Under the Lens: The Geography of Optical Science as an Emerging Industry

Maryann P. Feldman
209 Abernethy Hall
CB 3435
University of North Carolina at Chapel Hill
Chapel Hill, NC 27599
maryann.feldman@unc.edu

Iryna Lendel
Center for Economic Development
Cleveland State University
2121 Euclid Avenue, UR 354
Cleveland, OH 44115-2214
i.lendel@csuohio.edu

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abstract

Optical science is the study of light and the ways in which light interacts with matter. Although its origins coincide with the earliest scientific inquiry, modern optics is an enabling technology that is applied to a variety of intermediate markets—telecommunication equipment, medical devices, scientific instruments, semiconductors, imaging and reproduction, defense and security, and retail logistics. One difficulty in studying emerging technology is the limitation of current industrial categories and patent classes. This article examines the geography of optical science inventions using a new methodology that can be applied to study other emerging industries. We rely on companies that self-identify as working on optics on the basis of their voluntary membership in the Optics Society of America. We investigate the inventive activity of these companies from 2004 to 2007 and identify a set of International Patent Classes that defines the emergent technology space in optical science. Using this definition, we then analyze all the organizations that are inventing in optical science. We find that inventive activity is geographically concentrated: patenting takes place in 240 urban areas, although 84 percent of the patents were invented in 30 metropolitan areas and almost 50 percent were attributed to 11 metropolitan areas. The article considers the organizations that are shaping the emerging technology and the consequences for geographic clusters. Our results reveal that the geographic distribution of inventive activity does not reflect the location of self-designated regional optics clusters in the United States but suggests a more nuanced understanding of the emergence of industries. We conclude by considering lessons about the development of clusters in emerging industries.

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There is great academic and policy interest in identifying and tracking emerging technologies and industries. New industries, which combine knowledge in new and novel ways, are associated with innovation and entrepreneurial activities. What is most important, emerging industries provide the platform for future economic growth. The gales of innovation and technological change that Schumpeter (1911) colorfully described as driving economic growth are due, in large part, to the emergence of new technology and the evolution of industrial activities. Most notably, emerging industries tend to cluster spatially as advantages accrue to those at the locus of creative activity and opportunity.

By their very nature, emerging industries do not fit neatly into existing classification schemes, however. We are constantly looking at categories that described past activity while trying to predict and anticipate the future. With existing data, there is simply no good way to identify emerging industries. Thus, our ideas of emerging industries amount to the usual suspects that have been favored with extensive media coverage: biotechnology, nanotechnology, and dot-com firms. Although consequential, these industries are likely atypical, and our understanding of technological change—specifically how new industries emerge and their relationship to existing activity—would be greatly enhanced if we were to have a systematic quantitative method of identifying groups of firms that are engaged in similar new businesses or emerging industries. Moreover, there is little theory to assist places as they attempt to anchor new industries and harness their economic potential.

The purpose of this article is to provide an innovative look at the geographic and industrial anatomy of an emerging science-based industry. We use the example of the industrial applications of optical science, which arguably has characteristics of a general-purpose technology (Kodama 1992). Optics is the study of light and the ways in which light interacts with matter. Although its origins coincide with the earliest scientific inquiry, modern optical science is an enabling technology applied to a variety of intermediate markets—telecommunication equipment, medical devices, scientific instruments, semiconductors, imaging and reproduction, defense and security, and retail logistics. Known by various names, including optoelectronics and photonics, which may reflect the developmental stages of the technology, optical science is arguably a platform technology that is transformative in its economic effect, with a growth rate 3.5 times faster than other major technologies (International Society for Optical Engineering, SPIE 2006). One hundred and fifteen degree-granting academic programs in the United States are dedicated to optical science, and there are a large number of interdisciplinary institutes or focus areas in traditional academic departments. The optics industry is known to cluster spatially, especially around academic centers of excellence (Holton 2000), and case studies have provided the genesis of individual optics clusters (Hendry, Brown, and Defillippi 2000a; Sydow, Lerch, Huxham, and Hibbert 2007; Waits 2000). Little empirical work, however, has examined the range and geographic distribution of optical science applications. Moreover, many places are attempting to develop clusters that are related to optics, but there is a limited understanding of what contributes to the vibrancy of existing geographic concentrations for this specific industry.

