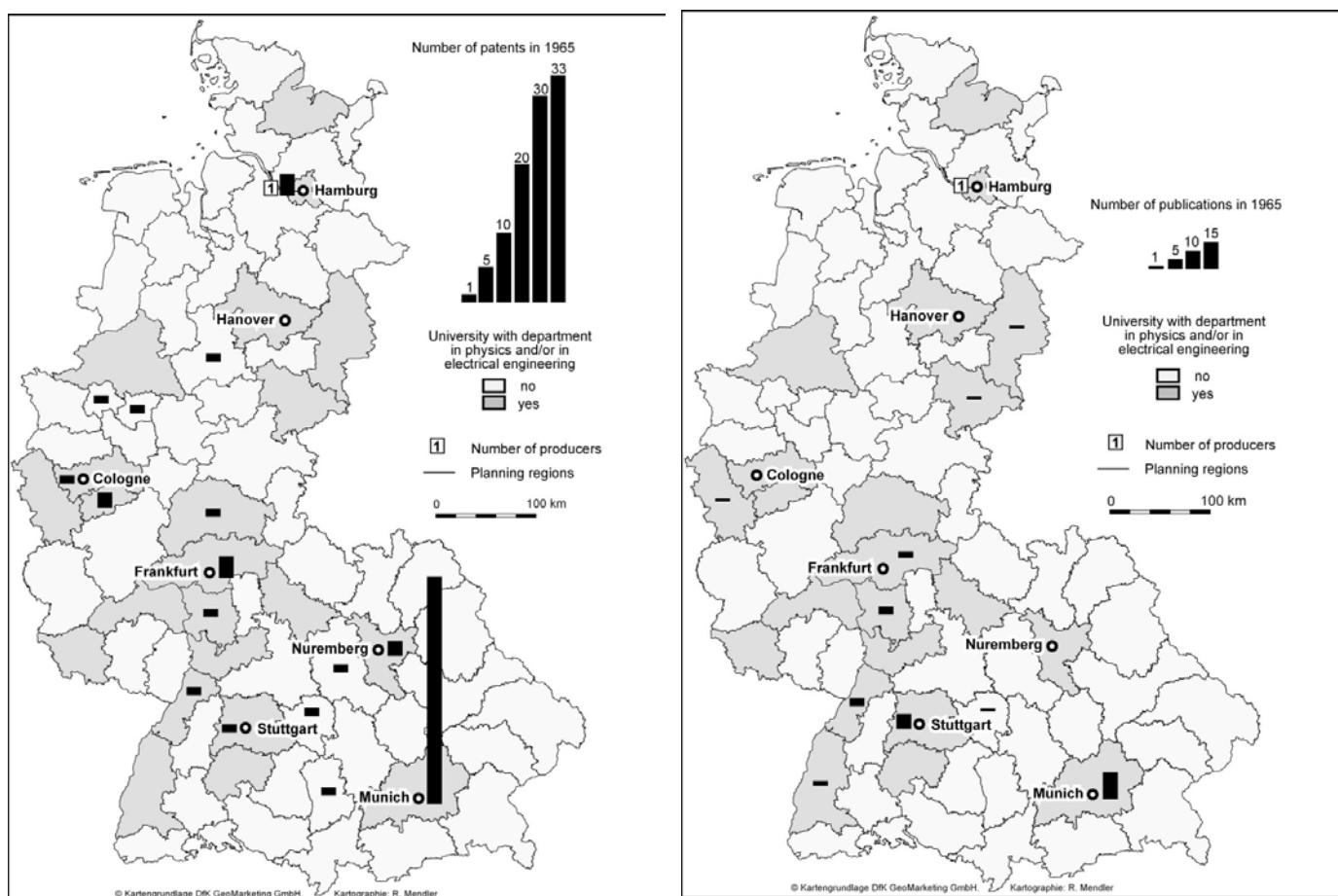


Figure 3: Number of laser patents, laser publications, and laser producers in West German regions, 1965

level of laser research, as indicated by patents and publications, was relatively low.¹⁶ The next entries occurred in the regions of Munich, Erlangen/Nuremberg, and Goettingen, but there is also mention of firms located in more remote and rural areas, such as *Haas*, a manufacturer of clocks and other fine mechanical products that is located in the Black Forest, which started to produce laser beam sources in 1975 (Figure 4).

In the 1970s and 1980s, the West German academic system was extended considerably with the creation of many new universities and departments. One result of this was that the number of universities with

¹⁶ For the development of the German market for laser beam sources see Buenstorf (2007).

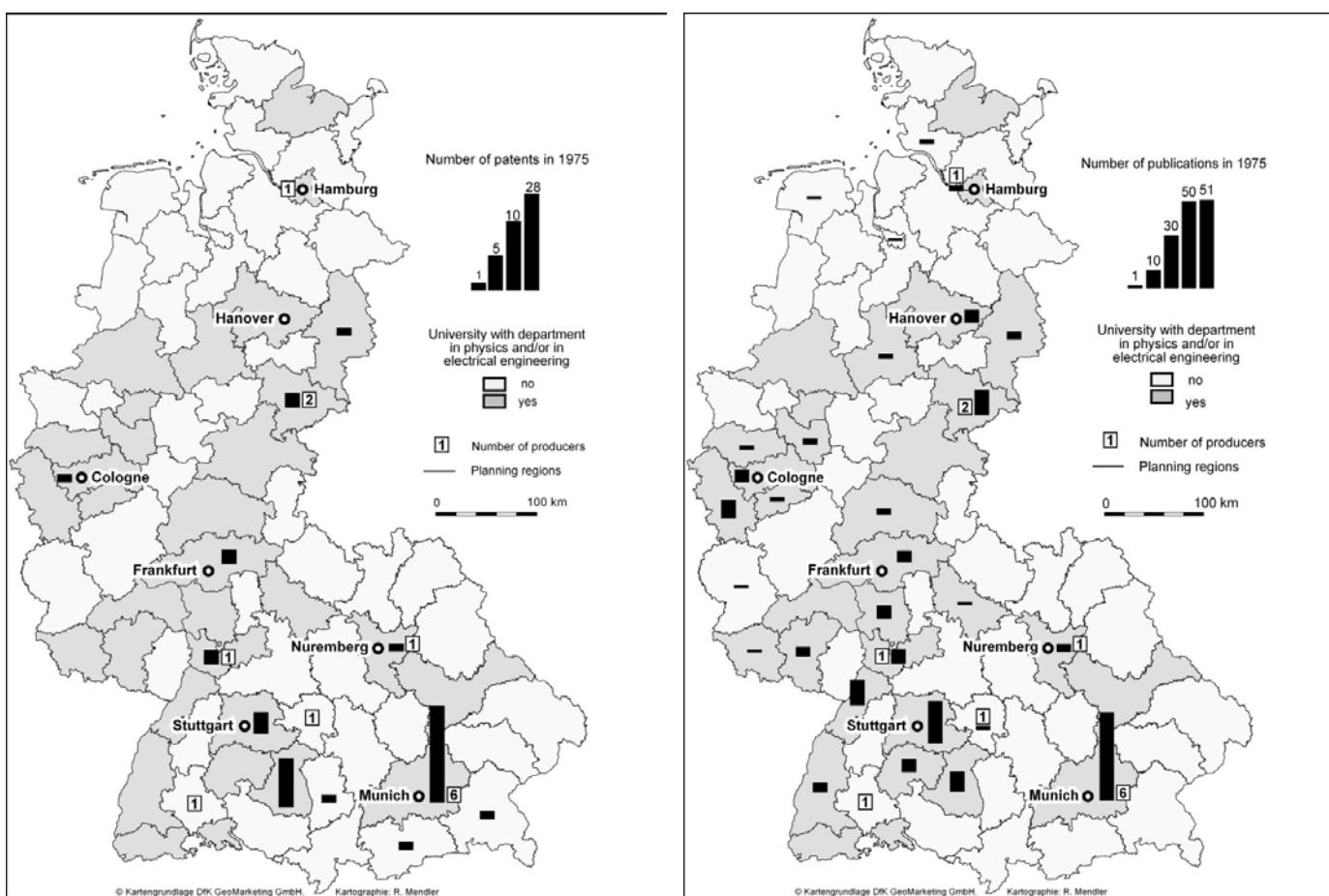


Figure 4: Number of laser patents, laser publications and laser producers in West German regions, 1975

departments in the fields of physics and electrical engineering increased from 44 percent across all planning regions in 1975 to 51 percent in 1985. In 1975, Munich was still the leading region in terms of number of publications and patent applications, and it also took the lead with regard to number of laser source producers, which increased to a total of six such firms being located in this region (Figure 4). The picture for 1985 is similar to that for 1975, with the Munich region still the undisputed leader in the field (Figure 5). Although patenting activity is limited to a few regions outside Munich, many more locations had scientific publications on laser

