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New technology in the region – agglomeration and absorptive capacity effects on laser technology research in West Germany, 1960–2005

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We analyze the spatial diffusion of laser technology research in West Germany from 1960, when this technology began, until 2005. Early adoption of laser technology research 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 negligibly 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. An interregional transfer of tacit knowledge was largely unimportant for the spatial diffusion of research in this technological field.

Keywords: research; spatial diffusion; laser technology; absorptive capacity; tacit knowledge

JEL classification: R11; O33; O52

1. Knowledge in space[1]

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 (Feldman 1994; Hägerstrand 1967; Stoneman 2002). Theoretical explanations for the spatial diffusion pattern highlight a number of regional factors, particularly face-to-face contact, agglomeration economies, actors' absorptive capacity, and the mobility of people between firms and regions. 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.

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Regional research and knowledge generation are important inputs for the generation of innovations and can, therefore, be regarded as a main determinant of *where* the production of new products is located or where a new process is applied (Buenstorf, Fritsch, and Medrano 2012). It is a key element of the regional innovation system that can be regarded as decisive for regional development. 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 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 twentieth century (Bertolotti 2005), with a great variety of applications that include range finding, transmission and storage of information, material processing, printing, medical technology, and weapons, to name just a few. The term 'laser' is an acronym for *l*ight *a*mplification by *s*timulated *e*mission of *r*adiation. 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 early adoption and spatial diffusion of laser technology research

Hägerstrand (1952, 1967) was the first scholar to intensively analyze spatial diffusion processes. Based on the empirical observations of the regional spread of process innovations, he hypothesized that new technology is first implemented in the 'center' – the large agglomerations – and then moves 'down' the spatial hierarchy, the last stop being the 'periphery', i.e. remote and sparsely populated regions. There are at least two factors that may explain this pattern: first, the transfer of tacit knowledge via face-to-face contact and second, the absorptive capacity of a region.

If the adoption, implementation, and use of a new technology require personal face-to-face transfer of tacit knowledge (Mansfield 1968; Stoneman 2002) and if each inhabitant of a region has an identical likelihood of personal contact with an external knowledge source, then the large number of actors and firms in an agglomeration should mean that there is a relatively high probability that this knowledge is first transferred to someone located in such a region. The tendency toward first adoption in large agglomerations should be even stronger if the contact networks of actors in these regions are of wide geographic scope with strong connections to global 'pipelines'. This may particularly be the case in larger cities host to research universities, other public research institutions, firm headquarters, and branches of multinational firms. Based on these considerations, our first hypothesis states:

> *H*1: Laser technology research should be adopted first in the largest agglomerations.

The concept of absorptive capacity was initially developed in the context of individuals and organizations (Cohen and Levinthal 1989; Zahra and George 2002), but it can also be applied to regions, in the sense of capturing the ability of regional actors to recognize the value of new information or knowledge, assimilate it, and then use it. On the assumption that absorptive capacity is important for technology adoption, then the probability that there is at least one actor with sufficient absorptive capacity to implement first adoption should be highest in regions with the largest number of actors. Since laser technology research requires some knowledge of physics and electrical engineering,[2] the region with the largest number of persons having this knowledge should have the highest likelihood of early adoption. Hence, 'cognitive proximity' and related variety of the regional industry structure (Boschma and Wenting 2007; Frenken, van Oort, and Verburg 2007) should play a role. In the case of laser technology, the science-based character of the technology (Bromberg 1991; Grupp 2000) may also require intensive interaction with academic institutions and therefore may be particularly likely to occur in regions that are home to academic research facilities in the appropriate scientific disciplines, namely, physics (including optics) and electrical engineering. For these reasons, we expect early adoption of laser technology research in those large agglomerations that host universities, other public research institutions, and private R&D laboratories. Hence, we expect:

> *H*2: Laser technology research should occur only in regions host to academic research facilities in the relevant disciplines (physics and electrical engineering).

'Second-tier' adopters may acquire the necessary knowledge from international sources or from domestic first-adopter locations. We therefore expect that second-tier adopters will be comprised of smaller cities having the appropriate absorptive capacity, particularly those host to academic research institutions in relevant fields. To the degree that transfer of tacit knowledge is important for 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. For these reasons our third hypothesis states that:

> *H*3: All else equal, regions located close to centers of early laser technology research are more likely to engage in this type of research than are regions located farther away.

Since the intraregional diffusion of knowledge requires time, we also expect that:

> *H*4: 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.

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 than do small and sparsely populated regions. Third, faster diffusion within the agglomerations may also be expected if the knowledge is transferred by job mobility between firms or research institutions because of the relatively large labor markets in these regions. Hence, we conjecture that:

*H*5: Laser technology research will diffuse faster in large agglomerations than in rural areas.

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 may be an attempt to commercialize the results of research conducted in the region. On the other hand, producers of laser beam sources may themselves engage in research and may also stimulate research by others in the same region, e.g. by entering into research cooperation activities with local universities.[3] Hence, we expect that:

*H*6: Regions that are home to 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).

One might suspect that the spatial distribution of potential lead users of laser technology has also played a role for the diffusion of laser research. However, given the wide variety of possible uses and the high level of uncertainty about commercially promising applications of laser technology during the first stages of its development, such lead users could hardly be identified.[4]

3. Data

To describe the diffusion of laser technology research in Germany, we use patent applications. Patent data and their citations were obtained from the database DEPATISnet (www.depatisnet.de), which is maintained by the German Patent and Trade Mark Office, and from the DOCDB database of the European Patent Office (www.epo.org), which has worldwide coverage.[5] From these databases 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. The total counts of forward citations are based on the INPADOC patent family information. The date assigned to the patents is based on the year of application. 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.[6] From the patent data we obtained information on the applicant organizations and the inventor’s residence at the time of application. The patent 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 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, 1993–2005, 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 engineering (electronic engineering, high-frequency technology, communication technology, and 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.[8] 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.[9] 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 possibility of generating microwave amplification by stimulated emission.[10] 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 (Collins et al. 1960; Maiman 1960a, 1960b) that became available around the end of that same year, generating a general sense of euphoria among scientists.

The first realization of a laser in Germany occurred in the Siemens Company's Munich laboratories.[11] At that time, Munich was one of Germany's largest cities, the home of two large universities, several extra-university public research institutes, and important R&D facilities of several private firms.[12] More than 7000 engineers and natural scientists worked in the *Siemens* laboratories alone, which was the largest private-sector research facility in West Germany at the time. Munich was clearly among the few regions in Germany with a high level of absorptive capacity for laser technology. Laser technology research in the Siemens laboratories began when news about the realization of a laser effect by US research groups inspired a young physicist, Dieter Röß, on his own initiative and on his own time, to replicate Maiman's experiment. Remarkably, this replication, which was completed by November 1960, was based solely on Maiman's first publication (Maiman 1960a) supplemented by standard knowledge and equipment, all of which were available at many universities and the research laboratories of larger firms at that time. There was no research cooperation between Siemens and either of the US laser research teams, or any transfer of personnel between them at that stage. This clearly indicates that the transfer of tacit knowledge is relatively unimportant if the relevant 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).[13] In February or March 1961, researchers at *Siemens* in Munich had already considerably improved Maiman's test arrangement.

