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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

Michael Fritsch
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Abstract

We analyze the spatial diffusion of the knowledge in laser technology in West Germany from the very beginning of the technology in the year 1960 until the year 2005. In the early years, a large firm of the electronics industry located in Munich, *Siemens*, played a dominating role. Laser technology research has been nearly exclusively done in regions with a university department in physics or electrical engineering. Early adoption of laser knowledge took particularly place in large agglomerations. While we cannot detect knowledge spillovers from adjacent regions the geographic proximity to the center of initial laser research, Munich, was rather conducive for early adoption of laser research as well as for the amount of laser research after adoption. The earlier a region entered this research field the higher the level of laser research later on indicating cumulativeness of knowledge generated in previous periods.

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

JEL classification: L22, L69, R11, 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; Stonemann, 2002). Theoretical explanations of the diffusion pattern highlight certain regional factors, particularly a regions' absorptive capacity for the respective technology and its ability of knowledge production, agglomeration economies, as well as the mobility of people between regions and between firms, as expressed, e.g., in the formation of spin-offs (Boschma and Wenting, 2007; Klepper, 2009). Understanding the spatial pattern of knowledge diffusion can make a considerable contribution to the explanation of regional innovation processes and is a basic precondition for the design of appropriate policy measures, if public intervention is deemed desirable.

In the present paper, we analyze the emergence and the spatial diffusion of knowledge in the field in the field of laser technology in West Germany from its beginning in the year 1960 until the year 2005, a period of 45 years. Apart from numerous studies of 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 here is on the diffusion of *research*, i.e. the generation of new knowledge in a certain technological field, not on applying a given technology. We try to answer three particular questions. First, in which locations has laser research in West Germany begun and why? Second,

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, and by the Technical University Bergakademie Freiberg. 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 in the 1961-2005 period considerably benefitted from the work of Martin Gehlert, Jana Hofmann, and Isabell Neumaier as documented in their diploma theses. All errors are, of course, responsibility of the authors. We considerably benefitted from comments by Steven Klepper, Koen Frenken, and Raquel Ortega Argilés on an earlier version of this paper.

what was the general spatial diffusion pattern of laser technology research in West Germany and, third, what are the reasons behind this diffusion pattern?

The laser can be regarded one of the most important scientific inventions of the 20th century (Bertolotti, 2005) that has a great multiplicity of applications from range finding and the transmission and storage of information to 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* and describes 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 a temporal sense. This coherent light can be generated by using different media, such as solid crystals and semiconductors, for example. The laser technology has often been described as rather ‘science based’ in that academic (analytical) knowledge played an important role in its development (e.g. Bertolotti, 2005; Bromberg, 1991; Grupp 2000). One main type of academic input that was needed for the development of laser technology was a respective theory. It was one thing to generate a laser effect which was initially a rather short flash of light. Being able to generate such a laser effect the task then was to make this light more durable and to control it.

In what follows we first discuss hypotheses about the spatial diffusion of laser technology research (section 2) and give a description of the underlying data (section 3). Section 4 describes the general pattern of the spatial diffusion of laser technology research in Germany. In particular, we discuss the reasons of the initial adoptors for their early engagement in research in this technological field. The empirical analyses and the tests of our hypotheses are reported in section 5. Section 6 concludes.

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

It has become common practice to distinguish two types of knowledge, codified knowledge that is well documented in a medium (e.g. written down on paper) and tacit knowledge that is not codified but incorporated in people. While codified knowledge can be communicated through the respective medium such as scientific publications, a transfer of tacit knowledge requires personal contact of people, in particular, direct face-to-face communication.² Particularly in newly emerging research fields, one may expect that the knowledge will not be completely codified but that there is a significant share of non-codified, tacit knowledge which is important for acquiring the full benefits of the codified part. Since codified knowledge can be, in principle, ubiquitously available, the problems of transferring tacit knowledge often require personal face-to-face contact which may lead to an uneven diffusion in space. Transfer of both types of knowledge, however, necessitate absorptive capacity, i.e. the ability of the receiving unit to identify relevant knowledge, to absorb it, and to apply it for own purposes (Cohen and Levinthal, 1989; Zahra and George, 2002). Hence, even if knowledge is available, be it codified or tacit in nature, it may not be transferred due to lacking absorptive capacity.

In a regional perspective there are a number of reasons why research in a new technological field should first be adopted in large agglomerations.³

² This argument corresponds to Mansfield's 'epidemic' model of technology diffusion (Mansfield, 1968). In order to explain the diffusion of process innovation Mansfield argues that the adoption of new processes is critically dependent on information that is transferred by direct personal contact. Because the share of 'infected' actors rises during the course of the diffusion process the likelihood of receiving the relevant new information and to adopt it first rises. After a certain point in the diffusion process is reached the adoption rate decreases again because more and more actors are already 'infected' and use the respective technology. This type of process leads to the s-shaped diffusion curve that could be observed for many different technologies (see Stoneman, 2002).

³ These arguments correspond to a great deal to the reasoning of Torsten Hägerstrand's (1952, 1967) most 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., that new processes are first

- First, large cities accommodate 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 are particularly characterized by a relatively high qualification level of the workforce and a high share of R&D activities which may be particularly relevant for adopting new knowledge. As far as laser technology can be characterized as being science-based (Bromberg, 1991; Grupp, 2000) laser research may require intensive interaction with academic institutions and may, therefore, particularly occur in regions with academic research facilities in the relevant scientific disciplines, which are particularly physics (including optics) and certain fields of engineering⁴. The larger the number of scientists working in such research facilities is the higher the number of potential adopters should be and, therefore, the higher the likelihood that laser knowledge will be absorbed in a respective region. Since such research facilities tend to be located in larger cities, we expect first occurrence of laser research in such regions. In the course of the diffusion process laser technology research should then diffuse to smaller cities. However, given the science based nature of laser technology research it should not occur in regions that do not have academic research facilities in the respective disciplines.
- Third, large agglomerations tend to have a higher share of large firms so that average firm size is relatively high. As far as large firms have an innovative advantage over smaller firms (Cohen and Klepper, 1996) they may adopt research in new technology relatively early.

implemented in the 'centre', the large agglomerations, and are then put into practice by actors in the 'periphery', i.e. in remote and sparsely populated regions.

⁴ We assume that the relevant fields of engineering are electrical engineering, high frequency engineering, information and communication technology, mechanical engineering, and general engineering.

- Fourth, due to the large number of employment opportunities large agglomerations are more likely to be the destination of labor market mobility and, thereby, to attract tacit knowledge from other regions than sparsely populated regions in the periphery.

In the course of the diffusion of laser technology research one may expect that the second-fast adopters are smaller cities which also have academic research institutions in the required fields. As far as the transfer of tacit knowledge should be important, it is plausible to assume that regions located close to the early centers of laser technology research should adopt the technology earlier than more distant locations because mobility of people is sensitive to geographic distance. The presence of producers of laser technology products in a region can be regarded a result and a cause of respective research. On the one hand, the regional production of laser products can be based on the respective regional knowledge. On the other hand these producers may conduct research by themselves and may also stimulate research results from other actors of the respective region.

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 small and sparsely populated regions. Since the intraregional diffusion of the technology takes time those regions which adopted laser research relatively early will in later years have a higher level of research activities in this field than those regions that adopted laser research later.

In summarizing our considerations about the spatial diffusion of laser research we can state that

- H 1: Laser technology research should be first adopted in large agglomerations.
- H 2: Laser technology research should only occur in regions with 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 regions located further away.
- H 4: Regions which started research on laser technology relatively early will have more research in this field in later years than regions which started relatively late.
- H 5: Regions with producers of laser technology products will have higher levels of research output than regions without producers of laser technology.

3. Data and methodology

For describing 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.depatisten.de) which is provided by the German Patent and Trade Mark Office. From this database we selected all patent applications with priority in West Germany which were assigned to the technological field “devices using stimulated emission” (IPC H01S) as the main class or as the secondary class. Hence, patents which are related to applications of laser-technology such as printing and measurement technology but not to the laser beam source as such were not considered. Because not all early patents have been electronically coded, we also 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 inventors residence at the time of application. The patent applications are assigned to the region in which the inventor has his residence. Since the focus of this study is on the inter-regional diffusion of 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 employed 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 recurred to the database INSPEC, which only includes the affiliation of the first author. Since the identification of scientific publications was based on key word search both in the title and in 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 may particularly include applications of the technology.⁶

The information on universities' departments and universities' institutes whose fields of activity and/or research were close to the emerging laser technology was obtained from two main sources: firstly the *Vademecum* registers, which contain relevant information on all the academic institutions in West Germany. This information includes the scientific discipline, location, and head(s) of department or institute. They are published in a four year interval and we employed the registries from 1961 to 1992. For the remaining years to 2005 the data was 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

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

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 so that lasers were frequently referred to as "optical maser". Besides the areas of 'laser' and 'stimulated photon emission' the search included "microwave frequency doubling in ruby", "parametric amplification and oscillation", and "resonators".

physics, theoretical physics, experimental physics, applied physics, technical physics and also physical chemistry) or in certain areas of engineering (electronic engineering, high frequency technology, communication technology, mechanical engineering, and optics).