The article is organized as follows. The next section discusses the theory related to the geographic clustering of economic activity, especially the reasons that are associated with the geographic clustering of inventive activity. So much has been written about industrial clusters over the past 10 years that it is perhaps more instructive to consider omissions in the literature, such as the lack of attention to how spatial concentrations of firms are differentiated and the relative paucity of understanding about how the existing structure of the industry influences the adaptation and potential to innovate further by incorporating breakthrough technology. The third section presents the case for studying optical science as an emerging industry and introduces a new methodology to define an emerging industry. The fourth section examines the geographic distribution of optical science, finding strong evidence of geographic concentrations of inventive activity with significant variation in place-specific industrial activity. The fifth section focuses specifically on what we define as self-designated clusters—places that are trying to define an identity and economic development strategy around the optics industry. The final section presents a summary and our conclusions.

The Geographic Context of Emerging Industries

An emerging industry is the fusion of a new technology with prior antecedent technologies. Specifically, emerging industries "blend incremental technical improvements from several previously separate fields of technology to create products that revolutionize markets" (Kodama 1992, 70). Examples include the growth of biomedicine, which introduced genetics into pharmaceuticals; nanotechnology, which incorporates molecular physics into material science; and new media, which blends the Internet, advances in digitization, and data management with communications. The more radical the combination, the more likely it is that a new industry will emerge with new suppliers, a new customer base, and fresh business models. These emerging industries provide new products, services, or processes that are the basis for productivity and economic growth.

Innovative industries, especially in the early stages of their life cycle, exhibit a pronounced tendency to collocate, and individual firms benefit greatly from the presence of other firms in their own industry (Audretsch and Feldman 1996). This fact has not gone unnoticed by policymakers. Martin and Sunley (2003) argued that the development of industrial clusters has emerged as the most prominent objective of economic development during the past decade, captivating a wide audience who seek some level of competitive advantage and future prosperity for a specific place. Emerging industries figure prominently in cluster-development efforts for two reasons. First, emerging industries are at an early stage in their life cycle, with a great potential for upside growth. Second, when an industry is in the emergent stage, no clear dominant place has already captured the activity; thus, it is possible for places to enter the competition and build a viable cluster around the emerging industry. Places that can accommodate the natural tendency of innovative industries to collocate will be in a better position to capture potential benefits. However, the potential benefits from proximity as well as collocation are likely to be mediated by the internal industrial dynamics and demography of firms within places. In addition, strategies of firms that affect openness, outsourcing of relationships, and attachment to the local area also affect opportunities for investments and innovation.

The concept of industry clusters is intertwined with the belief in the importance of knowledge spillovers (Krugman 1991). Unfortuantely, knowledge spillovers are often perceived to be limited to a concentration of similar firms in the same industry or a traditional Marshallian district. It is sometimes naively assumed that knowledge will automatically be shared and productivity will increase when firms are located in close geographic proximity. On the contrary, firms in the same industry have strong motivations to prevent proprietary knowledge from spilling over to their competitors, and there is little evidence of localized knowledge sharing and horizontal spillovers among firms in the same industry (e.g., Hendry and Brown 2006; Hendry, Brown, and Defillippi 2000b). Thus, a simple agglomeration of firms from the same industry may not be enough to induce the increased creativity and productivity that enhance innovation and economic growth. Indeed, the observed collocation of similar innovative firms can be conceptualized as an artifact of the formation of a successful cluster, rather than a determining force (see Braunerhjelm and Feldman 2007).