This early success and the promises of the new technology induced *Siemens* to engage in laser research on a larger scale, with two groups in Munich and a smaller group in Erlangen, a location about 160 km north of Munich. In the next 10 years, *Siemens* dominated German research in the field of laser technology (see Section 4.2 for details). At that time, the *Siemens* Company was already a large and highly diversified producer of all kinds of electric and electronic equipment, communications technology, data processing technology, and medical instruments. Being active in a number of related fields may have been conducive for the *Siemens* management to recognize the potentials of the new technology. Due to its size, *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. A maximum number of about 45 R&D personnel worked on laser technology in the central *Siemens* laboratory during this period, comprising about 0.6% of total R&D employment in this laboratory. In 1970, when it became apparent that the prospects for commercializing laser technology were somewhat dim, *Siemens* sharply reduced the capacities devoted to this type of research.

The early adoption of laser research by *Siemens* clearly illustrates the role of size and 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 first publication in which Maiman (1960a) describes his experiment. A transfer of tacit knowledge was unimportant in that case.

The importance of internal absorptive capacity may also explain why it took two years longer for the laser effect to be reproduced in East Germany (German Democratic Republic [GDR]). 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 Laboratories* 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 USA, 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 USA and West Germany. However, all these developments occurred *after* *Siemens* had started to devote substantial resources to research in this new technological field.

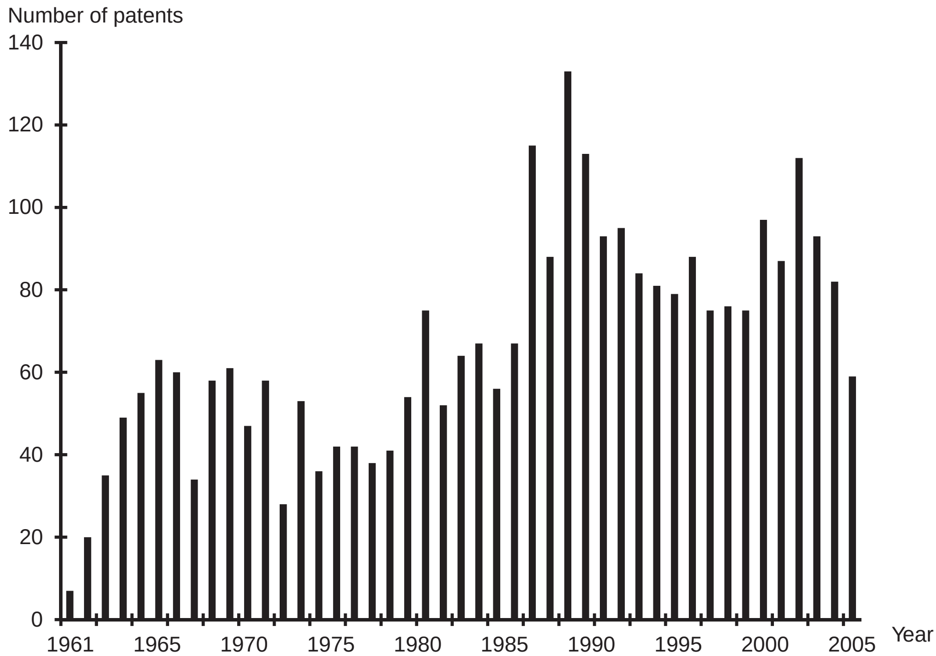

Figure 1. Number of patent applications in the field of laser technology (IPC H01S) in West Germany, 1960–2005.

4.2. *Laser patents in West Germany 1961–2005*

According to our data, there were 2860 patent applications by West German inventors in the field of laser beam sources (IPC H01S) from 1960 to 2005.[14] The number of patent applications reached a peak around the year 1990 (Figure 1). Since then, the yearly number of patent applications shows a decreasing trend, which may be an indication that the innovation system in the field of laser beam sources has reached a certain stage of maturity.

From 1961 to 1980, there were very few West German patent applicants in the field of laser beam sources (IPC H01S), never more than 18 different entities in any year. During this period, *Siemens* accounted for 387 of all 920 (42%) 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%) of all German patent applications in this technological field.[15] For the period of 1960–1980, 131 of the 530 inventors (25%) named in the laser beam-related patent applications were affiliated with *Siemens*.[16] These figures clearly indicate a high concentration of laser research and laser knowledge in one of Germany's largest firms as well as, not inconsequently, a high regional concentration of laser research, particularly in the Munich region.

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.[17]

4.3. *The spatial diffusion of laser technology research in Germany*

Where else, other than in Munich and Erlangen, where the early *Siemens* laboratories 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 or electrical engineering (Albrecht 1997), we might expect that laser research is conducted only in regions that have

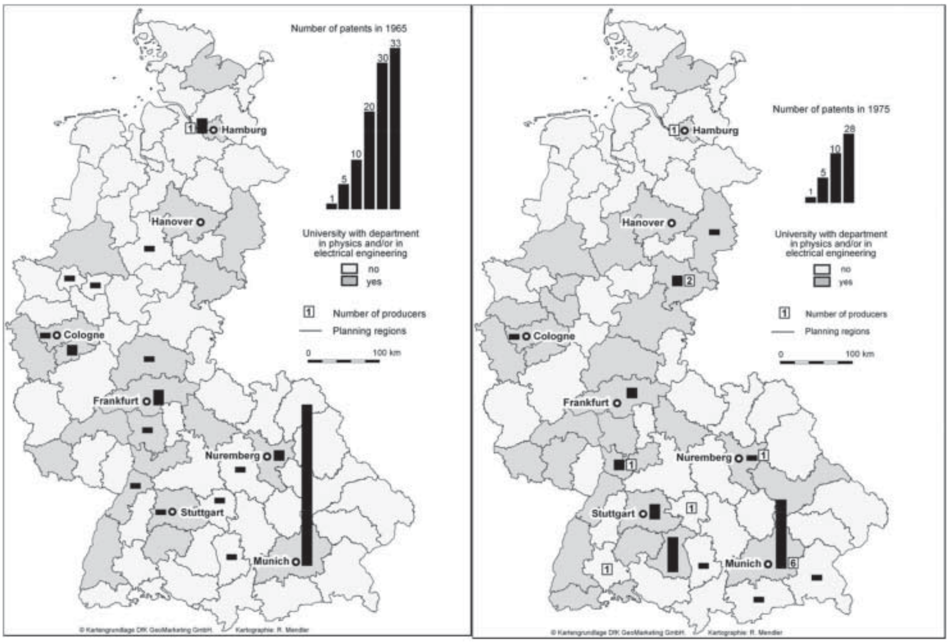

Figure 2. Number of laser patents and laser producers in West German regions, 1965 and 1975.