The spatial framework of our main analysis are the 74 planning regions (*Raumordnungsregionen*) of West Germany. East Germany and the former West Berlin are excluded in order to keep the regional setting constant. Planning regions consist of at least one core city and, in most cases, a surrounding area⁷. The advantage of planning regions in comparison 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 interactions between districts. Planning regions are slightly larger than what is usually defined as a labor market area. In contrast to this, a district may be a single core city or a part of the surrounding suburban area⁸. Using planning regions as spatial framework for the analysis is particularly appropriate since in a number of cases the R&D facilities are located in larger city while the inventor's place of residence is in a surrounding district that belongs to the same planning region as the respective R&D.

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

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

The theoretical foundations of laser technology date back to the year 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 the year 1928, *Rudolf Ladenburg* and *Hans*

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.

Kopfermann provided the first experimental evidence for stimulated emission and in the early 1950s, experimental evidence led to speculation about microwave amplification by stimulated emission.⁹ In the year 1960 a research group led by *Theodore H. Maiman* at the Laboratories of the *Hughes Aircraft Company* in Malibu (California, USA) was the first who succeeded to realize a laser effect. It was in the same year followed by the research group led by *Schawlow* at the *Bell Telephone Laboratories* (Bertolotti, 2005; Bromberg, 1991). Information about this breakthrough (Maiman 1960a and b, Schawlow, 1961) quickly spread world-wide through the buzz in the academic community, press releases, presentations at conferences as well as academic publications that became available about the end of the same year and generated euphoria among scientists.

In Germany, the news about the realization of a laser effect by US research groups in the year 1960 induced the German *Siemens* company, a large and highly diversified producer of all kinds of electric and electronic equipment, communications technology, data processing technology, and medical equipment, to dedicate considerable amounts of resources to research in laser technology. This strategic decision was already made in the summer of the year 1960 before the first academic articles with a description of the laser had been published. In late 1960 three labs of *Siemens*, two in Munich and one in Erlangen (about 160 km north of Munich), started laser research. The first successful replication of *Maiman's* experiment was realized in the *Siemens* labs as soon as in late 1960 or early 1961. In February or March of the year 1961 researchers at *Siemens* in Munich had already been able to considerably improve *Maiman's* test arrangement (Albrecht, 1997). It is rather remarkable that there is no indication for a research cooperation of *Siemens* with one of the US laser research teams or a transfer of personnel from these teams

⁹ In 1954, *Charles H. Townes*, *James P. Gordon*, and *Herbert J. Zeiger* presented the ammonia-gas beam oscillator creating an important technological breakthrough. *Townes* coined the term "maser" for this type of amplifier, an acronym for *microwave amplification by stimulated emission of radiation* (Bertolotti, 2005; Röss, 1969).

to *Siemens* at that stage. If *Siemens* has received tacit knowledge at that time it was mainly through informal contact. This suggests that not much transfer of tacit knowledge was needed in order to reproduce *Maiman's* experiment.

There are a number of explanations why *Siemens* adopted laser research that early. First, during the late 1950s, Siemens had already done 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 fields¹⁰. Third, because of its size and its high degree of diversification, *Siemens* was not only able to mobilize the respective resources but also to bear the high risk of early engagement in laser research characterized by extremely high uncertainty about profitable commercial applications. The *Siemens* management believed that laser technology was of high relevance for its product portfolio and that the early adoption of laser research would pay off in one or another way, at least in the longer run. Smaller and less diversified firms would not have been able to mobilize comparable amounts of resources to laser research and to bear the high risk of intensive research at this early stage of the technology. The early adoption of laser research by the German *Siemens* company clearly indicates 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 US research results based on the available codified knowledge, the publications. This clearly indicates that transfer of tacit knowledge is relatively unimportant if the respective knowledge base is of an 'analytical' character as is obviously the case in the science-based field of laser beam sources (Asheim and Gertler, 2005).

¹⁰ Reproducing the laser effect as described in the publications of Maiman (1960) and the Schawlow group (Collins et al, 1960) obviously required considerable skills in optics, electrical engineering, and solid state physics. Such skills have been available at many universities and research labs of larger firms.

The importance of the internal absorptive capacity could also explain why it took two years longer under the conditions of the socialist innovation system of the East German GDR until the laser effect could be reproduced there. GDR researchers at that time had the same state of knowledge than their West German counterparts. They had unhindered access to the all international scientific journals and leading scholars had attended all the main international conferences in physics where the first realization of a laser effect was an intensely discussed topic. In applying their knowledge they were faced with two bottlenecks. First, the permission of the authorities to devote resources to this kind of research. Second, the availability of respective equipment and particularly a ruby of sufficient purity (see Albrecht, 2005, for details).

Another important starting point of laser technology research in Germany was that *Hermann Haken*, a native German who had worked at the *Bell Telephone Laboratories* and had contact to the research group of *Arthur L. Schawlow*, became Chair of Theoretical Physics at the *University of Stuttgart* in October 1960. In the following years, *Haken* became a leading scholar in the development of laser theory. In the summer of 1962, *Wolfgang Kaiser*, also 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 to the US he became in the year 1964 Chair of Experimental Physics at the *Technical University of Munich* where he performed important research in the field of laser technology in the following decades (see Albrecht, 1997, for details). Hence, there was also some important transfer of tacit knowledge via the mobility of leading researchers to West Germany. But all this occurred *after* the decision of the *Siemens* company to devote large amount of resources to research in that new technological field.

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

According to our data, there have been 2,987 patent applications with West German inventors in the field of laser beam sources (IPC H01S) during the 1960 to 2005 period¹¹. The number of patent applications reached a peak value around the year 2000 (figure 1). Since then, the yearly number of patent applications has decreased what may be regarded an indication that the innovation system in the field of laser beam sources has reached some maturity stage. A similar pattern can be found for the number of scientific publications which have been identified by using a much broader definition of laser technology that particularly includes applications of the technology (figure 2). According to our data, there were 22,476 publications or German authors in the field of laser technology during the 1960 to 2005 period.

¹¹ The number of patent applications and publications is restricted to the 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 affiliation of authors of scientific publications named in second, third, etc. position for the years 1971-2005, the number of publications with German co-authors may be underestimated here.

Number of patents

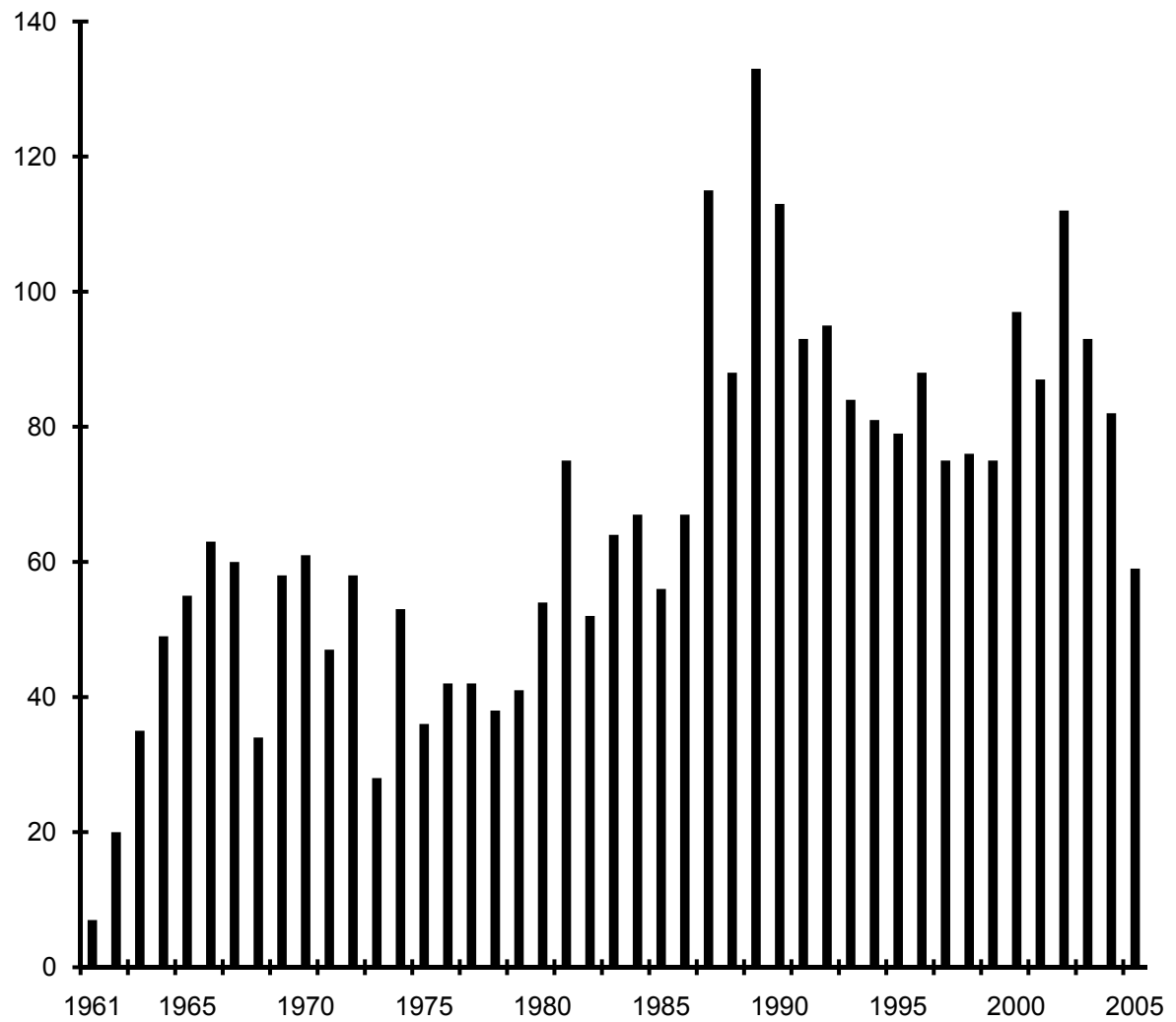


Figure 1: Number of patent applicants and in the field of laser technology (IPC H01S) in West Germany 1960-2005