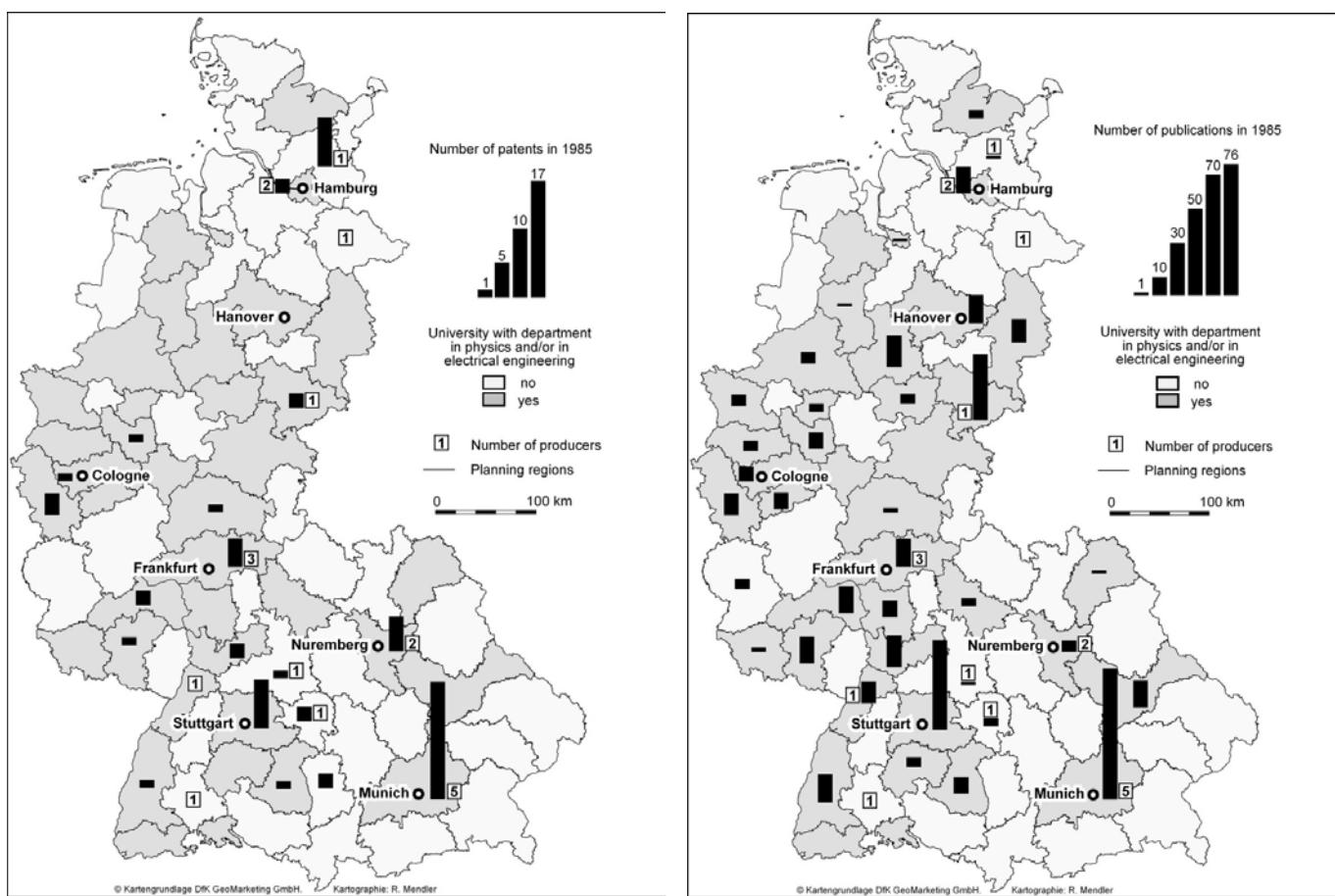


Figure 5: Number of laser patents, laser publications, and laser producers in West German regions, 1985

technology at that time, and these locations are fairly widely spread across the country. A very similar pattern is seen for 1995 and 2005 (Figures 6 and 7), with one noticeable deviation being the shift of patenting activity from Munich to the city of Regensburg, located about 100 km northwest of Munich, a change that is chiefly due to a reorganization of research within the *Siemens* group.¹⁷ The maps showing the spatial distribution of laser technology research for the different years suggest that particularly during the 1960s and 1970s the geographic distance to Munich worked as an

¹⁷ In 1978, *Siemens* finalized its acquisition of the *Osram* company, which then begins conducting research on laser beam sources in Regensburg and also became a producer.

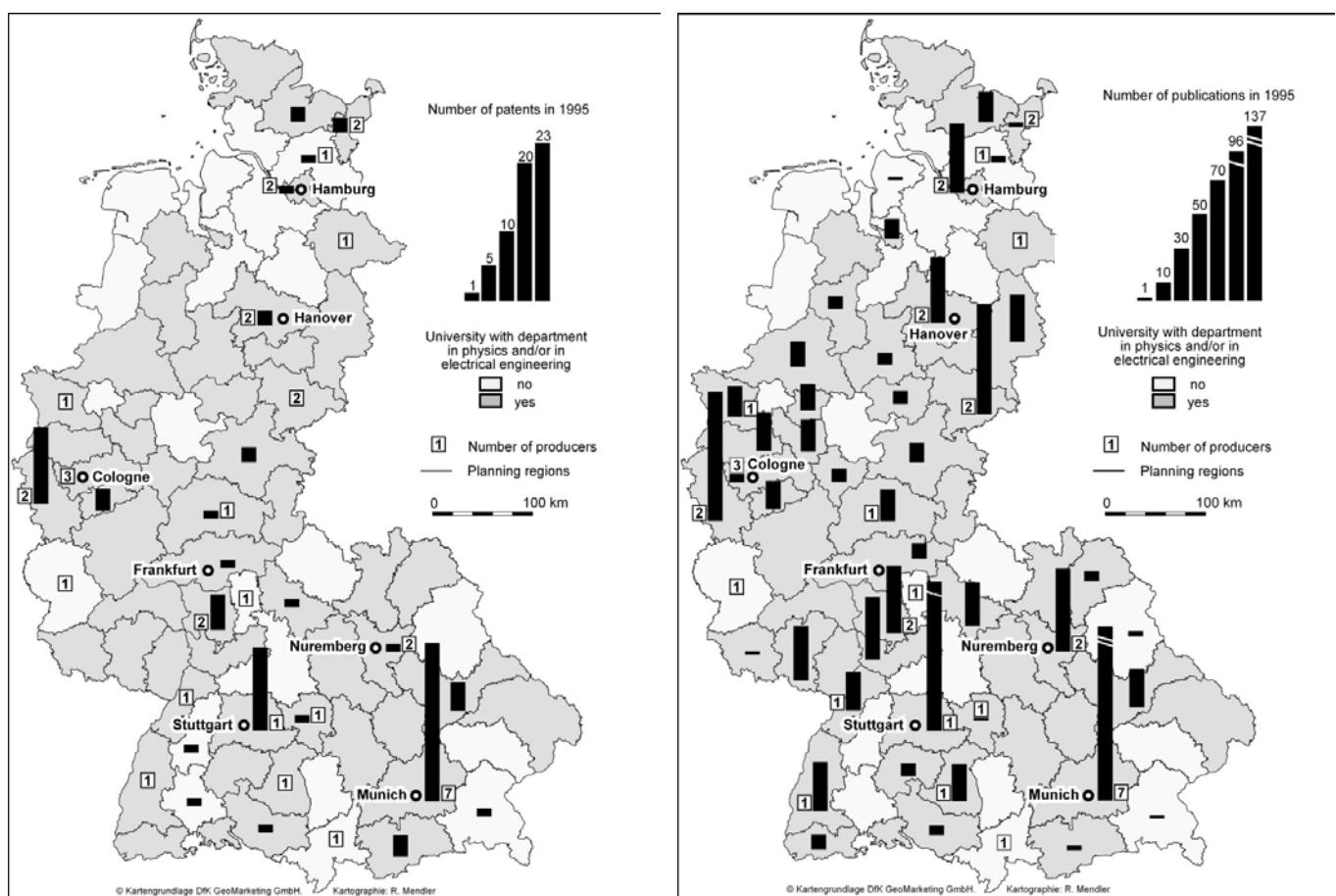


Figure 6: Number of laser patents, laser publications, and laser producers in German regions, 1995

impediment to adoption of laser technology research, particularly with regard to laser patents. We account for the geographic distance to Munich in our empirical analysis.

To assess the general spatial concentration of patents and scientific publications in the field of laser technology, we calculated Gini coefficients and the Herfindahl-Hirschman Index for each year of the 1961–2005 period (Figures 8 and 9). Both indicators reveal similar trends. We find a