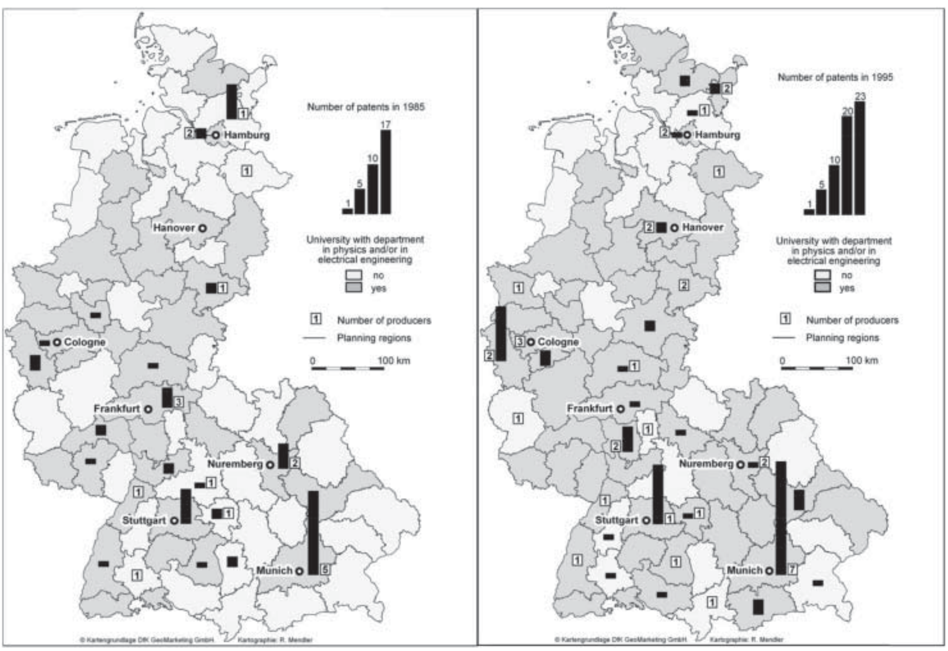

Figure 3. Number of laser patents and laser producers in West German regions, 1985 and 1995.

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% 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.

The maps suggest that 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 in the year 1965 are almost exclusively found in regions with university departments in these disciplines (Figure 2). Exceptions to this 'rule' are probably due to assigning the patent to the inventor's place of residence instead of

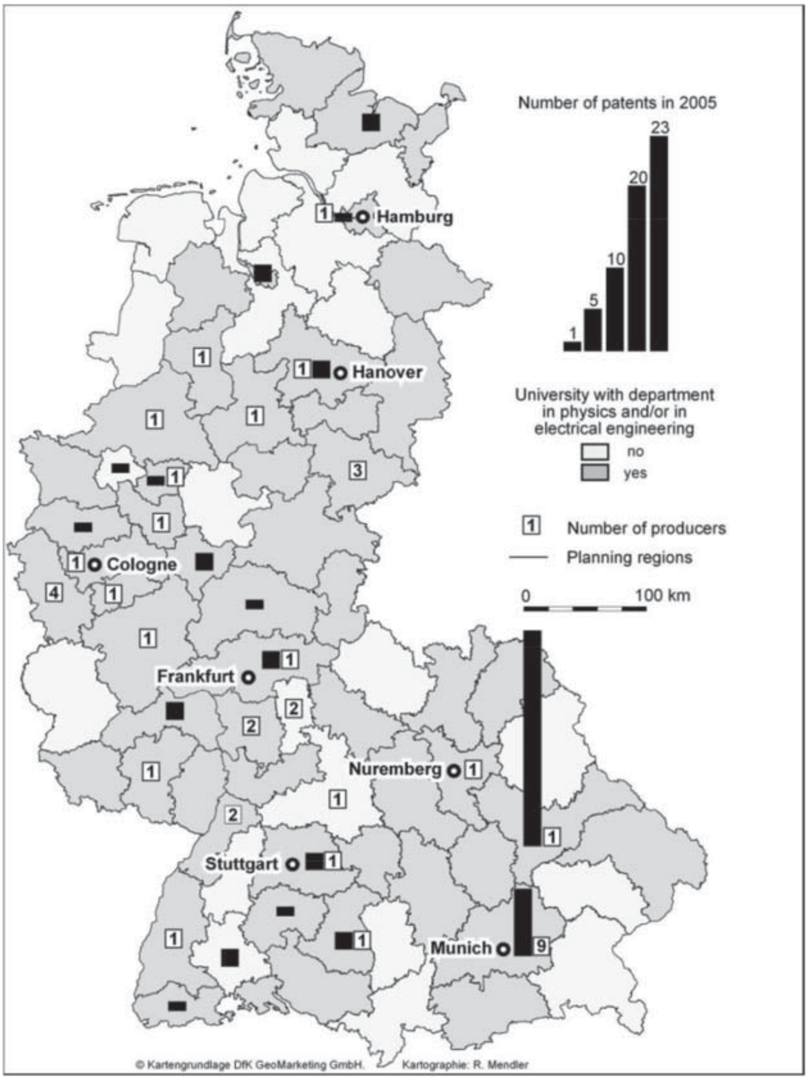

Figure 4. Number of laser patents and laser producers in German regions, 2005.

the place of work. At that time, the Munich region was clearly in the lead in terms of patents' applications, followed by Stuttgart, Darmstadt, and Frankfurt. Figure 2 also shows the earliest recorded industry entry, which occurred in Hamburg, a region where the level of laser research, as indicated by patents, was relatively low.[18] 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 2).

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 departments in the fields of physics and electrical engineering increased from 44% across all planning regions in 1975 to 51% in 1985. In 1975, Munich was still the leading region in terms of number of patent applications and it also took the lead with regard to number of laser source producers, which increased to a total of six such

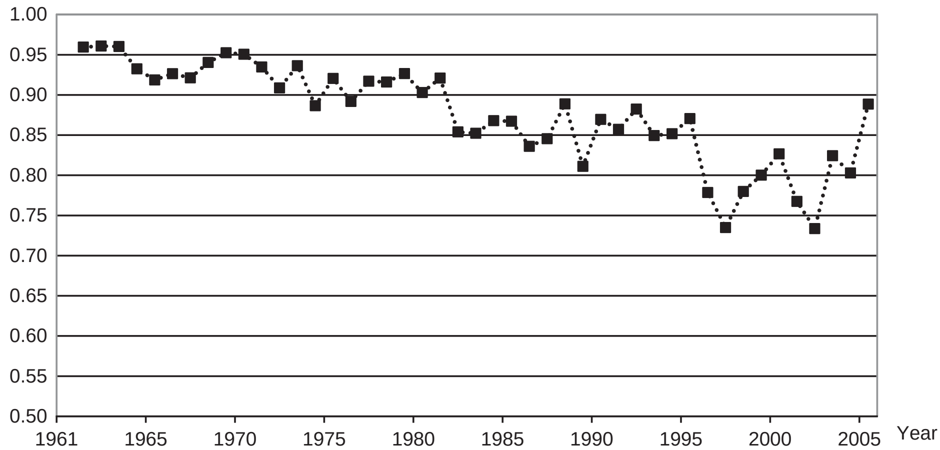

Figure 5. Regional concentration of laser patents applications in West Germany, 1960–2005: Gini coefficients.