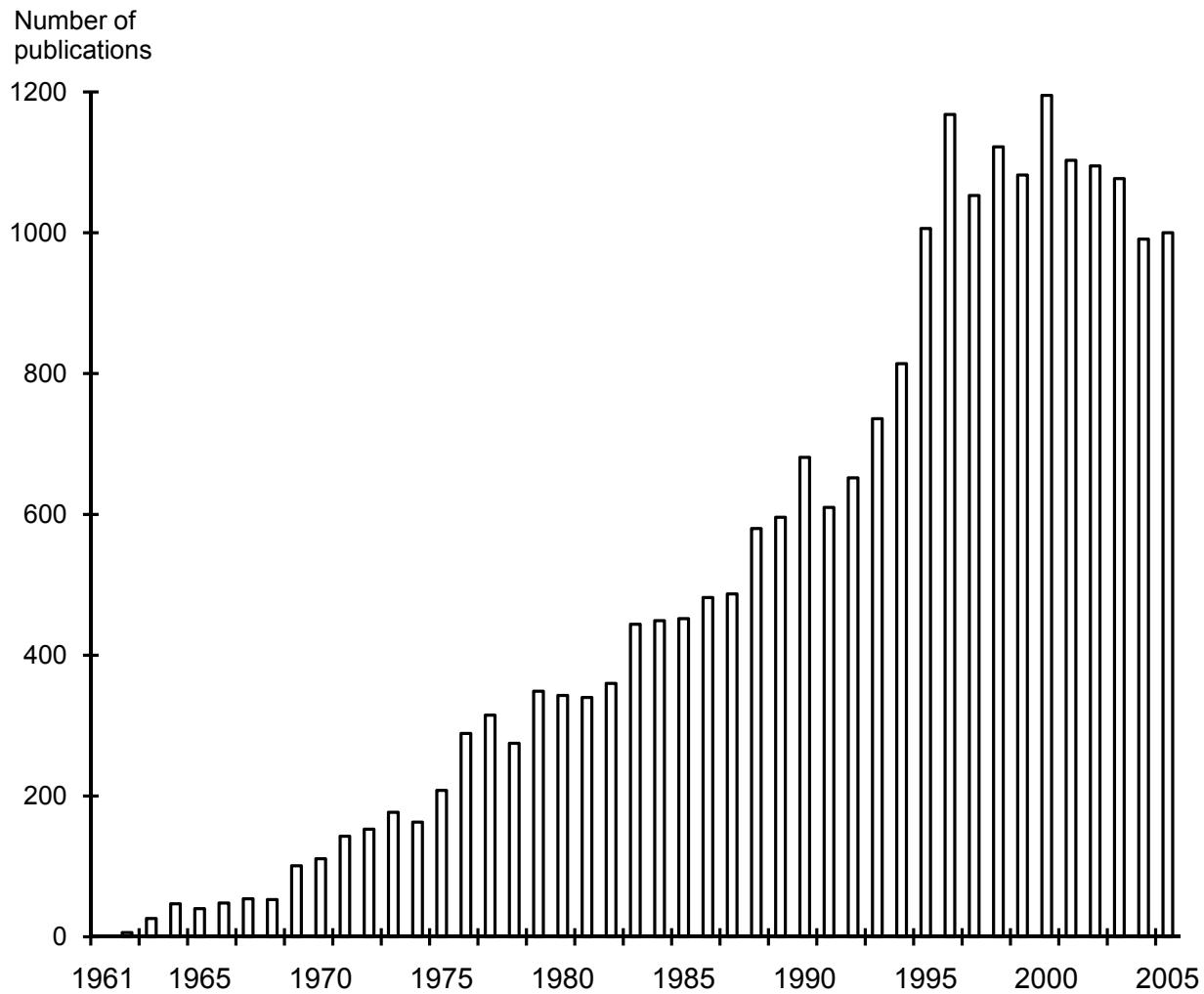


Figure 2: Number of scientific publications in the field of laser technology with West German authors 1960-2005

From the 1961 to 1980 the number of West German patent applicants in the field of laser beam sources (IPC H01S) has been rather small never exceeding 18 different organizations per year. Particularly the *Siemens* company played an important role in this respect. From 1961-1980 Siemens accounted for 387 of all 920 (42 percent) German patent applications in the field of laser beam sources. Over the first ten years (1961-1970) this share was more than half (56.7 percent) of all German

patent applications in this technological field¹². 131 of the 530 inventors (25 percent) that are named in the patent applications of the 1960-1980 period have been affiliated to *Siemens*.¹³ These figures clearly indicate a high concentration of laser research and laser knowledge in one of Germany's largest firms. This also reveals a high regional concentration of laser research, particularly in the Munich region.

The vast majority of inventors named in the patent applications were affiliated to private firms. Patents of university based inventors were a rare exception. Given the science-based character of laser technology this dominance of inventors from private sector firms may be regarded surprising.¹⁴ With regard to scientific publications in the field of laser technology we find, however, a rather different pattern. For the period 1960 to 1970 the bulk of publications is by authors affiliated to universities (57.62 percent) and to public research organizations (14.54 percent). Only 23.58 of the publications have been assigned to authors from private sector firms, and 1.95 percent to other affiliations such as the *Battelle Institute*, a non-profit organization conducting contract research. This clearly indicates a division of labor where the basic research is mainly conducted by universities and public research organizations while the

¹² In the first three years (1961-1964) the share of the *Siemens* company in all German patent applications in the field of laser technology amounted to about 72 percent.

¹³ This includes 13 'star scientists' that are named on ten or more patent applications. *Dieter Röß* from *Siemens* alone is named as an inventor in 95 patent applications followed by *Günter Zeidler* (27 applications), *Eberhard Groschwitz* (26 applications) and *Karl Gürs* 25 (applications), all at that time working for the *Siemens* company in one of their labs in Munich.

¹⁴ To identify those inventors in the patent applications which are affiliated to academic institutions is rather problematic since until the year 2002 German professors had the privilege to file their inventions on their own. Hence, patent applications by universities have been rather rare in the 1960-2002 period and many university scientists may be classified as independent inventors. In case that the invention emerged in a co-operation between a university and a private sector firm the university inventors may be assigned to industry. By matching names of inventors from patent statistics with authors of publications for which 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 where the university professor's privilege to file patents on their own does not apply, is also rather small (3.25 percent).

private sector firms focus on applied research the results of which can be patented.

4.3 The spatial diffusion of the laser technology in Germany

Where else than in Munich and Erlangen, the locations of the early *Siemens* labs, and in Stuttgart, the region 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 in communications technology (Albrecht, 1997) we may expect that laser research is only conducted in regions which have academic institutions in these disciplines. In the year 1960, when the message of the first realization of the laser effect quickly 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 of 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.

According to our hypothesis about the presence of academic institutions in physics or electrical engineering as 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 can almost exclusively be found in regions with university departments in these disciplines (figure 3). Exceptional cases in this respect are probably caused by the assignment of patents to the inventor's place of residence and not to his workplace. At that time, the Munich region clearly takes the leading role 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 level of laser research as indicated by patents and

publications in this field was relatively low. The next entries occurred in the regions of Munich, Erlangen/Nuremberg and in Goettingen but there were also firms in more remote and rural areas such as the *Haass* company located in the Black Forest which started to produce laser beam sources (figure 4).