For the effective transfer of knowledge to take place, geographic proximity should be assessed in relation to other dimensions of cognitive, organizational, social, and institutional proximity (Boschma 2005). Perhaps the most important influence on geographic proximity is underlying technical commonalities or related variety (Boschma, Eriksson, and Lindgren 2008; Boschma and Iammarino 2009). Related variety is similar to the concept of Jacob's externalities or the relevant diversity between industrial activities that would create the transfer of ideas and spawn innovation (Feldman and Audretsch 1999). Certainly, much discussion of agglomeration economies has focused on industry localization, which may represent a production orientation or reflect the mature stage of an industrial life cycle. Neither of these factors would be associated with new ideas and novelty.

Current thinking places great importance on the role of universities in technology-based economic development. Universities are important venues for exploration and discovery, producing scientific breakthroughs that often provide the basis for new technologies (Wolfe 2005). However, the presence of universities is not a sufficient condition for the development of clusters (Feldman and Desrochers 2003). Despite the well-known examples of Silicon Valley and Route 128, most universities have had a limited direct impact on local economic development. Although universities are able to generate ideas and engage in transactions to transfer technology, much of the process of commercializing technology and realizing the subsequent benefits is beyond their control (Bania, Eberts, and Fogarty 1993). Successful innovation requires the active and continuous involvement of commercial firms. Thus, while universities may aid in the initial development of a technology, the subsequent growth of an emerging industry is a subsequent, distinct process.

Emerging industries are often associated with entrepreneurship; however, to have a significant impact, a technology should also increase productivity across a range of existing companies. An important path of cluster development for emergent activity results from large firms not only acting as incubators of ideas and potential entrepreneurs but also acting as customers. In this manner, large existing firms act as anchors for ideas.

The preexisting industrial structure may dictate the way in which new technology is implemented: the resulting technical specializations and business models that are adopted may mimic local conditions. Related variety may offer a vehicle for the evolution of technology within the confines of enduring place-bound institutions (Grabher 2002). Thus, a region's existing industrial structure may determine its ability to develop and sustain an emerging industry. However, theories of technology-based economic development frequently do not incorporate a role for large, established firms or recognize the power relationships that may exist among different firms in the same place and industry (Christopherson and Clark 2007b).

The dynamics of competition and collaboration between different types of organizations will certainly have an impact on regional growth. Christopherson and Clark (2007a) found that although all firms operate in a global marketplace, larger firms dominate end-product markets, and small firms generally operate in intermediate product markets. The result is that "they are in direct competition primarily in input markets for skilled labor and research and development capacities within regions" (Christopherson and Clark 2007a, 63). The mix of ecologies, organizational dynamics, and strategies of firms that is most suitable for economic development in particular regional contexts has received little attention in the literature. Moreover, emerging industries that serve consumer markets are often the most visible focus for economic development policy. Equally important and often overlooked are intermediate producer goods that serve industries as intermediate inputs into goods and services for final consumers.

There are different typologies of clusters that consider the structural characteristics of places. Markusen (1996) provided a compelling typology of industrial clusters that is predicated on distinctiveness in the local economy. One of the most dynamic types of clusters is the *hub-and-spoke district,* with an industrial structure dominated by one large firm or a small number of large firms. Such a cluster is vertically integrated, with suppliers trading with the hub firm in the cluster as well as outside the cluster. The vertical integration of a cluster suggests that the most vibrant industrial clusters for producer platform inventions may occur with a diversified industrial structure when firms share knowledge through vertical supply-chain relationships and have external linkages outside the region. Held (1996) considered that clusters may be based on the integration of a supply chain, with strong interrelationships among firms. This integration implies that supply-chain relationships would suggest ideas for new products and processes, an idea that is congruent with von Hippel's (1989) idea of user-induced innovation.

Places are, of course, different in terms of their size, position in the urban hierarchy, and industrial structure. Yet these nuances are typically not appreciated in the literature on clusters. Certain places are likely to be the loci of inventive activity because they are large and diversified urban centers, benefitting from urbanization economies that are associated with the size of places. We expect that there are likely to be different types of places, reflecting location-specific characteristics that give rise to and support an emerging industry. Holding industry constant, we expect that inventive activity will emerge in different types of places, each with a specific industrial structure and ability to foster the emergent industry. Of course, the question arises as to how and why the existing industry structure developed.