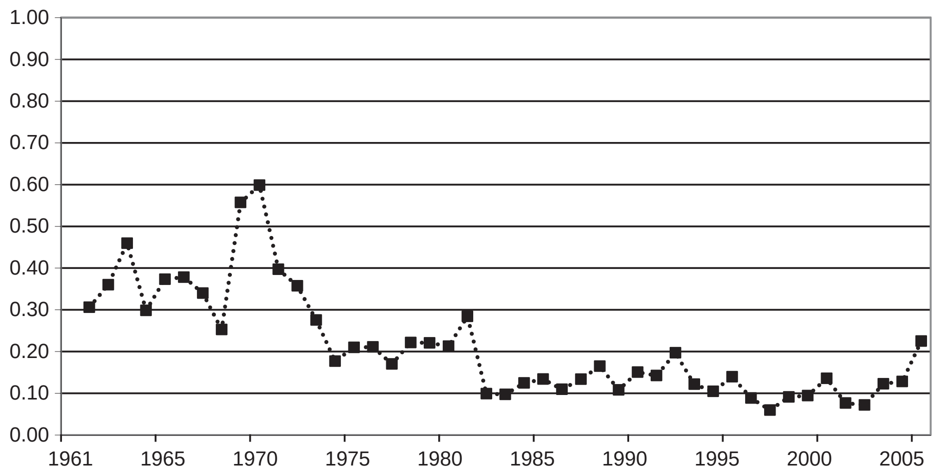

Figure 6. Regional concentration of laser patents in West Germany, 1960–2005: Herfindahl Index.

firms being located in this region (Figure 2). The picture for 1985 is similar to that for 1975, with the Munich region still the undisputed leader in the field (Figure 3). A very similar pattern is seen for 1995 and 2005 (Figures 3 and 4), 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.[19] This relocation of research on laser beam sources to a somewhat less central location may also be regarded as an indication that this technological field has reached a certain degree of maturity. 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 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.[20]

To assess the general spatial concentration of patents in the field of laser technology, we calculated Gini coefficients and the Herfindahl-Hirschman Index for each year of the 1961–2005 period (Figures 5 and 6). Both indicators reveal similar trends. We find a considerable decrease in spatial concentration for laser patents. 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.

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 the first laser patent application 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

To analyze a phenomenon such as time to first laser patent application 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:

$$h_i(t, X_{it}, Z_i) = h_0(t)\ \exp(\beta' X_{it} + \theta' Z_i), \tag{1}$$

where $h_i\,(t, X_{it}, Z_i)$ 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 USA, 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) in the region; otherwise the observation takes the value of zero. The baseline hazard function is denoted by $h_o\,(t)$.

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; Jenkins 2005).

The complementary log–log model has the form:

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

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 in terms of the number of actors and its population density. This variable particularly controls for the number of potential researchers. It may also capture other effects such as the strength of local demand, the depth and specialization of the labor pool, and the quality of the supplier base and infrastructure.
- *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 and no = 0). This variable is included in order to test the second hypothesis, 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 according to the sixth hypothesis.
- *Patents in adjacent regions* $(t-1)$ is the one-year lagged number of patents with inventors located in adjacent regions and is included as a control for spatial autocorrelation.

The time-invariant variable *distance to Munich* is the average geographical distance of a region from Munich measured in kilometer. This variable tests our third hypothesis, 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. In some models, the distance to Munich variable is also included in its squared form in order to test for non-linearities.

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.[21] All models have been estimated with robust-cluster standard errors, which control for the clustering of observations at the regional level.

Table A1 in Appendix 1 presents descriptive statistics and correlations between variables are given in Table A2. The results for 'time to first patent' are set out in Table 1. For each model, the first column presents the estimated coefficients and 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.

The results of all models indicate that population has a highly significant positive impact on the likelihood of having a first laser patent. In other words, regions with a bigger population have a higher probability of experiencing the event sooner, which supports the first hypothesis. We find that geographic distance to Munich has a significant negative impact on the likelihood of having a first patent application in the field of laser technology. This suggests that geographic distance plays a significant role in the diffusion of laser technology and that regions located in close spatial proximity to Munich – the first center of German laser research – 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,[22] and we thus conclude that the evidence supports the third hypothesis. Although the values of the hazard ratios are close to 1, the magnitude of this effect is quite considerable. For instance, the value of the hazard ratio of 0.997 in the first Cox model (column Ib) given in Table 1 indicates that being located 10 km closer to Munich would have increased the probability of the rate of technology adoption by 3%.

We do not find a significantly positive effect for the university variable, indicating that regions with academic institutions in physics and engineering do not have a higher chance of having a first patent application than do regions without an academic institution in the relevant field. This result appears not to support the second hypothesis. There is, however, a multicollinearity problem due to the close correlation between the university variable and the number of population. If the number of population is excluded from the model, then the university variable becomes highly significant what is in accordance with the second hypothesis. The exclusion of the population variable may, however, lead to a severe omitted variable problem, particularly to overestimation of the effect of universities in the region.[23]

The presence of one or more laser producers in the region also has no significant positive impact on the likelihood of first patent. A possible explanation for this result could be that most of the laser source producers entered the market many years after the event of a first laser 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. 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 IIa for Cox and column IIIa for the complementary log–log) although the

Table 1. Estimations for the time-to-first laser patent, 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	0.332	1.393	0.378	1.460	0.307	1.359	0.362	1.436
	(0.267)	(0.372)	(0.269)	(0.393)	(0.284)	(0.386)	(0.286)	(0.411)
Producer	0.790	2.204	0.758	2.133	0.750	2.117	0.767	2.154
	(0.598)	(1.318)	(0.571)	(1.217)	(0.655)	(1.387)	(0.641)	(1.381)
Population (ln)	0.928***	2.530***	0.977***	2.655***	1.053***	2.866***	1.124***	3.076***
	(0.220)	(0.556)	(0.221)	(0.586)	(0.234)	(0.669)	(0.238)	(0.731)
Number of patents in neighboring regions ($t-1$)	−0.011	0.989	−0.021	0.979	−0.009	0.991	−0.019	0.981
	(0.018)	(0.018)	(0.021)	(0.020)	(0.018)	(0.018)	(0.019)	(0.019)
Distance to Munich (km)	−0.003***	0.997***	−0.006**	0.994**	−0.003***	0.997***	−0.007***	0.993***
	(0.001)	(0.001)	(0.003)	(0.003)	(0.001)	(0.001)	(0.003)	(0.003)
Distance to Munich (km)^2			0.000	1.000			0.000*	1.000*
			(0.000)	(0.000)			(0.000)	(0.000)
Time dummies	No	No	No	No	Yes***	Yes***	Yes***	Yes***
Number of observations	1310		1310		1310		1310	
Number of regions	74		74		74		74	
Log likelihood	−227.4		−226.6		−239.9		−238.8	
Pseudo R^2	0.067		0.070		0.103[a]		0.107[a]	

Note: Robust−cluster standard errors in parentheses.
[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.
*Statistically significant at the 10% level.
**Statistically significant at the 5% level.
***Statistically significant at the 1% level.

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 patents applications

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 patent applications by inventors residing in a region as indicator for research output. The model has the form:

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

The dependent variable is the regional level of laser research as measured by the local number of patent applications. In addition to the explanatory variables already used to explain the first adoption of laser research, we include the *year of first regional laser patent* in testing the fourth hypothesis, in which we speculate 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 patenting activity on laser technology in Germany and 2005 as the end year. Regions that saw their first patent in 1961 are assigned the highest value – 45 years – and regions with their first patent in a later year are assigned decreasing values.[24] ζ_i represents the regional fixed effect and ε_{it} is the usual error term. Tables A3 and A4 in Appendix 1 present the descriptive statistics and correlations.