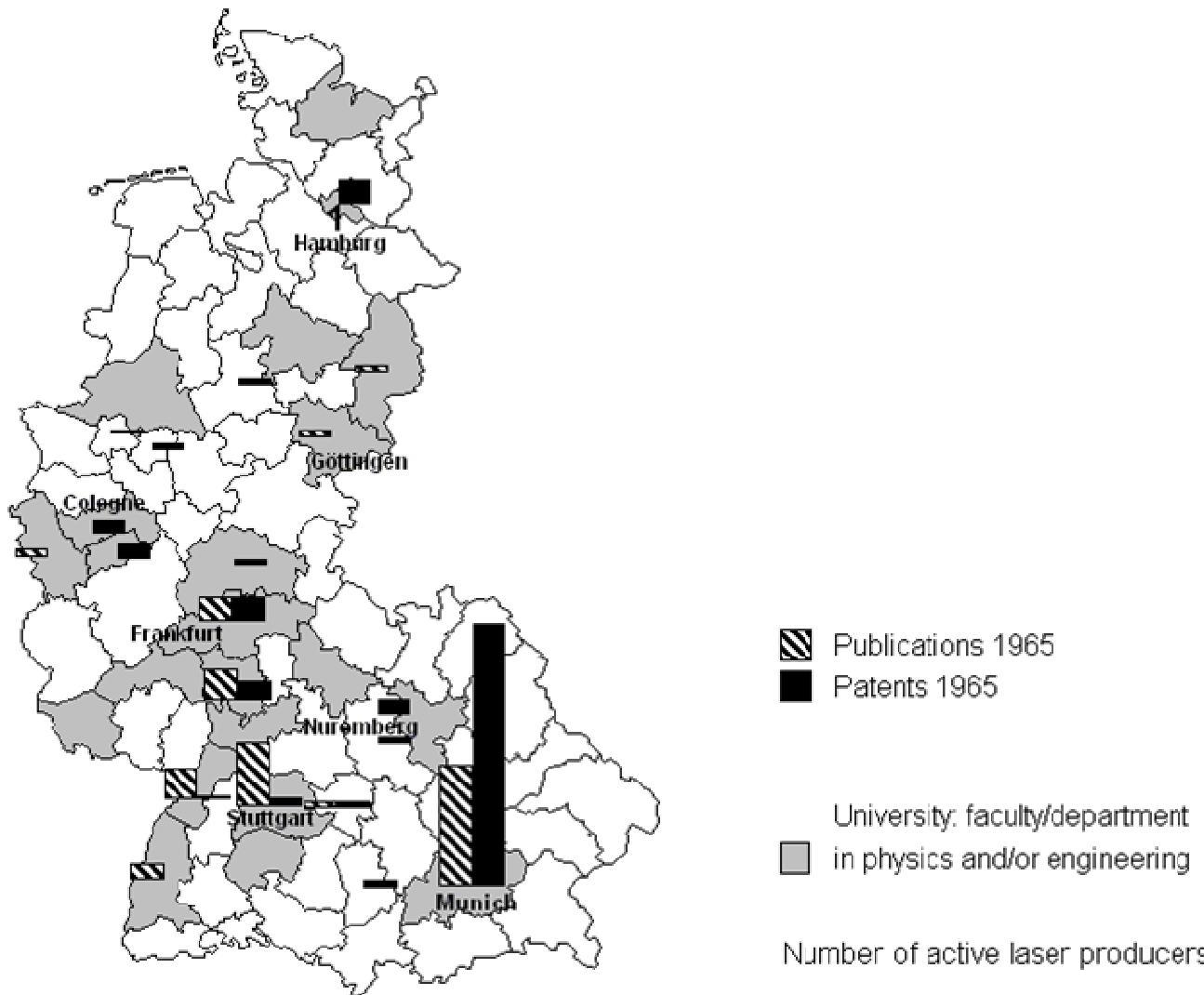


Figure 3: Number of laser publications, laser patents and laser producers in West German regions 1965

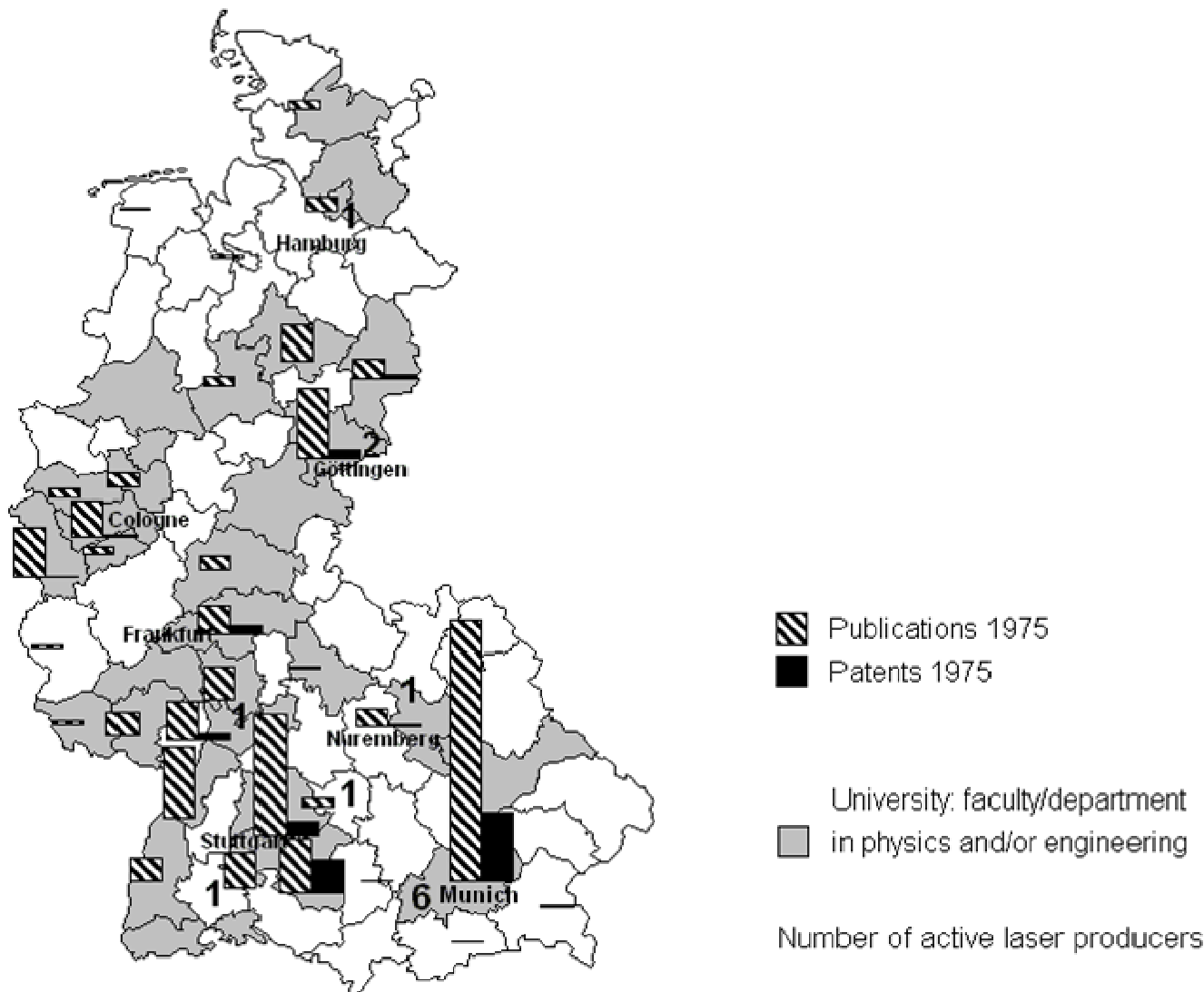


Figure 4: Number of laser publications, laser patents and laser producers in West German regions 1975

In the 1970s and the 1980s the West German academic system has been considerably extended by setting-up new universities and departments. In the course of this development the number of universities with departments in the field of physics and electrical engineering increased to 44 percent of all the (planning) regions until 1975 and to 51 percent in 1985. In the year 1975 Munich continued to be the leading region in terms of the number of publications and patent applications, but it

also took the lead with regard to the number of laser source producers which increased to six firms located in this region (figure 4). The picture for the year 1985 is quite similar to that of the year 1975 with the leading position of the Munich region undefeated (figure 5). Although patenting activity is limited to a few regions outside Munich, much more locations have scientific publication on laser technology, which tend to be much more widely spread across the country. About the same picture can be found for the following years 1995 and 2005 (figure 6 and 7). The maps for spatial distribution of laser technology research in the different years suggest that particularly during the 1960s and the 1970s the geographic distance to Munich has worked as an impediment for the adoption of laser technology research, particularly with regard to laser patents. We will account for the geographic distance to the Munich in our empirical analysis.