Although there is great academic and policy interest in identifying and tracking emerging industries, emerging industries, by their very nature, do not fit neatly into existing classification schemes, making them difficult to identify and study. In retrospect, given the fullness of time, the impact of an emerging technology may be evaluated (Helpman 1998; Rosenberg and Trajtenberg 2004; Crafts 2004; Lipsey, Carlaw, and Bekar 2005). Ideally, however, we would like to identify emerging industries contemporaneously at an early stage of their development. Instead, researchers have often focused on industries that have received extensive media coverage, such as biotechnology or nanotechnology (Zucker, Darby, and Armstrong 1998, 2002; Robinson, Rip, and Mangematin 2007; Zucker et al. 2007). Although consequential, these industries are likely to be atypical because of attention from the media and investors. The understanding of how industries emerge would be enhanced with a systematic quantitative method of identifying groups of firms that are engaged in similar new technologies.

Defining Optical Science as an Emerging Industry

Optics is a branch of physics that is concerned with the properties of light and the interaction of light with matter. Optical phenomena have fascinated scientists beginning with Aristotle and Ptolemy and moving forward to Newton and Maxwell. A major modern breakthrough came in 1960 with the invention of the laser, which made possible a variety of applications in fiber-optic communications, optical data storage, laser surgery, and materials processing. The laser alone is considered one of the most significant technological developments of the twentieth century (Bromberg 1991). Catts, Likins, and Wright (1999, 3) highlighted the dynamism of optics and noted that "the field encompasses a range of physical and digital technologies that are loosely associated with their basis in light and its application and manipulation to perform useful tasks." Optical science, the pure science aspects of the field of study, is an integral part of a wide range of scientific disciplines and was a key contributor to economically important applications in many areas (National Research Council 1998). Key optics technologies are lasers, fiber optics, liquid crystal displays, and infrared sensing systems (ACOST 1988). More recent optics activity has focused on optical bioimaging and biomarkers using nanotechnology (Farkas 2003; Haes, Chang, Klein, and Van Duyne 2005). Wiggins (2008) indicated that aerospace/defense, automotive, bioindustry, environmental technology, and industrial controls are industries that are closely associated with optics in Arizona.

Perhaps one of the most significant problems in studying optics is the diffused nature of its application and the large number of industries that use optical science technologies as an input. First and foremost, there is no generally accepted definition, and a plethora of alternative names are used: optics, electra-optics or optoelectronics, and photonics. The term *optics* conjures images of lenses and eyeglasses and perhaps cameras—certainly not the knowledge-intensive industries that characterize modern optics. The generic term *optoelectronics* refers to a new technology that has grown out of converging optical and electronic techniques (Organization for Economic Cooperation and Development 1993, 47). Optoelectronics has been defined as "the integration of optical and electronic techniques in the acquisition, processing, communication, storage and display of information" (ACOST 1988). *Photonics* specifically involves the intersection of photons or particles of light with electrons or particles of electricity (Kaounides 1995). Despite this precision in definition, the term is seen as too limiting to capture industrial activity (National Research Council 1998). Given the ambiguity in definition, which reflects the evolving nature of the industry, the Standard Industrial Classification (SIC) Codes and North American Classification System (NAICS), which are based on existing industries, are not reliable (Feldman and Lendel forthcoming).

Rosenkopf and Nerkar (2001) addressed the problem of defining the optical disk industry by considering product specifications. They consulted technical sources to identify eight component products and then searched the patent classification manual to locate the corresponding technical subclasses. Using this criterion, Rosenkopf and Nerkar identified a total of 3,598 applications and patents between 1971 and October 1995. These patents were owned by 413 firms, with more than 60 percent of the total patenting activity attributable to 22 large firms alone. This technique modified the classification of patents on the basis of product grouping. However, it relies on products that are already on the market. Pilkington, Romano, and Omid (2002) discussed the limitations of defining patent searches in terms of products when the intent is to study technologies.