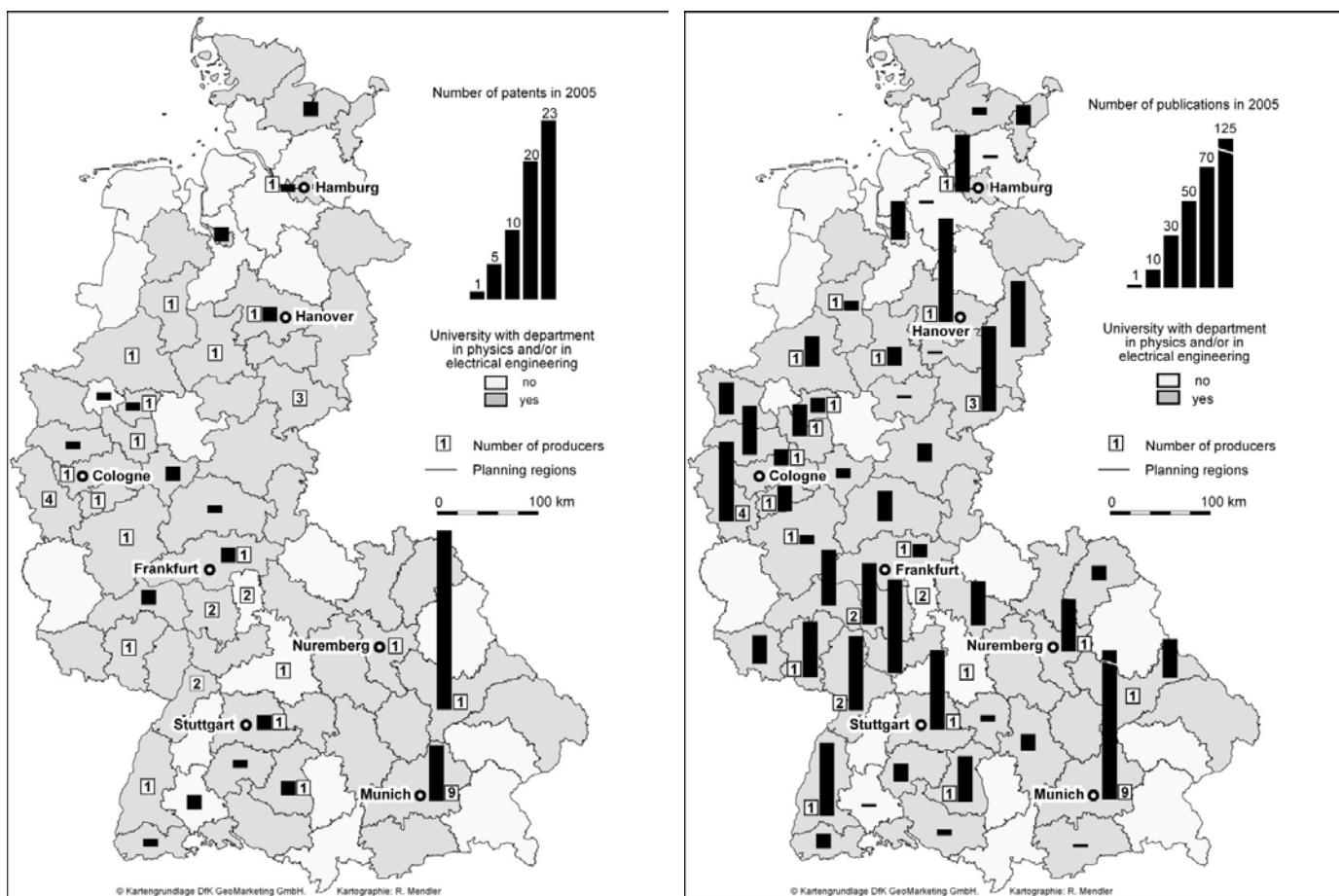


Figure 7: Number of laser publications, laser patents, and laser producers in German regions, 2005

considerable decrease in spatial concentration for laser patents and laser publications, as well as for the number of producers. All indicators seem to converge toward a certain level of spatial inequality. Both measures also indicate an increasing spatial concentration in laser patenting for the very last years of the period under study.

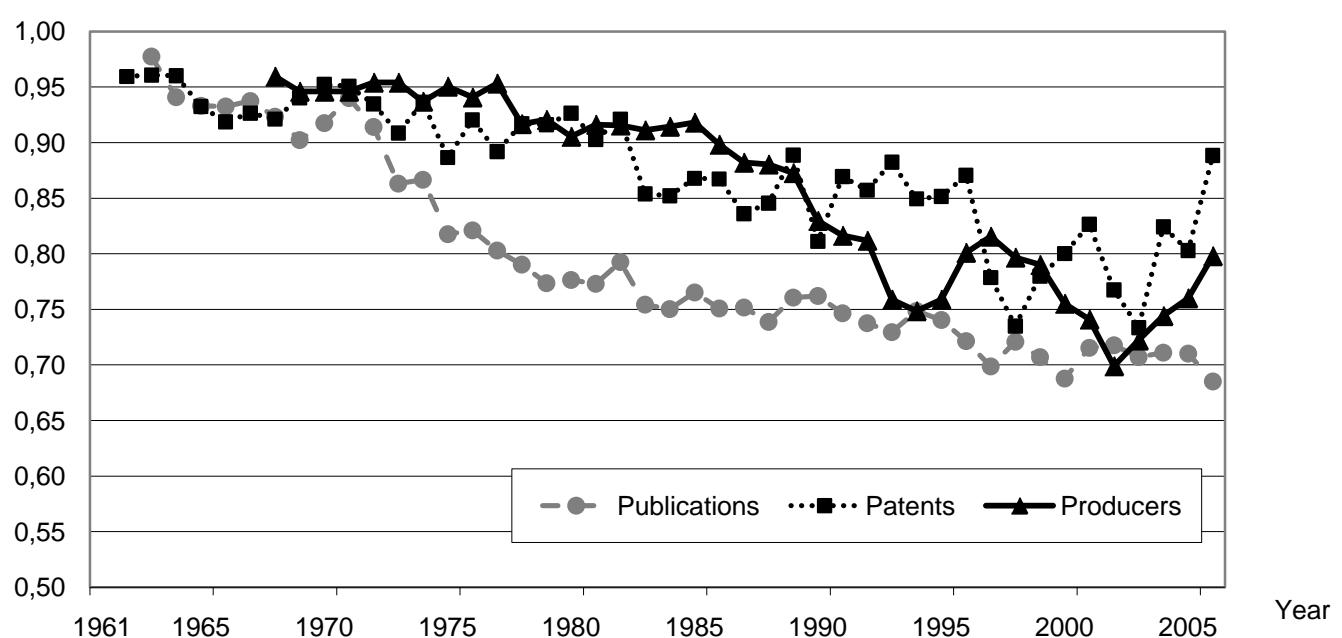


Figure 8: Regional concentration of laser publications and patents in West Germany, 1960–2005: Gini-coefficients

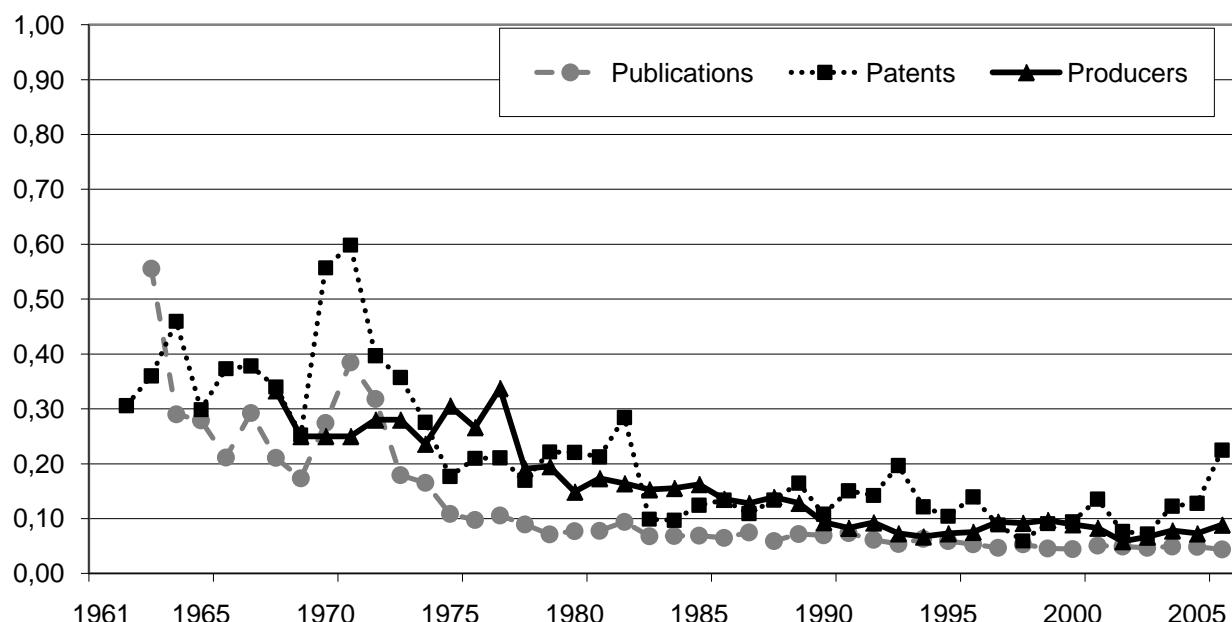


Figure 9: Regional concentration of laser publications and patents in West Germany, 1960–2005: Herfindahl Index

5. Econometric analysis

In this section, we perform empirical analyses to test the hypotheses formulated in Section 2. Basically, we aim to explain the reasons behind the regional diffusion of knowledge, particularly the extent to which regional factors influence the event of first laser publication or first laser patent in a region (Section 5.1). We then investigate the overall amount of regional laser technology research in a certain year (Section 5.2). Finally, we analyze the emergence of highly cited patents in a region in order to discover region-specific factors that stimulate high-quality research results (Section 5.3).

5.1 First adoption of laser technology research: Time to first patent and time to first publication

To analyze a phenomenon such as time to first laser patent or time to first laser publication in a region, conventional OLS regression techniques are inappropriate, for two reasons. First, duration data are generally censored because the dependent variable cannot assume values below zero or above the length of the observation period (Cleves, Gould, and Gutierrez, 2004). Second, distribution of the residuals of time-to-event observations in a linear regression tends not to follow a normal distribution. For instance, if the instantaneous likelihood of an event to occur is constant, distribution of time to event would follow an exponential distribution (Cleves, Gould, and Gutierrez, 2004, 2). A more appropriate methodology for our purposes is a hazard model in which the hazard function defines the probability that a region i experiences an event at time t conditional on a vector of covariates. In choosing the appropriate hazard model, a semi-parametric approach has the advantage of not making direct assumptions about the distribution of the time to-event variable, but only with respect to the covariates of interest (Cleves, Gould, and Gutierrez, 2004).