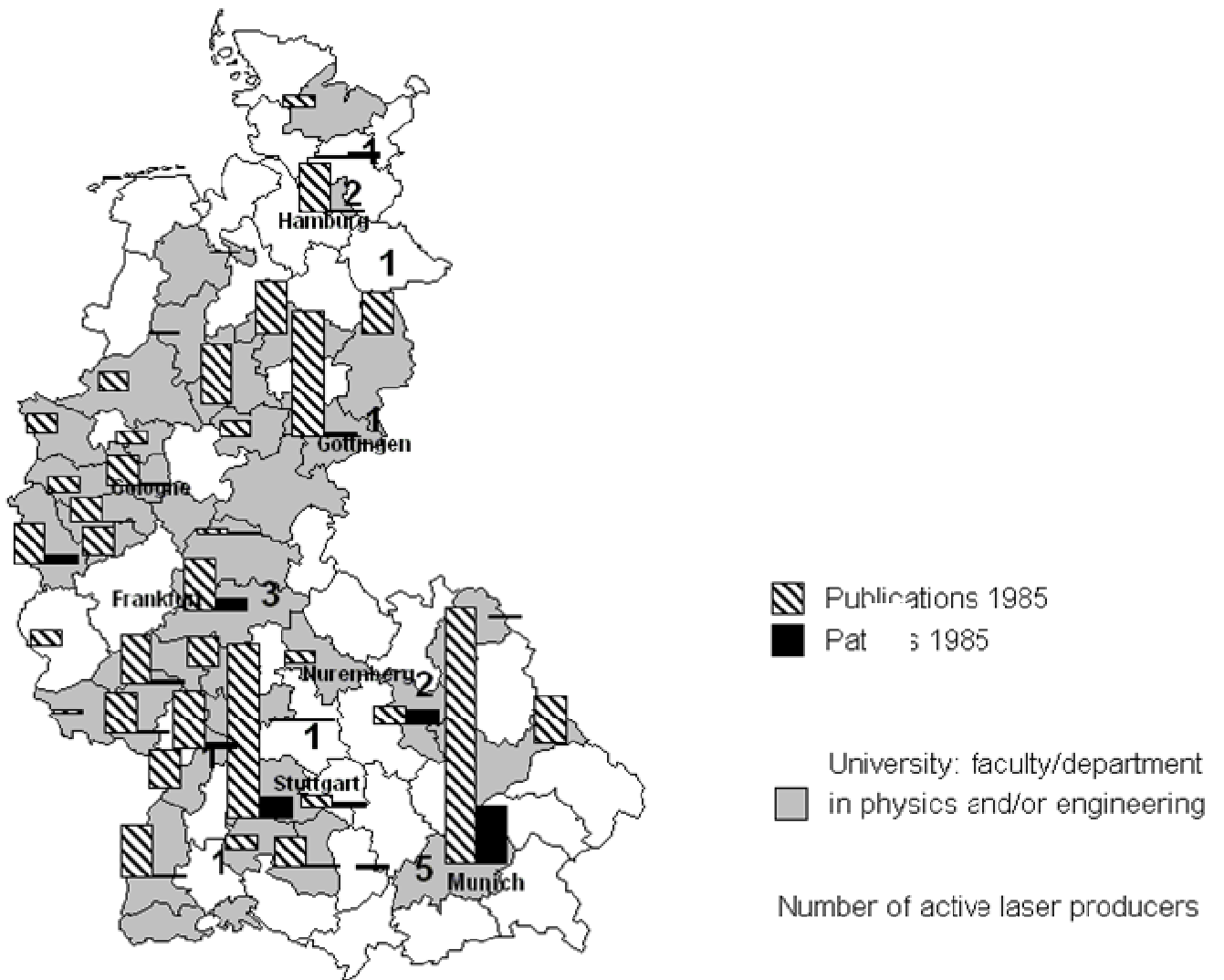


Figure 5: Number of laser publications, laser patents and laser producers in West German regions 1985

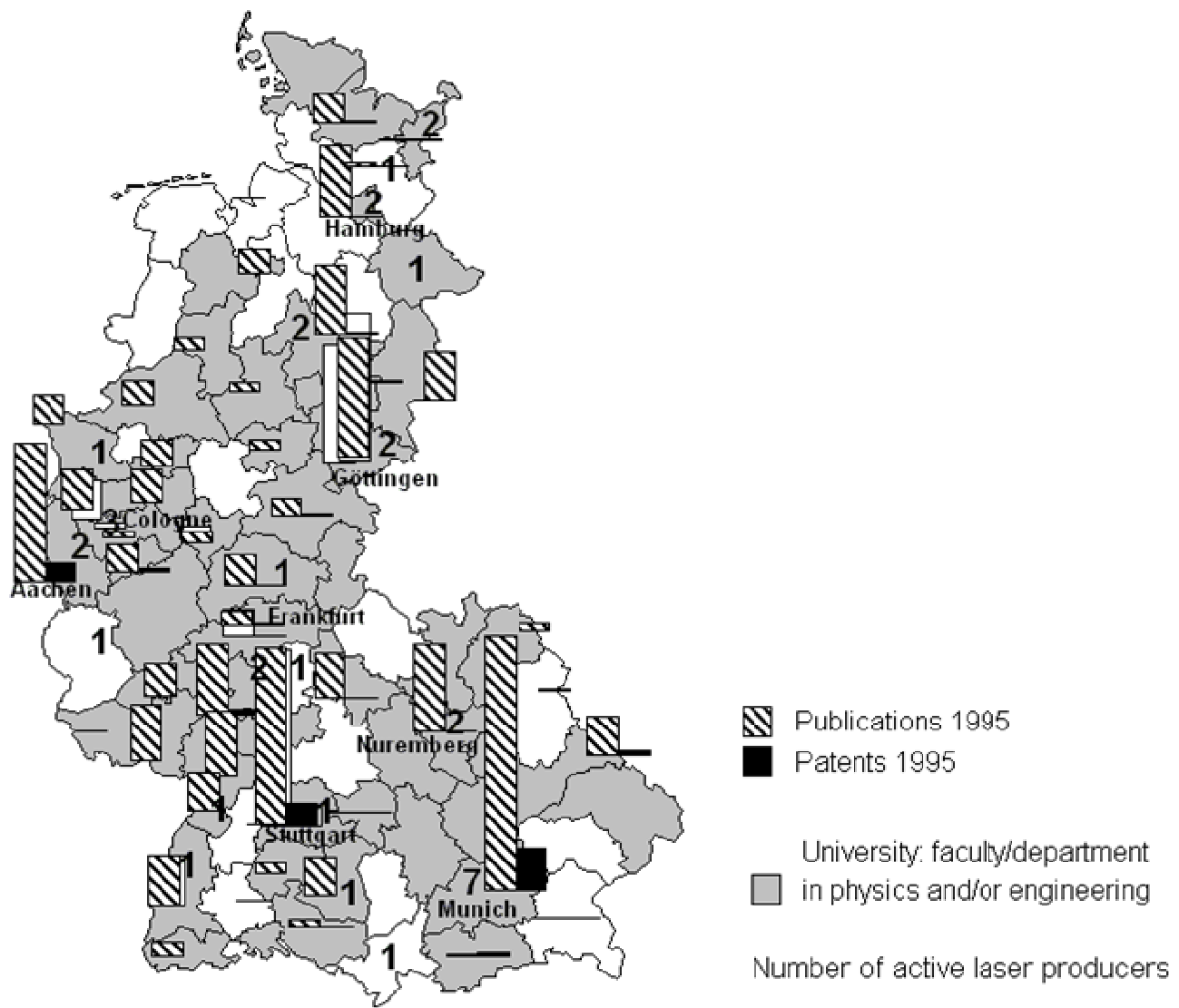


Figure 6: Number of laser publications, laser patents and laser producers in German regions 1995



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

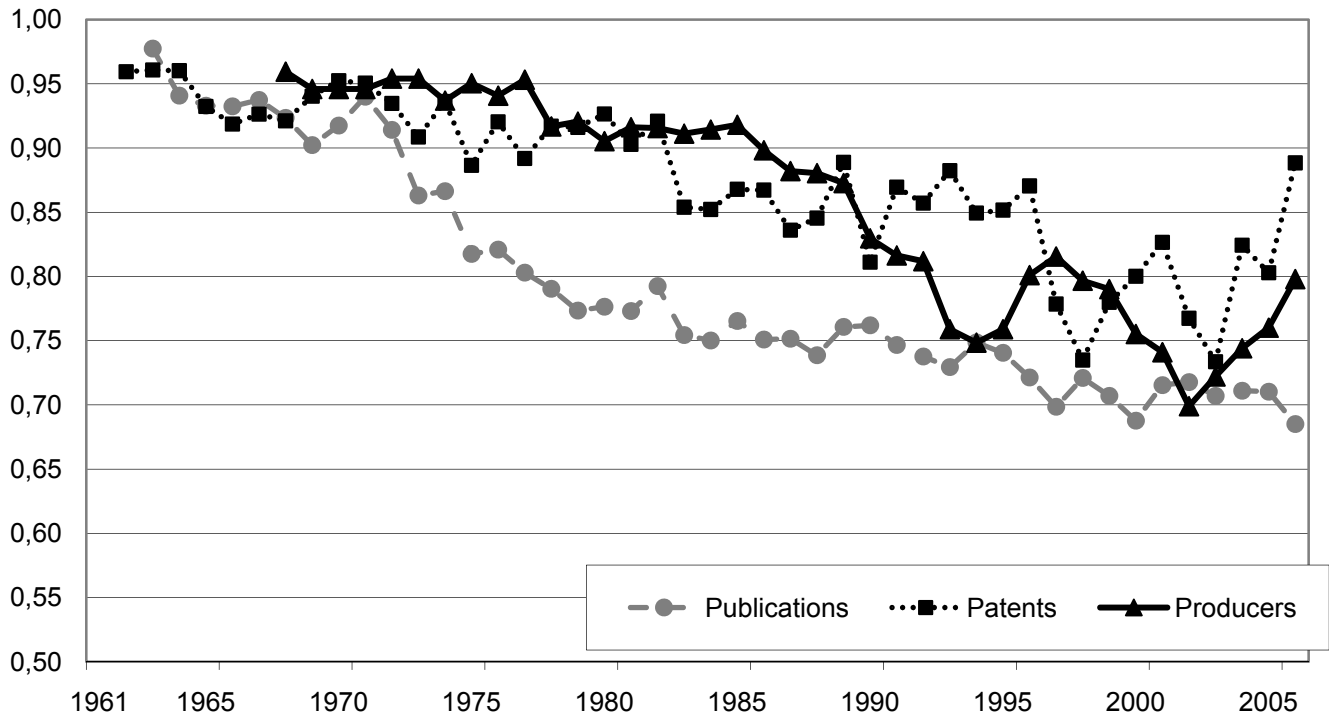


Figure 13: Regional concentration of laser publications and patents in West Germany 1960-2005 – Gini-coefficients