Directories or membership listings of industry associations are another means that have been used to define an industry. Sternberg (1992) used the membership list of SPIE to examine counts of firms. Often membership lists are used as marketing devices or sales directories, which provide information about products that are currently on the market but give little information about a firm's future direction or the new technologies it may be exploring. Hendry and Brown (2006) relied on the directory of the organization Photonics Spectra to provide a survey frame. A problem that plagues all surveys is the low response rate and potential response bias. Hassink and Wood (1998) examined catalogs of opto-electronic trade fairs and interviewed experts at universities and industry associations to gain an understanding of the industry. Although interviews and case studies provide useful in-depth information, their results are difficult to generalize. Interview questions, especially when there is a geographic emphasis, typically focus on why the firms and industry are located in a specific place and what factors provide an industrial advantage. It is difficult in an interview to obtain an assessment of an industry's future strategic direction because the information has proprietary value and may reveal competitive intelligence. Moreover, the point of view about emerging technologies would be highly subjective and would depend on the position of the interviewee in the organization.

In sum, there is no adequate means of examining emerging industries when the objective is to discern the cutting edge of a technology (Pilkington 2004). Prior studies have suggested a synthesis approach to defining the cutting edge of the technology space as the actual inventions of firms that belong to a well-defined and focused professional organization. Our approach is to use a voluntary industry association to define companies that focus on optics and then to examine the companies' patent portfolios to discern the relevant technology space in which they focus their inventive activity. As a final step, we consider all companies that invent within the focal technology profile.

In this article, we examine the patenting activities of the member companies of the Optical Society of America (OSA), the oldest optics association, which celebrated its 90th anniversary in 2007. OSA has multiple well-regarded journals, such as the *Journal of the Optical Society of America* (*A* and *B*), *Applied Optics*, *Optics Letters*, *Optics Express*, *Journal of Optical Networking*, *Virtual Journal of Biomedical Optics*, *Journal of Lightwave Technology*, *Journal of Optical Technology*, *Journal of Display Technology*, and *Chinese Optics Letters*. These journals span the range from theory to practice, all with an orientation toward science and scientific applications. Interviews with academics and individuals who were working in the private sector suggested that OSA is the most appropriate organization to represent the cutting edge in optical science, or what we define for our purposes as the optical sciences industry.[1]

OSA has an accessible corporate membership list that appears to provide a representative source of companies. Rather than being an all-inclusive corporate marketing directory, OSA corporate membership is based on the payment of fees, indicating that companies derive some perceived value from membership. Membership fees are based on a company's size, with $645 for firms with less than $10 million in annual sales to $3,255

[1] SPIE is the other major general organization in optics. We choose OSA because its mission is closer to science than is the more engineering-focused SPIE.

for companies with more than $50 million in annual sales. The OSA (2010) website notes that corporate memberships provide "access [to] a worldwide network of industry professionals to make new business contacts, connect with current customers, and establish innovative partnerships." There were 338 corporate members in 2007.

We examined the patenting activity of each OSA member. One immediate problem with the membership list is that large diversified multidivisional firms patent across diverse technology areas, diluting our definition of the focal technology. For example, Northrop Grumman Information Technology Division is an OSA member, but its patents are assigned to the parent organization. Similarly, Lockheed Martin is an OSA member, but its core business areas of aeronautics, electronic systems, information systems and global services, and space systems are much broader than optics. Since these large multidivisional firms patent prolifically and include a range of activities unrelated to optics, including all patents assigned to the corporate parent almost tripled the count of patents and increased the number of technology categories. For this reason, we concentrated on the 315 OSA member companies for which we were able to discern an unambiguous focus on optics. We then used the Delphion Thomson patent database (available online at http://www.delphion.com/research) to identify the U.S. patents to create a database of 1,747 patents that were applied for or granted during 2004 to 2007.