The standard approach is a Cox proportional hazard model, which is specified as:

$$h_i(t, X_{it}, Z_i) = h_0(t) \exp(g(t)/\sum_{k=1}^p \beta_k X_{it,k} + \theta_i Z_i) \quad (1)$$

where $h_i(t, X_{it}, Z)$ represents the likelihood that region i experiences the event under consideration at time t given a set of time-varying covariates, denoted by X_{it} , and of time-invariant ones given by Z_i . Time is measured in years starting with 1960 ($= 0$), the year during which the first laser was realized in the United States, and is measured as the number of years until the technology adoption event in the region. In our case, the event is the first patent application ($= 1$) or the first scientific laser publication ($= 1$) in the region; otherwise the observation takes the value of zero. The baseline hazard function is denoted by $h_0(t)$.

A disadvantage of the Cox model is that it implies that the transition to the event of interest may occur at any particular moment in a continuous timeline (Allison, 1982). Although the underlying process of technology diffusion can be considered as taking place in continuous time, our data provide information only at discrete yearly time intervals, i.e., we only observe in which year the technology adoption took place. Therefore, as an alternative to the Cox specification, we estimate a discrete-time hazard model. We choose a complementary log-log model because it allows the discrete representation of data generated in continuous time. Similar to the Cox model, it makes the proportional hazard assumption and has the desired semi-parametric characteristics. In short, the complementary log-log model is the discrete-time representation of a continuous time proportional hazard model (Allison, 1982).

The complementary log-log model has the form:

$$h_i(t, X, Z) = 1 - \exp(-\exp[c(j) + \beta' X_{it} + \theta' Z_i]) \quad (2)$$

where $h_i(t, X, Z)$ represents the likelihood that region i experiences the event under consideration at time t , $c(j)$ is the baseline hazard, and X_{it} and Z_i represent the independent variables.

The following time-varying explanatory variables are included in the model:

- *Population*: To test our first hypothesis that laser technology research should first be adopted in large agglomerations (H1), we include the log of regional population to control for the size of a region and its population density. This variable particularly controls for the number of potential researchers and authors of scientific publications.
- *University* is a dummy variable that denotes the presence of a university with a department in the fields of physics, engineering, or both in region i at time t (yes = 1, no = 0). This variable is included in order to test the second hypothesis (H2), namely, that laser technology research should only occur in regions with academic research facilities in physics and engineering.
- *Producer* is a dummy variable that assumes the value of 1 if a region contains one or more laser source producers and takes the value 0 if this is not the case. This variable is intended to control for the effect of laser research conducted by private-sector firms.
- *Publications (patents) in adjacent regions* ($t - 1$) is the one-year-lagged number of publications (patents) with authors (inventors) located in adjacent regions and is included as a control for spatial autocorrelation. *Patents in adjacent regions* are included in the models aimed at explaining the first patent; *publications in adjacent regions* are included in the models for the first regional laser publication.

We included time dummies so as to control for time-specific effects. Because the hazard function of the complementary log-log model cannot be estimated for years with no event, the time dummies cover five-year intervals, not single years. Using a five-year period assures that at least one event will be observed during this time span. This implies that the probability of an event occurring is constant over this five-year period. Since the Cox proportional hazard models could not be estimated with

time dummies, these variables were omitted in the estimations.¹⁸ All models have been estimated with robust-cluster standard errors, which control for the clustering of observations at the regional level.

We introduce the time-invariant variable *distance to Munich*, which is the average geographical distance of a region from Munich measured in km. This variable tests our third hypothesis (H3), which states that regions located close to the early center of laser technology research—the Munich region—are more likely to become adopters compared to regions located farther away.

Table A1 in the Appendix presents descriptive statistics; correlations between variables are shown in Table A2. The results for “time to first publication” are set out in Table 1. For each model, the first column presents the estimated coefficients; the respective hazard ratios are given in the second column. The hazard ratios are the exponential values of estimated coefficients and indicate the strength of the effect that a variable has on the likelihood of experiencing that event in a certain year. A hazard ratio larger than 1 implies that a one-unit change in the value of the covariate increases the likelihood of experiencing the event, whereas a value smaller than 1 represents a lower probability.¹⁹

¹⁸ The reason we could not estimate the Cox proportional hazard model with time dummies is probably that this type of model already accounts for the time dimension by the unspecified baseline hazard rate, so that the inclusion of time dummies creates redundant variables that add unnecessary complexity to the model with regard to the number of observations.

¹⁹ Multiplying the likelihood of an event with the hazard ratio gives the strength of the effect of the variable. For instance, the hazard ratio of 5.034 for the “university” variable in the complementary log-log regression in Column Ib of Table 1 indicates that regions with a university department in physics or electrical engineering have a five times higher rate of experiencing the first publication than regions without such a university department. The hazard ratio of 2.543 (Table 1, Column Ib) for the “producer” variable means that regions containing a beam source producer have a 2.5 times higher probability of adoption than regions without a producer. An increase of 1 km in the average distance to Munich (“distance to Munich”) reduces the rate of adoption by 0.999 times, which indicates that the effect of geographic distance to Munich is not very pronounced.

Table 1: Estimations for the time-to-first laser publication, 1961–2005

Variables	Cox regressions				Complementary log-log model			
	(Ia) coefficients	(Ib) hazard ratios	(IIa) coefficients	(IIb) hazard ratios	(Ia) coefficients	(Ib) hazard ratios	(IIa) coefficients	(IIb) hazard ratios
University	1.593*** (0.248)	4.920*** (1.218)	1.626*** (0.255)	5.085*** (1.295)	1.616*** (0.247)	5.034*** (1.241)	1.640*** (0.253)	5.156*** (1.302)
Producer	0.874*** (0.264)	2.397*** (0.634)	0.773*** (0.268)	2.167*** (0.581)	0.933*** (0.268)	2.543*** (0.682)	0.865*** (0.265)	2.375*** (0.630)
Population (ln)	0.754*** (0.236)	2.125*** (0.502)	0.855*** (0.231)	2.352*** (0.543)	0.771*** (0.227)	2.163*** (0.491)	0.843*** (0.217)	2.324*** (0.505)
Number of publications in neighboring regions (t – 1)	-0.003 (0.005)	0.997 (0.005)	-0.004 (0.005)	0.996 (0.005)	-0.002 (0.005)	0.998 (0.005)	-0.003 (0.005)	0.997 (0.005)
Distance to Munich (km)	-0.001** (0.001)	0.999** (0.001)	-0.005** (0.003)	0.995** (0.003)	-0.001** (0.001)	0.999** (0.001)	-0.005** (0.002)	0.995** (0.002)
Distance to Munich (km) ²			0.000 (0.000)	1.000 (0.000)			0.000 (0.000)	1.000 (0.000)
Time dummies	No	No	No	No	Yes***	Yes***	Yes***	Yes***
Number of observations	1,396		1,396		1,396		1,396	
Number of regions	74		74		74		74	
Log likelihood	-206.5		-205.6		-230.1		-229.3	
Pseudo R-squared	0.133		0.137		0.135 ^a		0.137 ^a	

^a The difference between the log likelihoods from the complete model vs. a base model without covariates, with respect to log likelihood of the base model.

Robust-cluster standard errors in parentheses. ***: statistically significant at the 1 percent level; **: statistically significant at the 5 percent level; *: statistically significant at the 10 percent level.

Table 2: Estimations for the time-to-first laser patent, 1961–2005

Variables	Cox regressions				Complementary log-log model			
	(IIIa) coefficients	(IIIb) hazard ratios	(IVa) coefficients	(IVb) hazard ratios	(IIIa) coefficients	(IIIb) hazard ratios	(IVa) coefficients	(IVb) hazard ratios
University	0.332 (0.267)	1.393 (0.372)	0.378 (0.269)	1.460 (0.393)	0.307 (0.284)	1.359 (0.386)	0.362 (0.286)	1.436 (0.411)
Producer	0.790 (0.598)	2.204 (1.318)	0.758 (0.571)	2.133 (1.217)	0.750 (0.655)	2.117 (1.387)	0.767 (0.641)	2.154 (1.381)
Population (ln)	0.928*** (0.220)	2.530*** (0.556)	0.977*** (0.221)	2.655*** (0.586)	1.053*** (0.234)	2.866*** (0.669)	1.124*** (0.238)	3.076*** (0.731)
Number of patents in neighboring regions ($t - 1$)	-0.011 (0.018)	0.989 (0.018)	-0.021 (0.021)	0.979 (0.020)	-0.009 (0.018)	0.991 (0.018)	-0.019 (0.019)	0.981 (0.019)
Distance to Munich (km)	-0.003*** (0.001)	0.997*** (0.001)	-0.006** (0.003)	0.994** (0.003)	-0.003*** (0.001)	0.997*** (0.001)	-0.007*** (0.003)	0.993*** (0.003)
Distance to Munich (km) ²			0.000 (0.000)	1.000 (0.000)			0.000* (0.000)	1.000* (0.000)
Time dummies	No	No	No	No	Yes***	Yes***	Yes***	Yes***
Number of observations	1,310		1,310		1,310		1,310	
Number of regions	74		74		74		74	
Log likelihood	-227.4		-226.6		-239.9		-238.8	
Pseudo R-squared	0.067		0.070		0.103 ^a		0.107 ^a	

^a The difference between the log likelihoods from the complete model vs. a base model without covariates, with respect to log likelihood of the base model.

Notes: Robust-cluster standard errors in parentheses. ***: statistically significant at the 1 percent level; **: statistically significant at the 5 percent level; *: statistically significant at the 10 percent level.