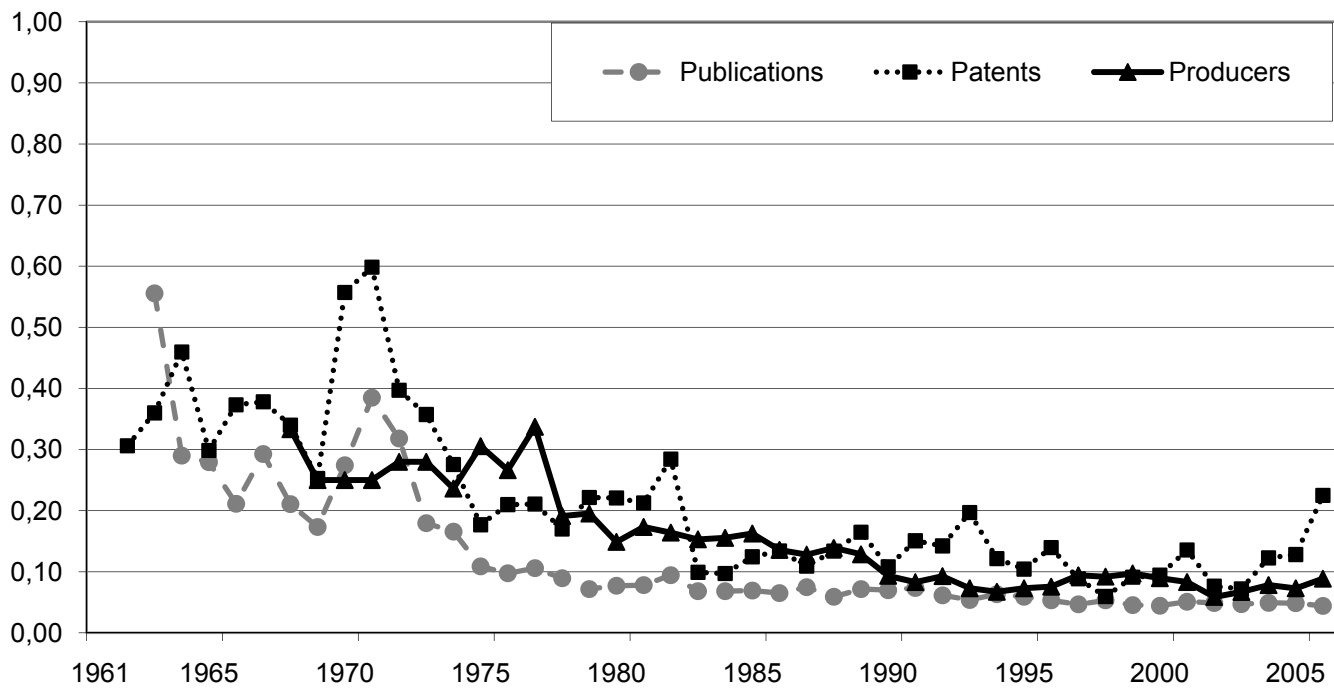


Figure 14: Regional concentration of laser publications and patents in West Germany 1960-2005 – Herfindahl Index

In order 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 (figure 13 and 14). Both types of indicators show about the same trend. We find a considerable decrease of spatial concentration for laser patents, laser publications as well as for the number of producers. All indicators seem to converge towards a certain level of spatial inequality. Both types of measures also indicate an increasing spatial concentration of laser patenting for the very last years of the period under inspection.

5. Econometric Analysis

In this section we perform empirical analysis for testing the hypothesis formulated in section 2. Basically we aim explain the reasons behind the regional diffusion of knowledge, in particularly the extent to what regional factors influence the adoption-event of the first laser publication or the first laser patent in the region (section 5.1). We then investigate the overall amount of laser technology research in a certain year (section 5.2).

5.1 The inter-regional technology diffusion: hazard models of time-to-first patent and time-to first publication

For the analysis of a phenomenon such as time-to-first laser patent or time-to-first laser publication in a region a conventional OLS regression techniques would not be adequate for two reasons. First the distributions of time-to-event observations tend not to follow a normal distribution and second, duration data is generally censored because the dependent variable cannot assume values below zero and above the length of the observation period (Cleves et. al., 2004). A proper methodology for such constellations is provided by a hazard models in which the hazard function defines the probability that a region i experience an event in 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 et. al., 2004).

The standard approach in this respect is a Cox proportional hazard model. A disadvantage of such a model is that it implies that the transition to the event of interest may occur at any particular moment in a continuous time (Allison 1982). Although the underlying process of technology diffusion can be considered as taking place in continuous time, we cannot observe the exact times in our data but rather the discrete time as yearly intervals, i.e. we only observe in which year the technology adoption took place. Therefore, as an alternative to the Cox specification, we consider a discrete-time hazard model. We choose the complementary log-log model, because it allows the discrete representation of data generated in continuous time. Similar to the Cox model, it has the proportional hazard assumption and 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 hazard function has the form

$$h_i(t) = 1 - \exp(-\exp[c(j) + \beta_1'X_{it} + \beta_2'Z_i]) \quad (1)$$

where $h_i(t)$ represents the likelihood that region i experience in time t the event under consideration. Time is measured in years starting in the year 1960 (=0) when the first laser was realized in the US, and the time-to-event occurrence is measured as the number of years until the technology adoption-event in the region. We define the event as 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 by denoted $c(j)$, X_{it} represents the set of time-varying variables, and Z_i the time-constant variables which is in our case the 'distance to Munich'.

The following variables have been included into the model:

- *Population*: in order 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 the size of a region and its population density. This variable also 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 field 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 occur in regions with academic research facilities in physics and engineering.
- Distance to Munich is the average geographical distance of a region to Munich measured in kms. This variable tests for our third hypothesis which states that regions located close to the early center of laser technology research, are more likely to become adopters in comparison to regions located further away (H3). By including this variable we also control for possible spillover effects emanating from this region.
- *Producer* is a dummy variable that assumes the value of 1 if a region is the location of one or more laser source producers and has the value of 0 if this is not the case. The variable is meant to control for the effect of laser research conducted by private sector firms.
- *Publications in adjacent regions* (t-1) is the one year lagged number of publications with authors located in adjacent regions and is included as a control for spatial autocorrelation. Correspondingly, for the case of the first patent, we include the variable '*patents in adjacent regions*' (t-1).

Furthermore, we include time dummies for five year intervals assuming that the hazard is constant over a longer interval than just one year. This assumption is also necessary because the hazard cannot be estimated for time values with no events. Descriptive statistics and correlations between variables are presented in table A1 and A2 in the Appendix.

All models have also been run with a Cox proportional hazard model which is specified as:

$$h_i(t, X_{it}, Z_i) = h_o(t) \exp([\sum_{k=1}^p \beta_k X_{it}] / \beta_l Z_i) \quad (2)$$

with $h_o(t)$ as the baseline hazard, and X_{it} and Z_i representing the same independent variables described above. We run separate regressions for the two dependent variables first patent and first publication. The results for first publication are presented in table 1. For each model, the first column presents the estimated coefficients followed by the respective hazard rates. A value of the hazard rate higher than one indicates that the region has an above average probability of experiencing the event while values lower than one indicate a lower probability.

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 more population have a significantly higher hazard of experiencing the event sooner, which support hypothesis H1. We also find a significantly positive effect for the university variable indicating that regions with academic institutions in physics and engineering have a higher hazard of having a first publication than regions without an academic institution in the respective research fields. This supports our hypothesis H2. We find that the 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 the geographic distance plays an important role for the diffusion of laser technology and that regions located in close spatial proximity to Munich as the leading laser center have a higher likelihood of being ‘infected’ with the new technology than regions located further away. This result remains robust to several extensions and alternative specifications¹⁵, and therefore we conclude that the evidence supports our hypothesis H3.