Patents are classified according to International Patent Classes (IPCs), which provide "a basis for investigating the state of the art in given fields of technology" (World Intellectual Property Organization 1997, para. 3).[2] Patel and Pavitt (1995, 1997) established the utility of IPCs to capture patterns of technological activity and technological competencies. We examined all the IPCs listed on OSA member patents. In total, 956 IPC subgroups were represented at least once. This figure indicates the diffuse nature of the industrial activity in which the OSA member companies engage but may also be an artifact that some of the OSA member companies had expansive technology portfolios. The 38 subgroups listed in Table 1 accounted for 40 percent of all OSA member companies' inventive activity and 46 percent of the companies' main inventive activity (the first IPC listed on the patent). The remaining 928 main patent classes had an average frequency of 2.1, with 50 percent of the patent classes appearing only once.[3]

We examined all U.S.-granted patents and patent applications filed between 1 January 2004 and 6 December 2007 that listed one of the 38 IPC codes as their main classification code. For this analysis, we restricted our attention to patents that were developed by inventors living in the United States. This search yielded 25,050 patent records. We were able to assign 24,813 records to the location of the inventors. We considered the locations of all the inventors on the patent, assigning to each inventor a portion of a patent inversely proportional to the number of the patent's inventors. Using the inventors' cities, addresses, and zip codes, we used U.S. Postal Service city-county information and manual data-reliability checks to correct misspelled place names. We assigned inventors to U.S. counties and then aggregated counties to Metropolitan Statistical Areas (MSAs), on the basis of the December 2003 Office of Management and Budget (OMB) Bulletin of MSAs. We were able to match more than 99 percent of all the records. These data provided the basis for our empirical analysis.

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[2] The IPC system classifies an invention according to function,while the U.S. Patent Classification System considers a broader set of criteria, such as industry of likely use (Adams 2001). The IPC classification allows for greater precision by capturing a larger number of OSA patents and greater parsimony, since fewer categories were required (see Feldman and Lendel forthcoming for details).

[3] A comparison of the selected set to the full set of OSA companies, including the multidivisional corporations, indicated that these codes were represented.

Table 1

Detailed Definition of the Emergent Optics Science Industry: OSA Member Patents by 38 IPC Subgroups

Patent Subgroup	Description of Patent Subgroup
B23K 26/00	Working by laser beam, e.g., welding, cutting, boring
B23K 26/06	Shaping the laser beam, e.g., by masks or multi-focusing (optical elements, systems, or apparatus, in general)
G01B 11/02	Measuring arrangements characterized by the use of optical means for measuring length, width, or thickness
G01B 09/02	Interferometers
G01J 03/00	Spectrometry; Spectrophotometry; Monochromators; Measuring Colors
G01J 03/12	Generating the spectrum; Monochromators
G01J 03/30	Measuring the intensity of spectral lines directly on the spectrum itself
G01N 21/00	Investigating or analyzing materials by the use of optical means, i.e., using infra-red, visible, or ultra-violet light
G01N 21/25	Color; Spectral properties, i.e., comparison of effect of material on the light at two or more different wavelengths or wavelength bands
G02B 27/10	Beam splitting or combining systems
G02B 05/28	Interference filters
G02B 06/00	Light guides; Structural details of arrangements comprising light guides and other optical elements
G02B 06/02	Optical fiber with cladding
G02B 06/10	Optical waveguide
G02B 06/12	Integrated circuit kind
G02B 06/26	Coupling light guides with optical coupling means
G02B 06/34	Coupling light guides utilizing prism or grating
G02B 06/36	Mechanical coupling means
G02B 06/42	Coupling light guides with opto-electronic elements
G02F 01/01	Devices or arrangements for the control of the intensity, phase, polarization or color
G02F 01/13	Devices or arrangements based on liquid crystals, e.g., single liquid crystal display cells (liquid crystal materials)
H01L 21/00	Processes or apparatus adapted for the manufacture or treatment of semiconductor or solid state devices or of parts thereof (processes or apparatus peculiar to the manufacture or treatment of devices provided for in groups)
H01L 21/02	Manufacture or treatment of semiconductor devices or of parts thereof (characterized by the use of organic materials)
H01L 29/02	Semiconductor bodies
H01L 31/00	Semiconductor devices sensitive to infra-red radiation, light, electromagnetic radiation of shorter wavelength, or corpuscular radiation and adapted either for the conversion of the energy of such radiation into electrical energy or for the control of electrical energy by such radiation; Processes or apparatus peculiar to the manufacture or treatment thereof or of parts thereof
H01L 31/06	Semiconductor devices adapted as conversion devices characterized by at least one potential-jump barrier or surface barrier
H01S 03/00	Lasers, i.e., devices for generation, amplification, modulation, demodulation, or frequency-changing, using stimulated emission, of infra-red, visible, or ultraviolet wave
H01S 03/04	Cooling arrangements
H01S 03/06	Construction or shape of active medium
H01S 03/067	Fiber lasers
H01S 03/08	Construction or shape of optical resonators or components thereof
H01S 03/10	Controlling the intensity, frequency, phase, polarization or direction of the emitted radiation, e.g., switching, gating, modulating or demodulating mode locking
H01S 03/11	Lasers controlling the intensity, frequency, phase, polarization or direction of the emitted radiation, in which the quality factor of the optical resonator is rapidly changed, i.e., giant-pulse technique
H01S 03/14	Lasers characterized by the material used as the active medium
H01S 03/30	Lasers using scattering effects, e.g., stimulated Brillouin or Raman effects
H01S 05/00	Semiconductor lasers
	Transmission systems employing beams of corpuscular radiation, or electromagnetic waves other than radio waves, e.g., light, infra-red
H04B 10/08	• Equipment for monitoring, testing or fault measuring
H04B 10/12	• Transmission through light guides, e.g., optical fibers