Our data constitute a balanced panel with yearly information from 1961 to 2005 for every region.[25] The dependent variable is whole numbers with positive values and can be regarded as the result of a Poisson-like process. We employ negative binomial regression as the estimation method because it is based on more general assumptions than the Poisson regression.[26] In particular, it allows for overdispersion (i.e. a level of the variance of the data that is much larger than the value of the mean) that is present in our data. We employ two main estimation approaches. First, panel data analysis is applied to exploit the time-series character of our observations. However, since some of the variables in our data-set 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 for the completely time-invariant variables years since first laser patent and distance to Munich. Therefore, we run random effects models and estimate robust standard errors by a bootstrapping method (Cameron and Trivedi 2009).[27]

Because many regions have never engaged in laser research or have conducted laser research only sporadically, our dependent variable may have ‘too many zeros’, which would imply a violation of the distribution assumptions of the estimation procedure (Hilbe 2007).[28] 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 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 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’ category. Based on this classification, the negative binomial model according to Equation (3) is estimated in the second step, predicting the counts for those regions that are not certainly zero (Hilbe 2007). For the logit models of the first step, 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.[29]

The results in columns I and IV in Table 2 show that the effect of academic institutions is only statistically significant in the zero-inflated negbin model. With respect to the effect of a laser source producer in the region, it has a significant positive effect on the number of patents in both the random effects and zero-inflated negbin models (columns I and IV in Table 2). Hence, the sixth hypothesis, which states that regions with producers of laser technology will have higher levels of research output, is confirmed.

To test the fourth hypothesis, 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 since first laser patent in the region*, 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.

The results given in columns II and V in Table 2 suggest that regions that engaged in laser research relatively early tend to have more laser patents in later years. In both models, the count of years since the first laser patent increases the likelihood of having more 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. Therefore, we find support for the fourth hypothesis. Regarding the effect of geographic distance to Munich, the result is similar to that found previously in that we find a significant negative effect on the amount of laser research. The regional population, which can be viewed as the pool of potential inventors, has a significantly positive effect in all models and specifications (Table 2). Furthermore, the significantly positive coefficients for population when controlling for other relevant variables such as the years since first patent (columns II and V in Table 2) also suggest that the laser technology research has diffused faster in large agglomerations than in rural areas supporting the fifth hypothesis.

In order to assess the relative strength of the influence of the variables *population* and *years since first patent*, we calculated the incidence rate ratios for the negative binomial model. Incidence rate ratios indicate the increase of the value of the dependent variables for a one-unit increase of the value of the independent variable, given that all other variables in the model are held constant. The *population* variable (Table 2, column II) has an incidence rate ratio of 1.329 (statistically significant at the 5% level) indicating that the number of patent applications would be 33% higher if the logged value of the number of population would increase by one. The incidence rate ratio of the number *of years since first patent* (Table 2, column II) is 1.060 (significant at the 1% level). Accordingly, one year more

Table 2. Effect of early adoption of laser technology research on number of regional patents, 1961–2005.

	Random effects			Zero-inflated negative binomial		
Variables	(I)	(II)	(III)	(IV)	(V)	(VI)
University	0.212	0.290	0.351*	1.013***	0.861***	1.301***
	(0.183)	(0.184)	(0.200)	(0.103)	(0.100)	(0.094)
Producer	0.314**	0.298**	0.316**	0.682***	0.104	0.207*
	(0.150)	(0.144)	(0.154)	(0.112)	(0.107)	(0.108)
Population (ln)	0.586***	0.285**	–	1.109***	0.822***	–
	(0.222)	(0.133)		(0.087)	(0.084)	
Number of patents in neighboring regions	−0.024**	−0.024***	−0.025***	0.005	−0.021***	−0.026***
	(0.009)	(0.007)	(0.008)	(0.006)	(0.006)	(0.006)
Distance to Munich (km)		−0.001**	−0.001**		−0.009***	−0.009***
		(0.001)	(0.001)		(0.001)	(0.001)
Years since first regional laser patent		0.058***	0.065***		0.036***	0.049***
		(0.009)	(0.008)		(0.005)	(0.005)
Time dummies	Yes***	Yes***	Yes***	Yes***	Yes***	Yes***
Federal State dummies	No	No	No	Yes***	Yes***	Yes***
Constant	−8.690***	−6.373***	−2.824***	−17.371***	−9.605***	1.081**
	(3.029)	(1.662)	(0.483)	(1.222)	(1.206)	(0.531)
Inflate						
Producer_count				−2.213*	−14.391	−3.767
				(1.262)	(809.633)	(5.382)
Constant				−1.385***	−1.674***	−1.254***
				(0.390)	(0.399)	(0.276)
Ln alpha				0.454***	0.129	0.183*
				(0.104)	(0.098)	(0.100)
Number of observations	3256	3256	3256	3256	3256	3256
Number of regions	74	74	74	74	74	74
Log likelihood	−2761	−2721	−2724	−3016	−2830	−2879
Pseudo R^2	0.052	0.065	0.065	0.132	0.185	0.171

Note: Standard errors in parentheses.
*Statistically significant at the 10% level.
**Statistically significant at the 5% level.
***Statistically significant at the 1% level.

time since the first patent application is related with a 6% increase of the number of patent applications in the regions. The incidence rate ratio of 0.999 (significant at the 5% level) for the *distance to Munich* indicates that this effect is considerably smaller than in the models for the time to first laser patent (Table 1).

The number of patents 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. Joint significance of the Federal State dummies, however, suggests that there are some similarities among regions located in the same Federal State (Table 2).

To shed more light on these relationships, we estimated alternative specifications. Because the size of population is highly correlated with other indicators, such as the university dummy, we performed regressions excluding the regional population (columns III and VI in Table 2). If the regional population is not contained, the university variable becomes slightly significant in the random effects model (column III in Table 2), suggesting that academic organizations may play an important role in regional patenting activity.

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 (Hall, Jaffe, and Trajtenberg 2001, 2005; Harhoff et al. 1999; Trajtenberg 1990). It is well-known that the distribution of citations per patent is highly skewed and that a significant number of patents receive no citations at all (Hall, Jaffe, and Trajtenberg 2001). Based on the information on all patent citations up to the year 2010, we take as a threshold the number of citations received by the upper decile of the distribution, which are 11 forward citations. Therefore, we classify a patent as being of high quality if it has received at least 11 forward citations and consider only the 10% of patents (321 patents) meeting this requirement. Spatially, seven regions are responsible for about 60% of all highly cited patents: Munich, again, leads with 23%, followed by Stuttgart (13%), Goettingen (7%), Regensburg (6%), and Erlangen/Nuremberg, Aachen, and Rhein-Main/Frankfurt with 4% each. The applicant with the largest number of highly cited patents is *Siemens*, with 86 patent applications (27% of all highly cited patents), which accounts for about 10% of all *Siemens*' applications in the IPC H01S.

The patents filed in the years 1961–1980 garner only 24% of all the observed citations; those applied for between 1981 and 2000 account for 71%. The patents from 2001 to 2005 are responsible for only 4% of the total citations, probably a right truncation effect due to the fact that patents do not usually receive citations immediately. Although in general the majority of the citations tends to occur within the first 10 years after application (Hall, Jaffe, and Trajtenberg 2001), the problem remains that we cannot observe the complete citation history of patents issued closer to the present. That is, for a patent applied for in 1961, we have a citation history of almost 50 years, whereas we have only five years of observation for a patent applied for in 2005. To solve this problem, we employ the methodology proposed by Hall, Jaffe, and Trajtenberg (2001, 2002) for estimating a model of citation frequency for each patent. We use these estimates to upwardly 'correct' the citation counts. Applying this method, we find that the upper decile of the citation distribution becomes 14 citations and we use this value for classifying a patent as 'highly cited'. The details of the correction model are presented in Appendix 2. For the following econometric analysis, we employ both the non-corrected and corrected counts and compare their results.