¹⁵ We also tested the impact of three distinctive measures of distance. Instead of the distance to Munich we included the distance to Stuttgart, a region which also had a leading role with respect to the number of laser publications and patents. This did lead to about similar results as the distance to Munich variable. Including the distance to Aachen, a region with a leading technical university but no early adoption of laser technology

The presence of one or more laser producers in the region has a significant positive impact on the likelihood for the first publication, which may be due to the fact that this variable can be considered as a proxy for the demand for laser research in the region. That we did not find any significant effect for the publications from adjacent regions indicates that there are no knowledge spillovers over short geographic distance which may be regarded a contradiction to the significance of the 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 only statistically significant effects for the number of population and for the distance to Munich with the same signs as in the models for the time-to-first publication supporting our hypotheses H1 and H3. The variable for the presence of a university department in the respective 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 to the previous mentioned alternative specifications, namely replacing distance to Munich by distance to Stuttgart, Aachen and Hamburg. A possible explanation for the non-significance 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 the first patent in the region. For instance, while Siemens filed its first laser patent as early as 1961, it entered the market of laser source producer as late as in the year 1967. As in the case of publications we did not find any statistically significant effect for the number of patents in adjacent regions. All of these results remain similar to the inclusion of the quadratic term of distance to Munich for both models (columns II for the complementary log-

showed no statistically significant effect while the distance to Hamburg, a region located far away from Munich with late adoption of laser research showed a significantly positive effect indicating that the larger the distance from Hamburg the lower the likelihood for adopting laser research.

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

Variables	Complementary log-log model				Cox regressions			
	(Ia) coefficients	(Ib) hazard rates	(IIa) coefficients	(IIb) hazard rates	(IIIa) coefficients	(IIIb) hazard rates	(IVa) coefficients	(IVb) hazard rates
University	1.616*** (0.247)	5.034*** (1.241)	1.640*** (0.253)	5.156*** (1.302)	1.593*** (0.248)	4.920*** (1.218)	1.626*** (0.255)	5.085*** (1.295)
Producer	0.933*** (0.268)	2.543*** (0.682)	0.865*** (0.265)	2.375*** (0.630)	0.874*** (0.264)	2.397*** (0.634)	0.773*** (0.268)	2.167*** (0.581)
Number of population (ln)	0.771*** (0.227)	2.163*** (0.491)	0.843*** (0.217)	2.324*** (0.505)	0.754*** (0.236)	2.125*** (0.502)	0.855*** (0.231)	2.352*** (0.543)
Number of publications in neighboring regions (t-1)	-0.002 (0.005)	0.998 (0.005)	-0.003 (0.005)	0.997 (0.005)	-0.003 (0.005)	0.997 (0.005)	-0.004 (0.005)	0.996 (0.005)
Distance to Munich(km)	-0.001** (0.001)	0.999** (0.001)	-0.005** (0.002)	0.995** (0.002)	-0.001** (0.001)	0.999** (0.001)	-0.005** (0.003)	0.995** (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	Yes	Yes	Yes	Yes	No	No	No	No
Number of observations	1396		1396		1396		1396	
Number of regions	74		74		74		74	
Log Likelihood	-230.1		-229.3		-206.5		-205.6	
Pseudo R-squared	0.135 ^a		0.137 ^a		0.133		0.137	
^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	Complementary log-log model				Cox regressions			
	(Ia) coefficients	(Ib) hazard rate	(IIa) coefficients	(IIb) hazard rate	(IIIa) coefficients	(IIIb) hazard rate	(IVa) coefficients	(IVb) hazard rate
University	0.307 (0.284)	1.359 (0.386)	0.362 (0.286)	1.436 (0.411)	0.332 (0.267)	1.393 (0.372)	0.378 (0.269)	1.460 (0.393)
Producer	0.750 (0.655)	2.117 (1.387)	0.767 (0.641)	2.154 (1.381)	0.790 (0.598)	2.204 (1.318)	0.758 (0.571)	2.133 (1.217)
Number of population (ln)	1.053*** (0.234)	2.866*** (0.669)	1.124*** (0.238)	3.076*** (0.731)	0.928*** (0.220)	2.530*** (0.556)	0.977*** (0.221)	2.655*** (0.586)
Number of patents in neighboring regions (t-1)	-0.009 (0.018)	0.991 (0.018)	-0.019 (0.019)	0.981 (0.019)	-0.011 (0.018)	0.989 (0.018)	-0.021 (0.021)	0.979 (0.020)
Distance to Munich(km)	-0.003*** (0.001)	0.997*** (0.001)	-0.007*** (0.003)	0.993*** (0.003)	-0.003*** (0.001)	0.997*** (0.001)	-0.006** (0.003)	0.994** (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	Yes	Yes	Yes	Yes	No	No	No	No
Number of observations	1310		1310		1310		1310	
Number of regions	74		74		74		74	
Log Likelihood	-239.9		-238.8		-227.4		-226.6	
Pseudo R-squared	0.103 ^a		0.107 ^a		0.067		0.070	
^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.								

log, and columns 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 almost zero.

5.2 The 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. In order 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 with inventors residing in a region as alternative indicators for research output. The model has the form

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

for laser publications and

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

for laser patents as indicator for the level of laser research. ζ_i represents the regional fixed effect and ε_{it} is the usual error term.

In addition to the explanatory variables that have been tested for explaining the first adoption of laser research we also include the 'year of first regional laser publication' and 'year of first regional laser patent' for testing for our hypothesis H 4 which suggests that regions which begun research on laser technology relatively early will have more research in this field in later years than regions which started relatively late. We take 1961 as the starting year of publications on laser technology in Germany and 2005 as the end year. Pioneering regions that had their first publication in the year 1961 are assigned the highest value of 45 years

and regions with the first publication in a later year are assigned decreasing values.¹⁶

Our data constitutes a balanced panel with yearly information from 1961 to 2005 for every region. Both dependent variables are whole-numbered with positive values and can be regarded a result of a Poisson-like process.¹⁷ Therefore we apply negative-binomial (negbin) regression as estimation method because it is based on more general assumptions than Poisson regression.¹⁸ We employ two main estimation approaches. Firstly, panel data analysis was 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 the adequate method because many 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 the number of population and to the distance to Munich which is completely invariant over time. Therefore, we also ran random effects models.

Because many regions have never engaged in laser research or have performed laser research only sporadically our dependent variables may be regarded to have 'too many zeros' which would imply a violation of the distribution assumptions of the estimation procedure (Hilbe, 2008).¹⁹ 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

¹⁶ For instance, if a region had its first scientific publication in laser technology in the year 1971 it is assigned the value of 35. If a region has its first publication in the year 2005 the value of the variable is 1. In case of no publication at all the value of the variable is 0.

¹⁷ Negative binomial regression allows for a greater variance of observations than is assumed in Poisson regression. For a more detailed description of these estimation methods, see Greene (2008, 909-912).

¹⁸ In the cases when co-inventors are located in different regions, the number of patent applications per regions may not always be whole numbered. Therefore these numbers have been rounded up.

¹⁹ Regarding the publications, the share of zero cases amounts to 54 percent of all observations. For patents this share is 73 percent.

different regimes. The 'true zeros' are cases (regions) which basically fulfill the preconditions to have laser patents or publications but did not succeed to have one. These cases should be included into the negbin estimation procedure. The 'excess zeros' are cases which 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 logit model estimates whether a region belongs to the 'true zero' or the 'certain zero' cases. 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 which are not certainly zero (Hilbe, 2008). For the logit models of the first step of the publications model, we used the university variable that indicates the presence of an academic institution working in the field of natural physics or engineering. The reason for choosing this variable here is the key role that these academic institutions play for scientific publications on the field of laser technology. In the model with the number of patents as dependent variable the certain zero cases have been 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.

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 has indeed a pronounced positive effect. For the number of patents such an effect of the academic institutions is only statistically significant in the zero-inflated negbin model (table 4). It is important to note that the university variable is highly correlated with the number of regional population indicating most academic institutions are located in larger cities. If the number of regional population is excluded from the model the university variable becomes also statistically significant in the fixed effects and in the 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: while the presence of laser source producers has always a significant positive effect on the number of patents in each model (table 4), the impact is insignificant in the fixed effects and the random effects estimates for the number of publications but has the expected effect in the zero-inflated negbin model. The regional population which can be regarded as the pool of potential authors or inventors has a significantly positive effect in all models (table 3 and 4). The number of patents and publications in neighboring regions which are included as a control for spatial autocorrelation show 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 of regions located in the same Federal State.²⁰

²⁰ Note that Western Germany consists of ten Federal States.

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

Variables	Fixed effects (I)	Random effects (II)	Zero inflated negative binomial (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)
Number of 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	-4650	-5087	-5962
Pseudo R-squared	0.217	0.205	0.129
Notes: Robust 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 4: Estimation of the regional number of patents, 1961-2005

Variables	Fixed effects (I)	Random effects (II)	Zero inflated negative binomial (III)
University	0.125 (0.209)	0.212 (0.183)	1.013*** (0.103)
Producer	0.255** (0.115)	0.314** (0.150)	0.682*** (0.112)
Number of population (ln)	0.439* (0.238)	0.586*** (0.222)	1.109*** (0.087)
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	-2447	-2761	-3016
Pseudo R-squared	0.055	0.052	0.132
Notes: Robust 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.			

For testing hypothesis H4 stating that regions which started research on laser technology relatively early will have more research in this field in later years than regions which 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. This variable is the total count of the number of years since the first laser publication (or the first laser patent respectively).²¹ Given the important role and weight that the Munich region had as pioneer adopter of laser technology, we also include the variable distance to Munich. Because these two variables are time invariant, the estimations are restricted to the random effects and zero-inflated negbin models (tables 5 and 6).