Source: http://www.wipo.int/classifications/ipc/ipc8/?lang=en

The Geography of Optics

Similar to most inventive and innovative activity, optical science is geographically concentrated. This section first discusses the distribution of optics patents in raw numbers and then on a per capita basis and looks at specific firms that drive the concentration of optics patenting activity. Invention in optical science occurs predominantly in cities: less than 30 percent of the patents between 2004 and 2007 are attributable to inventors who lived outside MSA boundaries. As Table 2 shows, more than 71 percent of all optics patents and applications were submitted by inventors who resided in a total of 240 MSAs. This figure indicates that 60 percent of the 362 U.S. MSAs had some inventive activity in optics during the period under study.

Only half of these MSAs, however, had at least 5 individuals who were active inventors in optical science, and only 98 areas had at least 10 such individuals from 2004 to 2007. During the same period, 30 MSAs had at least 100 optics inventors, and together these cities accounted for 60 percent of all optics patents and applications. Drilling down further, 17 MSAs produced 52.4 percent of all patents and applications, demonstrating the further geographic concentration of inventive activity. Thus, more than half of all inventive activity took place in a small number of cities. Each of these 17 cities accounted for more than 200 codified inventions from 2004 to 2007.

While 17 MSAs dominated the count of optical science invention, they represented diverse geographies. Figure 1 presents the geographic spread of optical science across the United States, representing the East Coast (New York, Rochester, and Poughkeepsie, New York; Burlington, Vermont; and Boston, Massachusetts), the West Coast (San Francisco, San Jose, Los Angeles, and San Diego, California; Boise City, Idaho; and Portland and Corvallis, Oregon), the heartland (Chicago, Illinois, and Minneapolis, Minnesota) and the Sun Belt (Dallas and Austin, Texas, and Phoenix, Arizona). Rather than a simple, bicoastal phenomenon, invention in optical science is more geographically distributed.

Table 3 presents cities that filed at least 200 applications from 2004 to 2007 and cities that are highly ranked in the number of patents per employee. Large metropolitan areas, such as New York, Los Angeles, and Chicago, are included, perhaps because these places have diversified economies with a range of industrial firms for which optics is an intermediate input. The list also includes smaller cities, such as Minneapolis, Minnesota, and Rochester, New York, which are prominent cities in the industrial heartland and are known to be centers of the optics industry. The small cities in the list of places that are high in optics patents, such as Corvallis, Burlington, Poughkeepsie, and Boise City, are less well known as core areas of optics invention.