The regression results for the regional number of high-quality patents (Table 3) are similar to the results obtained for the overall number of patents, one difference being a more pronounced effect of the university dummy, which becomes weakly significant in the random effects models and remains strongly significant in the zero-inflated negbin model, regardless of whether the non-corrected or corrected citation counts are used. This supports the claim that academic organizations play an important role in regional patenting, particularly in the case of high-quality patents.

We also obtain consistent results for each model and specification with respect to the geographic distance to Munich. Being farther away from Munich is statistically negatively related with having highly cited patents, both under corrected and non-corrected citation measures (Table 3). Also in line with our expectations, the *year since the first laser patent*

Table 3. Explaining the regional number of high-quality patents (forward citations), 1961–2005.

	Random effects		Zero-inflated negative binomial	
Variables	(I) Non-corrected citations	(II) Corrected citations	(III) Non-corrected citations	(IV) Corrected citations
University	0.491*	0.576*	0.825***	0.978***
	(0.279)	(0.322)	(0.198)	(0.208)
Producer	0.717**	0.525*	0.167	−0.118
	(0.299)	(0.315)	(0.292)	(0.274)
Population (ln)	0.298	0.424	0.712***	0.657***
	(0.285)	(0.259)	(0.139)	(0.149)
Number of patents in neighboring regions	−0.019*	−0.019*	−0.008	−0.008
	(0.010)	(0.011)	(0.010)	(0.010)
Distance to Munich	−0.002**	−0.002**	−0.008***	−0.007***
	(0.001)	(0.001)	(0.001)	(0.001)
Years since first laser patent	0.045***	0.042***	0.025***	0.017*
	(0.016)	(0.015)	(0.009)	(0.009)
Time dummies	Yes***	Yes***	Yes***	Yes***
Federal States dummies	No	No	Yes***	Yes***
Constant	−6.098*	−8.519***	−10.016***	−9.795***
	(3.582)	(3.240)	(2.087)	(2.258)
Inflate				
Producer_count			−2.764	−1.931*
			(3.758)	(1.013)
Constant			−0.594	−0.043
			(0.720)	(0.513)
Ln alpha			−0.397	−0.185
			(0.353)	(0.342)
Number of observations	3330	3330	3330	3330
Number of regions	74	74	74	74
Log likelihood	−842.8	−814.0	−858.5	−841.9
Pseudo R^2	0.088	0.103	0.167	0.140

Note: Standard errors in parentheses.
*Statistically significant at the 10% level.
**Statistically significant at the 5% level.
***Statistically significant at the 1% level.

is positively related with the regional production of high-quality patents in every model and each specification (Table 3).

Regarding the remaining variables of presence of a producer in the region, the regional population, and neighboring patents we obtain mixed results. Having a laser source producer still has a significant positive impact only in the random effects model (columns I and II in Table 3). The effect of population size is no longer present in all models and remains only in the zero-inflated ones (columns III and IV in Table 3). The coefficient estimates for the number of neighboring patents are virtually the same whether corrected or non-corrected counts are employed and weakly negative significant under the random effects model (columns I and II in Table 3).

The incidence rate ratios for the negative binomial model under both specifications (i.e. non-corrected and corrected patent citations) indicate that one year more time since the first patent application would have increased the region's number of highly cited patents by 4.6% (uncorrected citations) and 4.2% (corrected citations). Although the incidence rate for the population variable indicates a relatively strong effect, it is not statistically significant at the 5% level. The ratio for the distance to Munich is 0.998 for both models (statistically significant at the 1% and at the 5% levels) indicating a relatively small effect.

6. Conclusions and interpretation

Following realization of the first workable laser in the USA in 1960, the new technology was adopted almost immediately in Germany. Obviously, the main avenue for knowledge diffusion at this stage was the first publication that described the respective experiment. The initial impulse for the German laser innovation system was the autonomous replication of the laser experiment by a young researcher working in the central laboratory of Germany's largest producer of electrical equipment, *Siemens*. This laboratory was located in Munich, one of Germany's largest cities with large private and public research facilities. The successful generation of a laser effect in its laboratory motivated the *Siemens* management 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 US 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 of public research institutes working in the field of laser technology in the region.

We identified a number of factors that play a role in the spatial diffusion of laser technology as measured by the number of patents. The results of our analysis clearly indicate the strong, if not dominant, role played by a region's size in terms of number of actors and its 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 German company better suited for early adoption of laser technology in the early 1960s than *Siemens*. Not only that, due to its size, the company had the necessary resources and was able to bear the risk of engagement in the newly emerging technology. *Siemens* was also a supplier and doing R&D in a number of related technological fields. This may have been conducive to recognize the potentials of the new technology ('cognitive' proximity) and may have raised hopes of using it for further developments of these related products.

Because large firms tend to have their laboratories 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. 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 laser technology in agglomerations. 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 the *Siemens* company, for example, occurred without any transfer of technology-specific tacit knowledge but was based on the standard knowledge of a physicist and a publication in which the relevant experiment was described. If tacit knowledge was at all significant for the adoption of laser research at later stages of the development of the technology, this might be reflected by the geographic proximity to the center of early laser research in West Germany, Munich, which may indicate the sensitivity of researcher's mobility to geographic distance. The effect of the 'distance to Munich' variable on early adoption was, however, very small (Tables 1 and 2). Our analysis clearly suggests that other factors are much more important in this respect than geographic distance. This is underlined by the finding that the level of laser research in adjacent regions never had a statistically significant positive effect.

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 patents, we 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. We found that when controlling for time since first laser patent, regions with a relatively large population indeed tend to have more research output in the field of laser technology. The reason for such a faster intraregional diffusion may, however, simply be that these regions have more firms, more researchers, more and bigger universities, and more public research facilities than do smaller regions.

The importance of a region's size in terms of population clearly suggests that large agglomerations have an advantage over smaller cities and rural regions with regard to absorbing new knowledge and entering new technological fields. It is, however, not only the size of a region but also the absorptive capacity and innovativeness of regional actors that are important in this respect. Obviously, universities and innovative large firms play an important role here. In the case of early adoption of the *Siemens* company, it may also have been important that this firm was active in a number of related technological field suggesting a role of related variety and cognitive proximity (Boschma 2005; Frenken, van Oort, and Verburg 2007).[30] Although there is clearly a pronounced stochastic element involved in the diffusion of new knowledge[31], there are rather clear spatial patterns of this process and the likelihood of a region to be among the early adoptors. All in all, our results suggest that early adoption of research in a new technological field in a region particularly depends on the number of innovative actors with a high absorptive capacity for the respective technology. Fortune tends to favor the prepared firms and regions! The key role of the *Siemens* company for early research in laser technology shows the importance of firm size and diversification. Obviously, there exist clear advantages of a large hub as compared to networks of (small) firms and industrial district type clusters in this respect. Moreover, the presence of public research in related fields was important for starting research in this science-based technology.[32]

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 in the central laboratory of the *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.

Another question for further research is if the same patterns can be found for research in new technologies that represent a less radical change with lower levels of uncertainty about commercial applications. It may well be that the size of firms and regions come out to be less important in such cases.