The results of all models indicate that population has a significant positive impact on the likelihood of having a first laser publication. In other words, regions with a bigger population have a significantly higher probability of experiencing the event sooner, which supports Hypothesis 1. We also find a significantly positive effect for the university variable, indicating that regions with academic institutions in physics and engineering have a higher chance of having a first publication than do regions without an academic institution in the relevant field. This supports Hypothesis 2. We find that geographic distance to Munich has a significant negative impact on the likelihood of having a first scientific publication in the field of laser technology. This suggests that geographic distance plays an important role in the diffusion of laser technology and that regions located in close spatial proximity to Munich—the leading laser center—have a higher likelihood of being “infected” with the new technology than do regions located farther away. This result remains robust to several extensions and alternative specifications,²⁰ and we thus conclude that the evidence supports Hypothesis 3.

The presence of one or more laser producers in the region has a significant positive impact on the likelihood of first publication. To the extent that the authors of these publications are not affiliated with the producing firms but with public research organizations, this result may indicate a producer demand for regional laser technology research. That we did not find any significant effect for publications from adjacent regions indicates that there are no knowledge spillovers across short geographic distance, a finding that appears to contradict the significance of the

²⁰ We also tested the impact of three other measures of distance. Instead of distance to Munich, we included distance to Stuttgart, a region that also played a leading role with respect to the number of laser publications and patents. This led to results similar to those achieved with distance to Munich variable. Including the distance to Aachen, a region with a leading technical university but no early adoption of laser technology, showed no statistically significant effect, whereas the distance to Hamburg, a region located far from Munich and a late adoption of laser research, showed a significantly positive effect, indicating that the longer the distance to Hamburg, the lower the likelihood of adopting laser research. Several extensions of the models, including interaction terms, were tested, but the main results did not change.

distance to Munich variable. The distance to Munich variable in its squared form is not statistically significant.

Estimates with the time-to-first laser patent (Table 2) show statistically significant effects only for population and distance to Munich, and have the same signs as in the models for the time-to-first publication, supporting Hypotheses 1 and 3. The variable for the presence of a university department in the relevant field, as well as the variable for the presence of a laser producer, remain statistically insignificant. The results with respect to the distance to Munich remain robust across previously mentioned alternative specifications, namely, replacing distance to Munich by distance to Stuttgart, Aachen, or Hamburg. A possible explanation for the nonsignificance of the presence of one or more laser producers in the region could be that most of the laser source producers entered the market many years after the event of first patent in the region. For instance, while *Siemens* filed its first laser patent as early as 1961, it did not enter the laser source producer market until 1967. As in the case of publications, we found no statistically significant effect for the number of patents in adjacent regions. All these results remain similar with the inclusion of the quadratic term of distance to Munich for both models (Column II for the complementary log-log, and Column IV for Cox). The difference is that now the quadratic term becomes slightly significant with a positive sign under the complementary log-log model. However, the coefficient is very small and the hazard ratio of 1.000 indicates no substantial effect at all.

5.2 Regional determinants of laser research: Panel data analysis of the number of laser publications and patents

We now move beyond the first adoption of laser research and analyze the amount of research conducted in a region in a certain year. To test our hypotheses about the spatial diffusion of laser technology research (Section 2), we use the number of scientific publications and the number

of patent applications by inventors residing in a region as alternative indicators for research output. The model has the form

Number of publications_{it} = $\beta_0 + \beta_1 \text{population}_{it} + \beta_2 \text{university}_{it} + \beta_3 \text{distance to Munich}_i + \beta_4 \text{years since first regional laser publication}_{it} + \beta_5 \text{producer}_{it} + \beta_6 \text{number of regional laser patents}_{it} + \beta_7 \text{number of laser publications from adjacent regions}_{it-1} + \text{time dummies} + \zeta_i + \varepsilon_{it}$. (3)

for laser publications, and

Number of patents_{it} = $\beta_0 + \beta_1 \text{population}_{it} + \beta_2 \text{university}_{it} + \beta_3 \text{distance to Munich}_i + \beta_4 \text{years since first regional laser patent}_{it} + \beta_5 \text{producer}_{it} + \beta_6 \text{number of regional laser publications}_{it} + \beta_7 \text{number of laser patents from adjacent regions}_{it-1} + \text{time dummies} + \zeta_i + \varepsilon_{it}$. (4)

for laser patents as an indicator of the level of laser research. ζ_i represents the regional fixed effect and ε_{it} is the usual error term. Tables A3 and A4 in the Appendix present the descriptive statistics and correlations.

In addition to the explanatory variables used to explain the first adoption of laser research, we include the *year of first regional laser publication* and the *year of first regional laser patent* in testing Hypothesis 4, in which we posit that regions that began research on laser technology relatively early will have more research in this field in later years than will regions that started relatively late. We take 1961 as the starting year of publications on laser technology in Germany and 2005 as the end year. Regions that saw their first publication in 1961 are assigned the highest value—45 years—and regions with their first publication in a later year are assigned decreasing values.²¹

Our data constitute a balanced panel with yearly information from 1961 to 2005 for every region. Both dependent variables are whole-numbers with positive values and can be regarded as the result of a Poisson-like

²¹ For instance, if a region had its first scientific publication in laser technology in 1971, it is assigned the value of 35. If a region has its first publication in 2005, the value is 1. In case of no publication at all, the value is 0.

process.²² Therefore, we employ negative-binomial (negbin) regression as the estimation method because it is based on more general assumptions than the Poisson regression.²³ We employ two main estimation approaches. First, panel data analysis is employed to exploit the time-series character of our observations. However, since some of the variables in our dataset exhibit only slight changes over time or remain constant, fixed effects estimation may not be an appropriate method because as of the effects of variables with only minor changes may be assigned to the fixed effects. This pertains particularly to the presence of an academic research institution in the relevant fields, for size of population, and to distance to Munich, the latter of which is, of course, completely invariant over time. Therefore, we also run random effects models.

Because many regions have never engaged in laser research or have conducted laser research only sporadically, our dependent variables may have “too many zeros,” which would imply a violation of the distribution assumptions of the estimation procedure (Hilbe, 2008).²⁴ To account for such an effect, we also apply a pooled zero-inflated negbin model with time dummies and dummies for Federal States. The zero-inflated negbin model assumes that zero values are generated by two different regimes. The “true zeros” are cases (regions) that basically fulfill the preconditions for having laser patents or publications, but actually did not. These cases should be included in the negbin estimation procedure. The “excess zeros” are cases that have no potential to generate a laser patent or publication and should, therefore, not be accounted for in the negbin estimation. The zero-inflated negbin procedure consists of two steps. In the first step, a

²² Negative binomial regression allows greater variance of observations than is assumed in Poisson regression. For a more detailed description of these estimation methods, see Greene (2008, 909–912).

²³ If a patent has several inventors located in different regions, the patent is divided by the number of inventors and assigned to the region of inventor residence with the respective share of that patent. In the event this procedure leads to numbers of regional patent applications that are not whole numbers, the numbers are rounded up.

²⁴ Regarding the publications, the share of zero cases is 54 percent of all observations. For patents, this share is 73 percent.

logit model estimates whether a region belongs to the “true zero” or the “certain zero” category. Based on this classification, the negative binomial model according to Equations (3) and (4) is estimated in the second step, predicting the counts for those regions that are not certainly zero (Hilbe, 2008). For the logit models of the first step of the publications model, we used the university variable, which indicates the presence of an academic institution working in the field of physics or engineering. The reason for choosing this variable here is the key role that these academic institutions have in scientific publications in the field of laser technology. In the model with the number of patents as the dependent variable, the certain zero cases are predicted on the basis of the number of laser source producers in the region, accounting for the fact that most patent applications in this field came from private firms. We include dummies for the respective Federal States in the zero-inflated negbin models to control for region-specific effects.²⁵

Regarding the regional scientific publication in the field of laser technology, the results of all three models (Table 3) indicate that the presence of a university department in physics or engineering does indeed have a pronounced positive effect. For the number of patents, the effect of academic institutions is only statistically significant in the zero-inflated negbin model (Table 4). Note that the university variable is highly correlated with the size of regional population, indicating that most academic institutions are located in larger cities. If the size of regional population is excluded from the model, the university variable becomes statistically significant in the fixed effects and random effects estimates, but the overall share of explained variance decreases considerably. With respect to the effect of a laser source producer in the region, the results are the opposite: The presence of laser source producers always has a significant positive effect on the number of patents in each model (Table 4), the impact is insignificant in the fixed effects and random effects

²⁵ Note that West Germany consists of 10 Federal States. Estimations including dummies for each planning region were not feasible given the increased number of independent variables in the model.

Table 3: Estimation of the regional number of publications, 1961–2005

	<i>Fixed effects</i>	<i>Random effects</i>	<i>Zero-inflated negative binomial</i>
<i>Variables</i>	(I)	(II)	(III)
University	1.043*** (0.298)	1.196*** (0.334)	2.133*** (0.116)
Producer	0.101 (0.081)	0.108 (0.089)	0.807*** (0.060)
Population (ln)	0.407* (0.222)	0.523** (0.253)	1.017*** (0.052)
Number of publications in neighboring regions	-0.005*** (0.002)	-0.005* (0.002)	-0.004*** (0.001)
Time dummies	Yes***	Yes***	Yes***
Federal State dummies	No	No	Yes***
Constant	-7.829** (3.076)	-9.529*** (3.476)	-16.544*** (0.751)
Inflate university			-3.076*** (0.245)
Constant			0.443*** (0.166)
Ln alpha			-0.342*** (0.066)
Number of observations	2,904	3,256	3,256
Number of regions	66	74	74
Log likelihood	-4,650	-5,087	-5,962
Pseudo R-squared	0.217	0.205	0.129

Notes: Standard errors in parentheses. ***: statistically significant at the 1 percent level; **: statistically significant at the 5 percent level; *: statistically significant at the 10 percent level.

estimates for the number of publications, and it is statistically significant with the expected sign in the zero-inflated negbin model. Hence, Hypothesis 5, which states that regions with producers of laser technology will have higher levels of research output (Section 2), is confirmed only for the case of patents.