The results suggest that regions which started 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 the later years. This implies that being a pioneer region brings advantages over latecomers. Such advantages may particularly consist in the accumulation of knowledge over time. Moreover, early engagement can induce the establishment of respective scientific infrastructure that fosters further regional laser research. As for the time-to-first patent and publication we also find a significant effect for the geographic distance to the Munich region on the volume of laser research, particularly for the number of laser patents. In case of laser publications this effect appears to be somewhat weaker being only statistically significant in the negbin models but not in the random effects regressions. A possible explanation for this difference between the effect of the geographic distance to the early center of laser research on patents and publications may be the relatively strong role of public research institutions for publications. To the extent that the capacities of such organizations are relatively evenly distributed over the country the 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.

²¹ For the year counts we take 1961 as the starting year and 2005 as the last year. Therefore, pioneer regions that had their first publication (or patent) in 1961 are assigned the highest value of 45 years. Latecomers regions have lower values of this variable. For instance, if a region had its first publication (or patent) in 1971 it is assigned the value of 35.

Table 5: The effect of early adoption of laser technology research on the regional number of publications, 1961-2005

Variables	Random effects			Zero inflated negative binomial		
	(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)
Number of 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 University				-2.964*** (0.243)	-5.873*** (2.027)	-6.340** (3.012)
Constant				0.312* (0.173)	-0.163 (0.175)	-0.104 (0.168)
Ln alpha				-0.509*** (0.064)	-0.667*** (0.056)	-0.762*** (0.058)
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	-5087	-5007	-4993	-5850	-5508	-5465
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: The effect of early adoption of laser technology research on the regional number of 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)
Number of 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	-2750	-2721	-2721	-2861	-2830	-2811
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.

For controlling 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 estimation 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 non-significant 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 carefully considered because both publications and patents 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 the 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 left out the university variable (columns XII and XV in table 8). Additionally, because the number 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 table 7 and 8. Overall, the results and interpretations remain similar 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 number of population university variable becomes slightly significant in the random effects model (columns X and XI, table 8). This suggests that academic organizations may have also play an important role for regional patenting activity.

Similar to the previous findings the regional publications still have no significant effect on the number of patents in the random effects models

but in the zero-inflated negbin estimations (columns XII and XV, table 8). One possible interpretation of these results is as following: regional patents have an effect on the regional publications because the local academic organizations are influenced by the applied and industry-oriented research that takes place within the region. However the opposite may not be true at the same magnitude. Regional industry-oriented research may not be so strongly and directly influenced by local academic research.

Finally, we analyze to what extent the previous findings prevail 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 a high quality if it has received at least ten forward citations. The results for the regional number of high quality patents (table 9) are rather similar to the results we have obtained for the overall number of patents. One difference is, however, 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 have an important role for regional patenting. As before, the presence of a producer in the region has a significant positive impact under the random effects model. The geographic distance to Munich and the years since the first patent are statistically significant with the expected signs in every model and each specification (table 9).

Table 7: The effect of early adoption of laser technology research on the regional number of publications, 1961-2005 – alternative specifications

Variables	Random effects			Zero inflated negative binomial		
	(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	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 patents			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)
Observations	3256	3256	3256	3256	3256	3256
Number of regions	74	74	74	74	74	74
Log Likelihood	-5099	-5007	-4998	-6042	-5605	-5472
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: The effect of early adoption of laser technology research on the regional number of patents, 1961-2005 – alternative specifications

Variables	Random effects			Zero inflated negative binomial		
	(X)	(XI)	(XII)	(XIII)	(XIV)	(XV)
University	0.398* (0.216)	0.351* (0.200)		1.359*** (0.093)	1.301*** (0.094)	
Producer	0.383*** (0.131)	0.316** (0.154)	0.284* (0.172)	0.413*** (0.103)	0.207* (0.108)	-0.052 (0.109)
Population (ln)			0.365* (0.200)			0.878*** (0.086)
Neighboring patents	-0.035** (0.014)	-0.025*** (0.008)	-0.024** (0.010)	-0.032*** (0.006)	-0.026*** (0.006)	-0.020*** (0.006)
Distance	-0.002* (0.001)	-0.001** (0.001)	-0.001** (0.001)	-0.012*** (0.001)	-0.009*** (0.001)	-0.008*** (0.001)
Years since first laser patent		0.065*** (0.008)	0.059*** (0.008)		0.049***	0.034*** (0.005)
Number of regional laser publications			-0.000 (0.008)			0.018*** (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						
Producer_count				-2.448** (1.089)	-3.767 (5.382)	-28.926 (695,577)
Constant				-0.828*** (0.212)	-1.254*** (0.276)	-1.973*** (0.564)
Ln alpha				0.122 (0.108)	0.183* (0.100)	0.215** (0.097)
Observations	3256	3256	3256	3256	3256	3256
Number of regions	74	74	74	74	74	74
Log Likelihood	-2762	-2724	-2724	-2936	-2879	-2841
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.

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							
Producer_count					-0.667** (0.336)	-0.570*** (0.168)	-1.738 (1.942)
Constant					0.325 (0.502)	0.914*** (0.282)	0.033 (0.626)
Ln alpha					-0.712 (0.704)	-1.476* (0.885)	-0.081 (0.484)
Observations	1760	3256	3256	3256	3256	3256	3256
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.

8. Conclusions and interpretation

After the first workable laser had been realized in the USA in the year 1960, the new technology was nearly immediately adopted in Germany. Obviously, the main media of knowledge diffusion at that stage were publications and conferences. A very important impulse for the German laser innovation system at that time was the decision of the *Siemens* company to devote large amounts of resources to this technology. Since most of this research has been carried out in Munich, this region became the center of early laser research in Germany. An important inflow of laser knowledge into Munich may have been that a member of one of the leading US-teams became a professor at the Technical University of Munich in the year 1964. In addition, the position of Munich was considerably strengthened by the set-up of public research institutes working in the field of laser technology in this region.

Regarding the determinants of the spatial diffusion of laser technology as measured by the number of patents and publications, we could identify a number of factors that play a role. First, the presence of universities with the relevant departments seems to have been a precondition for the adoption of the new technology. For this reason the expansion of universities in West Germany during the period under inspection had an effect on the diffusion of laser technology research among German regions. Among the regions that fulfilled this precondition research on laser technology has been first adopted in larger agglomerations. Moreover, geographic proximity to the center of early laser research in Germany, Munich, has been found to be conducive for the early adoption of laser research. The level of laser research in adjacent regions had, however, no statistically significant effect.

We found that relatively early adoption of laser research in a region has a positive effect on the level of laser research in later periods indicating cumulateness of the respective knowledge. While the presence of a university department in the field of physics or engineering

has a positive effect on scientific publications on laser technology we found a pronounced effect of laser producers on patenting activities in this technological field.

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Appendix

Table A1: Descriptive Statistics

Variable Name	Variable Label	Mean	Median	Minimum	Maximum	Standard Deviation	Number of observations
Publications	Number of laser publications	6.75	0.00	0.00	162.00	15.90	3
Patents	Number of laser patents	0.90	0.00	0.00	47.00	3.27	3
University	University dummy	0.52	1.00	0.00	1.00	0.50	3
Producer_count	Number of producers	0.33	0.00	0.00	16.00	1.05	3
Producer	Producer dummy	0.19	0.00	0.00	1.00	0.39	3
Population (ln)	Population (ln)	13.43	13.28	12.45	14.92	0.58	3
Number of publications in neighboring regions	Number of laser publications in adjacent regions (one year lagged)	35.52	19.00	0.00	233.00	42.71	3
Number of patents in neighboring regions	Number of laser patents in adjacent regions (one year lagged)	5.20	2.00	0.00	50.00	8.28	3
Distance to Munich (km)	Average distance to the Munich region	432.03	428.53	0.00	892.56	228.41	3
Years since first publication	Number of years since first laser publication	27.03	30.00	0.00	44.00	14.31	3
Years since first patent	Number of years since first laser patent	28.22	31.00	0.00	45.00	14.04	3

Table A2: Correlation Table

	Variables	1	2	3	4	5	6	7	8	9	10
1	Number of publications	1									
2	Number of patents	.609*	1								
3	University	.397*	.201*	1							
4	Number of producers	.747*	.533*	.220*	1						
5	Producer (yes / no)	.504*	.293*	.277*	.660*	1					
6	Population	.439*	.304*	.536*	.326*	.310*	1				
7	Number of publications in neighboring regions	.063*	.015	.094*	.043*	.139*	0.034	1			
8	Number of patents in neighboring regions	-.018	.017	-.112*	.021	-.010	-0.136*	.543*	1		
9	Distance to Munich (km)	-.132*	-.242*	.011	-.125*	-.033	0.060*	-.311*	-.527*	1	
10	Year since first publication	.378*	.231*	.573*	.239*	.287*	0.569*	-.050*	-.052*	-.097*	1
11	Year since first patent	.2845*	.222*	.328*	.235*	.264*	0.455*	.109*	.106*	-.326*	.531*

* Statistically significant at the 5% level.