Notes

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2. The most relevant fields of engineering for laser technology research are electrical engineering, high-frequency engineering, as well as information and communication technology.
3. Producers of laser beam sources did indeed conduct a large share of the research and applied for about 53% of German patents in the IPC class H01S. Taking also into account private firms that did not supply laser beam sources, this share amounts to about 78%.
4. One industry that has been of considerable importance for laser applications in the German context was mechanical engineering. Empirically, the distinction between suppliers of laser sources and users in the early stages of the German laser industry is somewhat fuzzy. Buenstorf, Fritsch, and Medrano (2012) provide evidence that most of the producers of laser sources diversified downstream at some time by supplying whole laser systems for certain applications such as mechanical engineering, measurement, etc. Also some of the producers of laser systems that first purchased the laser sources on the market started to develop and manufacture beam sources themselves. A main motivation for such a diversification upstream was that these firms wanted laser sources that were better suited for their specific needs than those available on the market.
5. For considering the patent applications that may have taken the Patent Cooperation Treaty route, we have further consulted the STN database (www.stn-international.de).
6. These sources are the *Bibliographische Mitteilungen der Universitätsbibliothek Jena, 1960–1971* (Universitätsbibliothek Jena 1972).
7. However, for historical reasons, the cities of Bremen/Bremerhaven, and Hamburg are planning regions without surrounding districts.
8. Having functional regions is particularly advantageous for the regional assignment of inventors. As stated above, we locate inventors by their place of residence that is in most cases not where the respective research is performed. At the rather small-scale level of districts to assign inventors to the region where they reside would lead to mistakes if the respective laboratory would be in a different district. At the level of planning regions this problem is negligible. In our analysis, we do not account for any address changes that could be detected in the patent statistics in the case that an inventor has filed another patent at a later point of time for two reasons. First, such a 'correction' of the regional knowledge base could only be done for those inventors that have filed other patents. Second, the level of interregional mobility that can be detected from the patent statistics is rather low and the results are in no way sensitive to this kind of mobility.
9. See German Federal Office for Building and Regional Planning (2003) for the definition of planning regions and districts.
10. 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*adiation (Bertolotti 2005; Röss 1969).

11. The information on the early adoption of laser technology research by *Siemens* is largely based on Albrecht (1997) and on personal conversation with Dieter Rößs, who was the first to realize a laser in Germany.
12. In terms of inhabitants, the Munich region was somewhat smaller than West Berlin but can be regarded as having had better preconditions for laser technology adoption because private firms avoided locating important research facilities in West Berlin due to the city's precarious political-geographic situation. Chiefly for this reason, *Siemens* relocated its main administrative and research facilities to Munich and to Erlangen after World War II.
13. Analytical knowledge is largely based on formal models and codified science so that its communication requires much less transfer of related tacid knowledge as is the case for 'synthetic' knowledge that is more based on experience. See Asheim and Gertler (2005) for a more detailed description of the two types of knowledge base.
14. The number of patent applications 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.
15. In the first three years (1961–1964), *Siemens*' share of all German patent applications in the field of laser technology amounted to about 72%.
16. 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 its Munich laboratory.
17. 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 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% 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 patents in their own names is also small (3.25%) during that period.
18. For the development of the German market for laser beam sources, see Buenstorf (2007).
19. In 1978, *Siemens* finalized its acquisition of the *Osram* company, which in the 1990s begun to conduct research on laser beam sources in Regensburg and also became a producer.
20. That we approximate the regional diffusion of research by the event of patent applications leads to certain limitations that are well recognized in the literature (see, Griliches 1990). Six regions did not have any patent application until 2005 but may have patented afterwards.
21. 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.
22. 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 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.
23. Running models with one of the two variables only, we find a considerably stronger effect for the number of population.
24. For instance, if a region had its first patent application in 1971, it is assigned the value of 35. If a region has its first patent in 2005, the value is 1. In the case of no patent applications at all, the value is 0.

25. 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.
26. For a more detailed description of these estimation methods, see also Greene (2008, 909–912).
27. For fixed effects estimations, see Table A5 in Appendix 1.
28. The share of zero cases is 73% of all observations.
29. 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.
30. Unfortunately, data about industry structure of the regional firm population are not available for the period under inspection so that the effect of related variety cannot be tested systematically here.
31. There are 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 IPC H01S in the year 1973.
32. Public policy did not play any significant role in the early development stages of laser technology in Germany. For a detailed assessment of innovation policy in the field of laser technology in Germany, see Albrecht (1997) and Fabian (2012).
33. Specifically, when obsolescence is the same across different fields and diffusion is allowed to vary, the estimated value of β_1 is 0.104. When the diffusion is taken as similar for different technological fields and depreciation is allowed to vary, their estimate of β_2 is of 0.436 (Hall, Jaffe, and Trajtenberg 2002, 445).
34. Such conditions are also present in a former study from Jaffe and Trajtenberg (1999) that uses a much larger of covariates including also the geographical information of both the potentially cited patent and the potentially citing patent.

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Appendix 1

Table A1. Descriptive statistics: event – first patent.

Variable name	Mean	Median	Minimum	Maximum	Standard deviation	Number of observations
First patent	0.052	0.000	0.000	1.000	0.222	1310
University	0.291	0.000	0.000	1.000	0.454	1310
Producer	0.028	0.000	0.000	1.000	0.166	1310
Population (ln)	13.190	13.097	12.450	14.915	0.501	1310
Number of patents in neighboring regions	3.394	1.000	0.000	50.000	7.779	1310
Distance to Munich (km)	490.079	504.421	0.000	892.560	229.634	1310

Table A2. Correlation table: event – first patent.

Variables	1	2	3	4	5	6
(1) First patent	1.000					
(2) University	0.100*	1.000				
(3) Producer (yes/no)	0.043	0.175*	1.000			
(4) Number of patents in neighboring regions	0.011	−0.077*	−0.032	1.000		
(5) Population (ln)	0.111*	0.434*	−0.052	−0.158*	1.000	
(6) Distance to Munich (km)	−0.077*	−0.022	0.089*	−0.496*	0.051	1.000

*Statistically significant at the 5% level.

Table A3. Descriptive statistics.

Variable name	Mean	Median	Minimum	Maximum	Standard deviation	Number of observations
Patents	0.897	0.000	0.000	47.000	3.272	3330
University	0.519	1.000	0.000	1.000	0.500	3330
Producer (yes/no)	0.186	0.000	0.000	1.000	0.389	3330
Producer_count	0.330	0.000	0.000	16.000	1.046	3330
Population (ln)	13.430	13.278	12.450	14.915	0.581	3330
Number of patents in neighboring regions	5.085	2.000	0.000	50.000	8.226	3330
Distance to Munich (km)	432.034	428.531	0.000	892.560	228.405	3330
Years since first patent	28.216	31.000	0.000	45.000	14.040	3330
Highly cited patents in the region (non-corrected), $\geq$ 11 citations	0.110	0.000	0.000	7.000	0.482	3330
Highly cited patents in the region (corrected), $\geq$ 14 citations	0.103	0.000	0.000	7.000	0.451	3330

Table A4. Correlation table.