Table 4: Estimation of the regional number of patents, 1961–2005

<i>Variables</i>	<i>Fixed effects (I)</i>	<i>Random effects (II)</i>	<i>Zero-inflated negative binomial (III)</i>
University	0.125 (0.209)	0.212 (0.183)	1.013*** (0.103)
Producer	0.255** (0.115) 0.439* (0.238)	0.314** (0.150) 0.586*** (0.222)	0.682*** (0.112) 1.109*** (0.087)
Population (ln)			
Number of patents in neighboring regions	-0.030*** (0.011)	-0.024** (0.009)	0.005 (0.006)
Time dummies	Yes***	Yes***	Yes***
Federal State dummies	No	No	Yes***
Constant	-6.623** (3.220)	-8.690*** (3.029)	-17.371*** (1.222)
Inflate			
Producer_count			-2.213* (1.262)
Constant			-1.385*** (0.390)
Ln alpha			0.454*** (0.104)
Number of observations	2,992	3,256	3,256
Number of regions	68	74	74
Log likelihood	-2,447	-2,761	-3,016
Pseudo R-squared	0.055	0.052	0.132
Notes: Standard errors in parentheses. ***: statistically significant at the 1 percent level; **: statistically significant at the 5 percent level; *: statistically significant at the 10 percent level.			

The regional population, which can be viewed as the pool of potential authors or inventors, has a significantly positive effect in all models (Tables 3 and 4). The number of patents and publications in neighboring regions, which are included as a control for spatial autocorrelation, shows a significantly negative sign in nearly all models. These results indicate that laser research regions did not benefit from positive knowledge spillovers from adjacent regions but tend to be surrounded by regions with

relatively low levels of laser patents and laser publications. Joint significance of the Federal State dummies, however, suggests that there are some similarities among regions located in the same Federal State.

To test Hypothesis 4, stating that regions that started research on laser technology relatively early will have more research in this field in later years than will regions that adopted laser research relatively late, we extended the models by including the variable *year of first laser publication*' and *year of first laser patent*, respectively. Given the important role and weight that the Munich region had as a pioneer adopter of laser technology, we also include the *distance to Munich* variable. Because these two variables are time invariant, the estimations are restricted to the random effects and the pooled zero-inflated negbin models (Tables 5 and 6).

The results suggest that regions that engaged in laser research relatively early tend to have more laser publications and laser patents in later years. In every specification and model, the count of years since the first laser publication or the first laser patent increases the likelihood of having more publications or patent applications in later years. This implies that being a pioneer region has its advantages, particularly in regard to the accumulation of knowledge over time. Moreover, early engagement can be conducive to the establishment of necessary scientific infrastructure, which, in turn, fosters further laser research. As for the time to first patent and publication, we also find a significant effect for geographic distance to Munich on the volume of laser research, particularly for the number of laser patents. In the case of laser publications, the effect is somewhat weaker, being statistically significant only in the negbin models but not in the random effects regressions. A possible explanation for this difference between the effect of geographic distance to the early center of laser research on patents and publications may be the relatively strong role of public research institutions in publications. To the extent that such organizations are relatively evenly distributed over the country, the

Table 5: Effect of early adoption of laser technology research on number of regional publications, 1961–2005

Variables	<i>Random effects</i>			<i>Zero-inflated negative binomial</i>		
	(IV)	(V)	(VI)	(VII)	(VIII)	(IX)
University	1.196*** (0.324)	0.913*** (0.265)	0.915*** (0.319)	2.059*** (0.113)	1.412*** (0.105)	1.374*** (0.102)
Producer	0.108 (0.073)	0.134 (0.085)	0.119 (0.083)	0.483*** (0.057)	0.222*** (0.054)	0.195*** (0.052)
Population (ln)	0.522* (0.300)	0.065 (0.218)	0.038 (0.217)	1.010*** (0.052)	0.662*** (0.046)	0.501*** (0.047)
Number of publications in neighboring regions	-0.005** (0.002)	-0.004* (0.002)	-0.004 (0.002)	-0.008*** (0.001)	-0.005*** (0.001)	-0.004*** (0.001)
Distance to Munich (km)	0.000 (0.001)	0.001 (0.001)	0.001 (0.001)	-0.006*** (0.000)	-0.003*** (0.000)	-0.001*** (0.000)
Year since first regional laser publication		0.116*** (0.011)	0.117*** (0.010)		0.096*** (0.004)	0.096*** (0.004)
Number of regional patents			0.020*** (0.007)			0.048*** (0.006)
Time dummies	Yes***	Yes***	Yes***	Yes***	Yes***	Yes***
Federal State dummies	No	No	No	Yes***	Yes***	Yes***
Constant	-9.531** (3.970)	-7.691*** (2.828)	-7.422*** (2.747)	-13.141*** (0.766)	-13.009*** (0.669)	-11.850*** (0.651)
Inflate				-2.964*** (0.243)	-5.873*** (2.027)	-6.340** (3.012)
University				0.312* (0.173)	-0.163 (0.175)	-0.104 (0.168)
Constant				-0.509*** (0.064)	-0.667*** (0.056)	-0.762*** (0.058)
Ln alpha						
Number of observations	3,256	3,256	3,256	3,256	3,256	3,256
Number of regions	74	74	74	74	74	74
Log likelihood	-5,087	-5,007	-4,993	-5,850	-5,508	-5,465
Pseudo R-squared	0.205	0.217	0.220	0.145	0.195	0.201

Notes: Standard errors in parentheses. ***: statistically significant at the 1 percent level; **: statistically significant at the 5 percent level; *: statistically significant at the 10 percent level.

Table 6: Effect of early adoption of laser technology research on number of regional patents, 1961–2005

Variables	Random effects			Zero-inflated negative binomial		
	(IV)	(V)	(VI)	(VII)	(VIII)	(IX)
University	0.267 (0.230)	0.290 (0.184)	0.292 (0.187)	0.820*** (0.098)	0.861*** (0.100)	0.766*** (0.099)
Producer	0.323* (0.168)	0.298** (0.144)	0.296** (0.151)	0.246** (0.104)	0.104 (0.107)	-0.062 (0.106)
Population (ln)	0.624*** (0.189)	0.285** (0.133)	0.280 (0.188)	0.984*** (0.082)	0.822*** (0.084)	0.631*** (0.089)
Number of patents in neighboring regions	-0.030** (0.012)	-0.024*** (0.007)	-0.024** (0.010)	-0.025*** (0.006)	-0.021*** (0.006)	-0.015*** (0.006)
Distance to Munich (km)	-0.002*** (0.001)	-0.001** (0.001)	-0.001** (0.001)	-0.011*** (0.001)	-0.009*** (0.001)	-0.008*** (0.001)
Years since first regional laser patent		0.058*** (0.009)	0.058*** (0.008)		0.036*** (0.005)	0.035*** (0.005)
Number of regional publications			0.000 (0.007)			0.014*** (0.002)
Time dummies	Yes***	Yes***	Yes***	Yes***	Yes***	Yes***
Federal State dummies	No	No	No	Yes***	Yes***	Yes***
Constant	-8.698*** (2.659)	-6.373*** (1.662)	-6.312*** (2.414)	-2.828*** (0.387)	-9.605*** (1.206)	-7.557*** (1.242)
Inflate						
Producer_count				-13.173 (463.018)	-14.391 (809.633)	-32.547 (4015611.742)
Constant				-1.486*** (0.362)	-1.674*** (0.399)	-1.625*** (0.399)
Ln alpha				0.113 (0.101)	0.129 (0.098)	0.067 (0.100)
Number of observations	3,256	3,256	3,256	3,256	3,256	3,256
Number of regions	74	74	74	74	74	74
Log likelihood	-2,750	-2,721	-2,721	-2,861	-2,830	-2,811
Pseudo R-squared	0.056	0.065	0.065	0.176	0.185	0.190

Notes: Standard errors in parentheses. ***: statistically significant at the 1 percent level; **: statistically significant at the 5 percent level; *: statistically significant at the 10 percent level.

distance to the center of early research (Munich) may not be as relevant as in the case of laser patents, which are primarily generated by private producers.

To control for the possible effects of patents on publications, we also included the yearly number of patents in each region as an additional explanatory variable in the models for the number of publications. The results show that this variable has a significantly positive impact on the number of publications (Columns VI and IX in Table 5). Correspondingly, we included the number of regional publications in the patents model and found that this variable was nonsignificant in the random effects models but highly significant with the expected positive sign when applying the zero-inflated negbin estimation method (Columns VI and IX in Table 6). These results must be viewed with some caution, however, because publications and patents both are highly correlated with the other explanatory variables. For instance, there is a strong statistical relationship between the number of laser publications and the university dummy, as well as between the number of patents and the producer variable.