Variables	1	2	3	4	5	6	7	8	9
(1) Patents	1								
(2) University	0.201*	1							
(3) Producer (yes/no)	0.292*	0.277*	1						
(4) Producer_count	0.533*	0.220*	0.660*	1					
(5) Population (ln)	0.304*	0.536*	0.309*	0.326*	1				
(6) Number of patents in neighboring regions	0.02	−0.104*	−0.003	0.026	−0.131*	1			
(7) Distance to Munich (km)	−0.242*	0.011	−0.033	−0.125*	0.060*	−0.518*	1		
(8) Years since first patent	0.222*	0.328*	0.264*	0.235*	0.455*	0.104*	−0.326*	1	
(9) Highly cited patents in the region (non−corrected), ≥ 11 citations	0.661*	0.154*	0.245*	0.35*	0.226*	0.019	−0.164*	0.172*	1
(10) Highly cited patents in the region (corrected), ≥ 14 citations	0.646*	0.159*	0.233*	0.348*	0.208*	0.039*	−0.154*	0.152*	0.920*

*Statistically significant at the 5% level.

Table A5. Estimation of the regional number of patents, 1961–2005.

	Fixed effects	Random effects	Zero-inflated negative binomial
Variables	(I)	(II)	(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)
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*** (0.104)
Ln alpha			0.454*** (0.390)
Number of observations	2992	3256	3256
Number of regions	68	74	74
Log likelihood	−2447	−2761	−3016
Pseudo R^2	0.055	0.052	0.132

Note: Standard errors in parentheses.
*Statistically significant at the 10% level.
**Statistically significant at the 5% level.
***Statistically significant at the 1% level.

Appendix 2

Hall, Jaffe, and Trajtenberg (2001, 2002) propose a method for solving the problem of truncation in patent citation data. Building on a former model of Caballero and Jaffe (1993) and Jaffe and Trajtenberg (1996), they model citation frequency as the likelihood that any patent applied for in year t (citing patents) will cite a patent applied for in year s (cited patents). They assume that citation is determined by the combination of an exponential process by which knowledge becomes obsolete, a second exponential process by which knowledge diffuses, and finally by the specific effects coming from different technology fields, citing years, and cited years (Hall, Jaffe, and Trajtenberg 2001; Jaffe and Trajtenberg 1999). Their citation frequency model is as follows:

$$\frac{C_{kst}}{P_{ks}} = \alpha'_o \alpha'_s \alpha'_t \alpha'_k \exp(f_k(L)), \tag{A1}$$

where C_{kst} is the total number of citations to patents in year s and technology k coming from patents applied for in year t. P_{ks} is the total of patents observed in technological field k in years s. Their ratio is the average number of citations received by each s patent from the total of patent counts in year t. This citation frequency is modeled as a multiplicative function of several cited year (s), citing year (t), technology field (k), and citation lag ($L = t - s$) effects. The citation lag L is the years between the application year of the citing patent (t year) and the application year of the cited patent (s year). The function $f_k(L)$ represents the citation-lag distribution, which in Hall, Jaffe, and Trajtenberg (2001, 2002) is modeled as:

$$f_k(L) = \exp(-\beta_{1k}L)(1 - \exp(-\beta_{2k}L)). \tag{A2}$$

The parameter β_{1k} captures the obsolescence or depreciation of knowledge, while β_{2k} reflects the diffusion of knowledge. The summation of $f_k(L)$ over L is normalized to unity. Hall, Jaffe, and Trajtenberg (2001, 2002) estimate such model by non-linear least squares, and group the cited years in five-year intervals, reflecting their assumption that 'the true fertility of invention changes only slowly' (Hall, Jaffe, and Trajtenberg 2002, 443).

We choose a simpler version of their model given that we focus on only one main technological field. Furthermore, the cited-year and citing-year effects are included in an additive way to make the estimation feasible. Our model is:

$$\frac{C_{st}}{P_s} = \alpha_o^* \exp(-\beta_1 L)(1 - \exp(\beta_2 L)) + \alpha_s + \alpha_t + e_{st} \tag{A3}$$
$$s = 1961, \ldots, 2005;\ t = 1964, \ldots, 2010.$$

Year dummies are included to control for possible effects due to the increased number of citations made per patent and the increased number of citing patents. We also grouped the cited years into five-year intervals, while the citing years are included separately. We estimate Equation (A3) with non-linear least squares and employ cluster-robust standard errors grouping at the level of assignee. In this way, we aim to control for the fact that patent applications from the same assignee are not independent observations.

The choice of starting values is very important in non-linear least square estimation and any good information about them should be used (Greene 2008, 293). For the initial values of the parameters β_1 and β_2, we take the estimates from Hall, Jaffe, and Trajtenberg (2001, 2002). These studies provide the most reliable information in this respect, even though they use US patent citation data (i.e. the NBER Patent Citations File). Their coefficients for the diffusion and obsolescence processes, when one is allowed to vary across different technological fields and the other remains constant, are smaller than 1 and their addition is also below unity.[33] From such estimates we derived the following conditions for initial values: (i) a positive number between 0 and 1 and (ii) numbers whose addition is below unity.[34]

The estimated β_1 and β_2 from Equation (A3) are used for constructing the expected distribution of the citation lags after controlling for the citing-year and cited-year effects. From such cumulative distribution we derive upward correcting coefficients, which are given in the first column in Table A6. As a comparison, the second column presents the results from Hall, Jaffe, and Trajtenberg (2002) for their technological field 'electrical and electronic', which is the closest one to the laser source technology. The two estimates are fairly similar.

These coefficients can be used to adjust the total citation count for each patent. Take, for instance, two patents with five citations each, one applied for in 1961 and the second in 2001. The first patent can be observed until its final 49th year lag of the citation-lag distribution (2010 – 1961 = 49); that

Table A6. Simulated cumulative lag distributions – comparison with the NBER Patent citations data's estimates.

Lag (years)	Laser source patent citation data[a]	NBER Patent citation data, technological field 'electrical and electronic'[b]
1	0.043	0.048
2	0.109	0.115
3	0.183	0.187
4	0.259	0.259
5	0.332	0.327
6	0.401	0.390
7	0.465	0.448
8	0.522	0.502
9	0.575	0.550
10	0.622	0.594
11	0.664	0.635
12	0.701	0.671
13	0.735	0.705
14	0.765	0.735
15	0.791	0.763
16	0.815	0.788
17	0.836	0.811
18	0.855	0.832
19	0.871	0.851
20	0.886	0.868
21	0.899	0.884
22	0.911	0.898
23	0.921	0.911
24	0.930	0.923
25	0.938	0.934
26	0.946	0.943
27	0.952	0.952
28	0.958	0.960
29	0.963	0.968
30	0.968	0.975
31	0.972	0.981
32	0.975	0.986
33	0.978	0.991
34	0.981	0.996
35	0.984	1.000
36	0.986	
37	0.988	
38	0.990	
39	0.991	
40	0.993	
41	0.994	
42	0.995	
43	0.996	
44	0.997	
45	0.998	
46	0.998	
47	0.999	
48	1.000	
49	1.000	

[a]Cited years run from 1961 to 2005 and citing years from 1961 to 2010. Own estimation.
[b]Source: Hall, Jaffe, and Trajtenberg (2002, 450). Cited years run from 1963 to 1999 and citing years from 1975 to 1999.

is, its citation history up to 2010 equals its expected 'life-time' citation count in Table A6. However, the second patent, applied for in 2001, can be observed only until its 9th lag from the complete 49 'life-time' citation lag distribution (2010 – 2001 = 9). The correcting coefficient estimates that a 'typical' laser source patent is expected to obtain approximately 57% of its 'life-time' citations nine years after its application. Therefore, in order to correct the total citation counts, we 'deflate' these five citations by the coefficient 0.575, which gives an upward corrected total count of 8.7 citations.