To shed more light on these relationships, we estimated alternative specifications of the models. For the publications model, we included the regional number of patents but excluded the producer variable (Columns XII and XV in Table 7). Correspondingly, we included the number of regional publications in the patent model but omitted the university variable (Columns XII and XV in Table 8). Additionally, because the size of population is also highly correlated with other indicators, such as the university dummy, we performed regressions excluding the regional population. These latter results are presented in the first two columns of Tables 7 and 8. Overall, the results and interpretations remain similar to those for the publications case (Table 5). A more fundamental difference is found with respect to the determinants of the regional laser patents. By excluding the size of population, the university variable becomes slightly significant in the random effects model (Columns X and XI, Table 8). This suggests that academic organizations may also play an important role in regional patenting activity. Similar to the previous findings, regional

Table 7: Effect of early adoption of laser technology research on number of regional publications, 1961–2005: Alternative specifications

Variables	<i>Random effects</i>			<i>Zero-inflated negative binomial</i>		
	(X)	(XI)	(XII)	(XIII)	(XIV)	(XV)
University	1.140*** (0.370)	0.905*** (0.301)	0.916*** (0.301)	2.595*** (0.121)	1.600*** (0.110)	1.335*** (0.102)
Producer	0.125 (0.068)	0.137 (0.094)		0.710*** (0.064)	0.356*** (0.057)	
Population (ln)			0.076 (0.246)			0.526*** (0.047)
Neighboring publications	-0.005** (0.002)	-0.004** (0.002)	-0.004* (0.002)	-0.008*** (0.001)	-0.005*** (0.001)	-0.005*** (0.001)
Distance to Munich (km)	0.000 (0.001)	0.001 (0.000)	0.001 (0.001)	-0.007*** (0.000)	-0.003*** (0.000)	-0.002*** (0.000)
Years since first laser publication		0.118*** (0.013)	0.116*** (0.012)		0.114*** (0.004)	0.099*** (0.004)
Number of regional laser patent			0.021*** (0.005)			0.049*** (0.006)
Time dummies	Yes***	Yes***	Yes***	Yes***	Yes***	Yes***
Federal states dummies	No	No	No	Yes***	Yes***	Yes***
Constant	-2.333*** (0.468)	-6.889*** (0.448)	-7.955*** (3.059)	1.253*** (0.309)	-4.580*** (0.339)	-12.150*** (0.651)
Inflate						
University				-2.811*** (0.243)	-17.624 (683.407)	-6.172*** (2.309)
Constant				0.276 (0.186)	-0.235 (0.183)	-0.078 (0.164)
Ln alpha				-0.225*** (0.063)	-0.477*** (0.047)	-0.748*** (0.057)
Number of observations	3,256	3,256	3,256	3,256	3,256	3,256
Number of regions	74	74	74	74	74	74
Log likelihood	-5,099	-5,007	-4,998	-6,042	-5,605	-5,472
Pseudo R-squared	0.203	0.217	0.220	0.117	0.181	0.200

Notes: Standard errors in parentheses. ***: statistically significant at the 1 percent level; **: statistically significant at the 5 percent level; *: statistically significant at the 10 percent level.

Table 8: Effect of early adoption of laser technology research on number of regional patents, 1961–2005: Alternative specifications

Variables	Random effects			Zero-inflated negative binomial		
	(X)	(XI)	(XII)	(XIII)	(XIV)	(XV)
University	0.398*	0.351*		1.359***	1.301***	
	(0.216)	(0.200)		(0.093)	(0.094)	
Producer	0.383***	0.316**	0.284*	0.413***	0.207*	-0.052
	(0.131)	(0.154)	(0.172)	(0.103)	(0.108)	(0.109)
Population (ln)			0.365*			0.878***
			(0.200)			(0.086)
Neighboring patents	-0.035**	-0.025***	-0.024**	-0.032***	-0.026***	-0.020***
	(0.014)	(0.008)	(0.010)	(0.006)	(0.006)	(0.006)
Distance to Munich (km)	-0.002*	-0.001**	-0.001**	-0.012***	-0.009***	-0.008***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Years since first laser patent		0.065***	0.059***		0.049***	0.034***
		(0.008)	(0.008)			(0.005)
Number of regional laser publication			-0.000			0.018***
			(0.008)			(0.003)
Time dummies	Yes***	Yes***	Yes***	Yes***	Yes***	Yes***
Federal states dummies	No	No	No	Yes***	Yes***	Yes***
Constant	-0.313 (0.417)	-2.824*** (0.483)	-7.345*** (2.429)	4.653*** (0.409)	1.081** (0.531)	-10.390*** (1.229)
Inflate				-2.448** (1.089)	-3.767 (5.382)	-28.926 (695,577)
Producer_count				-0.828*** (0.212)	-1.254*** (0.276)	-1.973*** (0.564)
Constant				0.122 (0.108)	0.183* (0.100)	0.215** (0.097)
Ln alpha						
Number of observations	3,256	3,256	3,256	3,256	3,256	3,256
Number of regions	74	74	74	74	74	74
Log likelihood	-2,762	-2,724	-2,724	-2,936	-2,879	-2,841
Pseudo R-squared	0.051	0.065	0.064	0.154	0.171	0.182

Notes: Standard errors in parentheses. ***: statistically significant at the 1 percent level; **: statistically significant at the 5 percent level; *: statistically significant at the 10 percent level.

publications continue to have no significant effect on the number of patents in the random effects models but are highly significant in the zero-inflated negbin estimations (Columns XII and XV, Table 8).

5.3 The generation of highly cited patents in a region

As a final step of our analysis, we investigate to what extent the previous findings hold if a measure of patent quality is applied. Previous research provides evidence that patent citations, especially forward citations, tend to be an adequate measure of both the technological quality and the economic relevance of patents (Trajtenberg, 1990; Harhoff et al., 1999).

Therefore, we assess a patent as being of high quality if it has received at least 10 forward citations. Only about 10 percent of the patents (312 patents) fulfill this criterion. Most of these patents were filed in the 1980s and 1990s; the early patents of the 1960s and 1970s are rarely cited.

Spatially, six regions are responsible for 64 percent of all highly cited patents: Munich, again, leads with 26 percent, followed by Stuttgart (18 percent), Goettingen (8 percent), Erlangen/Nuremberg (8 percent), and Aachen and Rhein-Main/Frankfurt (4 percent each). The applicant with the most highly cited patents is *Siemens* with 57 (18 percent of all highly cited patents), which comprises about 7 percent of all *Siemens'* patents in the IPC H01S.²⁶

The regression results for the regional number of high-quality patents (Table 9) are rather similar to the results obtained for the overall number of patents, one difference being a more pronounced effect of the university dummy, which is strongly significant in all specifications of the random effects and the zero-inflated negbin models. This supports the claim that academic organizations play an important role in regional patenting, particularly in the case of high-quality patents. As in the previous analyses,

²⁶ With regard to the relative share of highly cited patents in the respective organization's stock of H01S patents, *Siemens* is in ninth place. The firms with the highest share of highly cited patents include, among others, *Adlas Lasertechnik*, *Dilas Diodenlaser*, *Rofin Sinar* and *TRUMPF*.

Table 9: Explaining the regional number of high-quality patents (forward citations), 1961–2005

Variables	Fixed effects		Random effects		Zero-inflated negative binomial		
	(I)	(II)	(III)	(IV)	(V)	(VI)	(VII)
University	0.181 (0.462)	0.742* (0.447)	0.928*** (0.330)		1.082*** (0.260)	1.540*** (0.242)	
Producer	0.685** (0.294)	0.850*** (0.266)	0.891*** (0.310)	0.832*** (0.291)	0.258 (0.264)	0.409* (0.230)	0.034 (0.349)
Population (ln)	0.729 (1.029)	0.516** (0.253)		0.693** (0.309)	0.689*** (0.178)		0.949*** (0.185)
Number of patents in neighboring regions	-0.012 (0.014)	0.003 (0.011)	-0.001 (0.010)	0.001 (0.011)	0.007 (0.013)	0.009 (0.013)	-0.005 (0.013)
Distance to Munich		-0.002** (0.001)	-0.002** (0.001)	-0.002* (0.001)	-0.006*** (0.002)	-0.006*** (0.001)	-0.006*** (0.002)
Years since first laser patent		0.053*** (0.016)	0.064*** (0.015)	0.055*** (0.016)	0.045*** (0.012)	0.055*** (0.012)	0.047*** (0.012)
Number of regional laser publications				0.002 (0.008)		1.540*** (0.242)	0.005 (0.005)
Time dummies	Yes***	Yes***	Yes***	Yes***	Yes***	Yes***	Yes***
Federal States dummies	No	No	No		Yes***	Yes***	Yes***
Constant	-12.116 (14.126)	-11.213*** (3.319)	-4.658*** (0.750)	-13.275*** (5.032)	-12.126*** (2.675)	-2.857** (1.169)	-15.037*** (2.632)
Inflate					-0.667** (0.336)	-0.570*** (0.168)	-1.738 (1.942)
Producer_count					0.325 (0.502)	0.914*** (0.282)	0.033 (0.626)
Constant					-0.712 (0.704)	-1.476* (0.885)	-0.081 (0.484)
Ln alpha							
Number of observations	1,760	3,256	3,256	3,256	3,256	3,256	3,256
Number of regions	40	74	74	74	74	74	74
Log likelihood	-520.4	-654.7	-656.7	-657.5	-657.6	-664.8	-666.8
Pseudo R-squared	0.130	0.139	0.136	0.135	0.199	0.191	0.189

Notes: Standard errors in parentheses. ***: statistically significant at the 1 percent level; **: statistically significant at the 5 percent level; *: statistically significant at the 10 percent level.

the presence of a producer in the region has a significant positive impact in the random effects model. The geographic distance to Munich and

years since first patent are statistically significant with the expected signs in every model and each specification (Table 9).

8. Conclusions and interpretation

Following realization of the first workable laser in the United States in 1960, the new technology was adopted almost immediately in Germany. Obviously, the main avenues for knowledge diffusion at this stage were publications and conferences. A very important impulse for the German laser innovation system was *Siemens'* decision to devote substantial resources to this technology. Since most of this research was conducted in Munich, that region became the center of early laser research in Germany. An important flow of laser knowledge into Munich may have occurred when a member of one of the leading U.S. laser research teams became a professor at the Technical University of Munich in 1964. In addition, Munich's position was strengthened considerably by the creation in this region of public research institutes working in the field of laser technology.

We identify a number of factors that play a role in the spatial diffusion of laser technology, as measured by the number of patents and publications. First, the presence of universities with relevant departments appears to have been a precondition for the adoption of the new technology. Thus, the increase in the number of universities in West Germany during the period under study had an effect on the diffusion of laser technology research across German regions. Among the regions that fulfilled this precondition, i.e., had a university with a relevant department, research on laser technology first occurred in larger agglomerations. Moreover, geographic proximity to the center of early laser research in Germany, Munich, was conducive to the early adoption of laser research. The level of laser research in adjacent regions, however, had no statistically significant effect.

The results of our analysis clearly indicate the strong, if not dominant, role played by a region's absorptive capacity in commencing and

conducting research in a new technological field. Several characteristics are key to this capacity, one of which is the presence in a region of large, innovative firms. For example, it is hard to imagine a company better suited for early adoption of laser technology than *Siemens*. Because large firms tend to have their labs in large cities, such as Munich, agglomerations have a much higher likelihood of starting research in a new field than do more sparsely populated rural regions. A second important precondition for the early adoption of research in a science-base technology such as lasers is the presence of a university department in a related academic field. Our estimates indicate that the presence of such a university department raises the probability of a first scientific publication in the field of laser technology research by a factor of five (Table 1). Universities were less crucial for the generation of early laser patents, but they obviously played a considerable part in the research behind these patents, especially in the case of highly cited patents. Universities and other scientific research institutions tend to be located in larger cities, and their presence also favored early adoption of the technology in agglomerations.²⁷ Generally, large agglomerations have a higher probability of adopting novelties relatively early simply because they are home to relatively many actors and institutions with different types of knowledge so that there is a good chance that the necessary absorptive capacity is present.

We found no strong indication that the interregional transfer of tacit knowledge was important for commencing research in the field of laser technology. Early adoption of laser technology research by *Siemens*, for example, was a strategic management decision in which the transfer of

²⁷ There are, however, several firms in more remote locations that engaged in laser technology research at a rather early date. One such example is *Haas*, a mid-sized and in the 1960s well-established producer of clocks and other fine mechanical products located in a small town in the Black Forest. *Haas*, together with the *Batelle Institute* in Frankfurt (Main) located more than 200 km away, developed applications of laser technology (welding) for its own production purposes as early as the late 1960s. It then started to produce this type of equipment for other firms and became a producer of laser beam sources in 1975. *Haas* filed its first patent application in the IPS H01S in the year 1973.

technology-specific knowledge was unimportant. If tacit knowledge was significant for the adoption of laser research by *Siemens*, it was internal tacit knowledge, which is an important component of a company's absorptive capacity, not interregional transfer of tacit knowledge. Neither could we identify any knowledge spillovers from neighboring regions, a type of knowledge that may also be tacit in nature. We did, however, find that geographic distance to the center of early laser research in West Germany, Munich, was significant for the commencement of laser technology research in other regions, which may signal a certain degree of relevance for interregional transfer of tacit knowledge, most probably accomplished by the mobility of researchers. However, mobility tends to be rather cost-sensitive to geographic distance, which may explain why the effect on early adoption of the "distance to Munich" variable was very small (Tables 1 and 2).

Having once embarked on research into laser technology, regions may benefit from an accumulation of the knowledge resulting from such research. That relatively early adoption of laser research in a region has a positive effect on the level of laser research in later periods can be seen as an indication of such an effect. Analyzing the level of regional research in the field of laser technology in terms of the number of publications and the number of patents, we found that the presence of a university department in the field of physics or engineering was conducive to scientific publications as well as to laser patents, particularly high-quality patents, as measured by the number of forward citations. We also found a pronounced positive effect of the presence of laser producers on patenting, which can be explained by the dominance of private firms in the matter of laser technology patent applications. It has been argued that one advantage large agglomerations have in regard to technological research is that they provide a great deal of opportunity for face-to-face contact, which can facilitate cooperation and, especially, the intraregional transfer of tacit knowledge. Based on our analysis, we can neither confirm nor deny such an effect. That regions with a relatively large population indeed

tend to have more research output in the field of laser technology may simply be because these regions have more firms, more researchers, more and bigger universities, and more public research facilities than do smaller regions.

This study provides many important insights, but it must be remembered that the empirical evidence is limited to a certain technological field and thus the findings here may not be generalizable to other technological fields. Laser technology is science based, meaning that analytical knowledge (Asheim and Gertler, 2005) plays an important role in its inception and development. Depending on the extent to which this academic knowledge is codified, transfer of tacit knowledge may be largely unnecessary, as was obviously the case for the early adoption of laser technology research by the German *Siemens* company. It would be interesting to see whether this particular finding holds for other technological fields, particularly those founded on a different type of knowledge base.

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Appendix:

Table A1: Descriptive Statistics

<i>Event: First publication (n = 1,369)</i>						
Variable Name	Mean	Median	Minimum	Maximum	Standard Deviation	Number of Observations
University	0.189	0.000	0.000	1.000	0.392	1,396
Producer	0.041	0.000	0.000	1.000	0.198	1,396
Population (ln)	13.153	13.038	12.478	14.913	0.471	1,396
Number of publications in neighboring regions	21.255	5.000	0.000	199.00	34.850	1,396
Distance to Munich (km)	448.975	459.514	0.000	892.560	237.658	1,396
<i>Event: First patent (n = 980)</i>						
Variable Name	Mean	Median	Minimum	Maximum	Standard Deviation	Number of Observations
First patent	0.044	0.000	0.000	1.000	0.205	980
University	0.182	0.000	0.000	1.000	0.386	980
Producer	0.018	0.000	0.000	1.000	0.134	980
Population (ln)	13.133	13.033	12.478	14.913	0.481	980
Number of patents in neighboring regions	3.733	1.000	0.000	50.000	8.575	980
Distance to Munich (km)	475.575	498.652	0.000	892.560	230.082	980

Table A2: Correlation Table

<i>Event: First publication</i>							
	Variables	1	2	3	4	5	6
1	First publication	1.000					
2	University	0.220*	1.000				
3	Producer (yes / no)	0.073*	0.039	1.000			
4	Number of publications in neighboring regions	0.000	-0.032	0.150*	1.000		
5	Population (ln)	0.145*	0.431*	-0.072*	-0.135*	1.000	
6	Distance to Munich (km)	-0.020	0.049	-0.007	-0.308*	0.105*	1.000
<i>Event: First patent</i>							
	Variables	1	2	3	4	5	6
1	First patent	1.000					
2	University	0.093*	1.000				
3	Producer (yes/no)	0.045	0.039	1.000			
4	Number of patents in neighboring regions	0.015	-0.123*	0.019	1.000		
5	Population (ln)	0.095*	0.431*	-0.072*	-0.191*	1.000	
6	Distance to Munich (km)	-0.088*	0.049	-0.007	-0.525*	0.105*	1.000

* Statistically significant at the 5% level.

Table A3: Descriptive Statistics

Variable Name	Mean	Median	Minimum	Maximum	Standard Deviation	Number of observations
Publications	6.750	0.000	0.000	162.000	15.896	3,330
Patents	0.897	0.000	0.000	47.000	3.272	3,330
University	0.519	1.000	0.000	1.000	0.500	3,330
Producer_count	0.333	0.000	0.000	16.000	1.046	3,330
Producer	0.186	0.000	0.000	1.000	0.389	3,330
Population (ln)	13.430	13.278	12.450	14.915	0.581	3,330
Number of publications in neighboring regions	34.733	19.000	0.000	233.000	42.560	3,256
Number of patents in neighboring regions	5.085	2.000	0.000	50.000	8.226	3,256
Distance to Munich (km)	432.034	428.531	0.000	892.560	228.405	3,330
Years since first publication	27.027	30.000	0.000	44.000	14.306	3,330
Years since first patent	28.216	31.000	0.000	45.000	14.040	3,330
Highly cited patents in the region	0.094	0.000	0.000	8.000	0.510	3,330

Table A4: Correlation Table

	Variables	1	2	3	4	5	6	7	8	9	10
1	Number of publications	1.000									
2	Number of patents	0.609*	1.000								
3	University	0.397*	0.201*	1.000							
4	Number of producers	0.747*	0.533*	0.220*	1.000						
5	Producer (yes/no)	0.504*	0.293*	0.277*	0.660*	1.000					
6	Population	0.439*	0.304*	0.536*	0.326*	0.310*	1.000				
7	Number of publications in neighboring regions	0.063*	0.015	0.094*	0.043*	0.139*	0.034	1.000			
8	Number of patents in neighboring regions	-0.018	0.017	-0.112*	0.021	-0.010	-0.136*	0.543*	1.000		
9	Distance to Munich (km)	-0.132*	-0.242*	0.011	-0.125*	-0.033	0.060*	-0.311*	-0.527*	1.000	
10	Year since first publication	0.378*	0.231*	0.573*	0.239*	0.287*	0.569*	-0.050*	-0.052*	-0.097*	1.000
11	Year since first patent	0.285*	0.222*	0.328*	0.235*	0.264*	0.455*	0.109*	0.106*	-0.326*	0.531*

* Statistically significant at the 5% level.