Nevertheless, the distribution of patents across metropolitan areas is uneven. The San Jose–Sunnyvale–Santa Clara MSA accounted for 2,615 patents, and geographically

Table 2

Optics Invention as a Metropolitan Phenomenon: Distribution of Optics Patents and Applications in U.S. Metropolitan Statistical Areas (MSAs)

Number of MSAs	Number of Patents, 2004–2007	Percentage of Total 24,813 Patents	Mean	Median	Standard Deviation
240	17,707	71.4	73.8	5.6	255.0
98	17,329	69.8	176.8	47.4	376.8
30	14,871	59.9	495.7	226.9	567.5
17	13,010	52.4	765.3	631.3	636.3

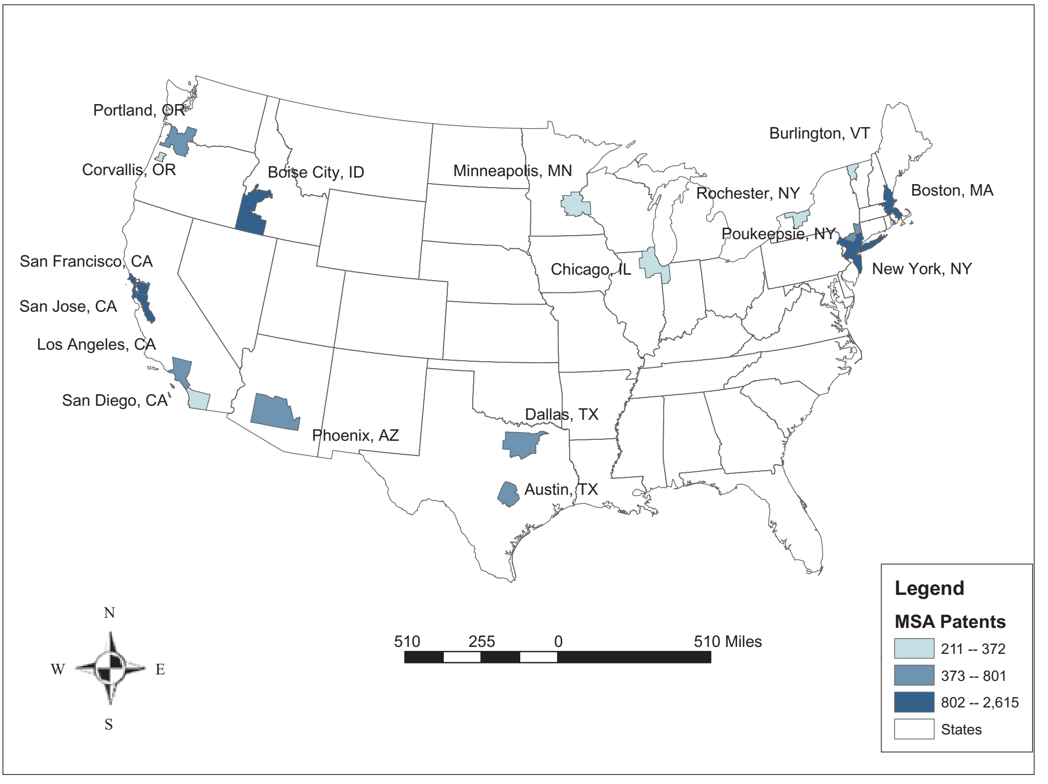

Figure 1. The 17 most prominent patenting metropolitan statistical areas (MSAs) in optics: total number of patents and applications, 2004–2007.

contingent San Francisco–Oakland–Fremont accounted for 1,280 patents. This region alone accounted for 15.5 percent of all inventive activity in optical science. This finding is perhaps not surprising because the San Jose–San Francisco region is arguably the epicenter of innovation and emerging technologies. More remarkable is the fact that Boise City alone accounted for 1,848 patents (7.4 percent). Together, these three MSAs, arguably two regions, accounted for about one-third (5,743) of all U.S. optics patents that were applied for and granted between 2004 and 2007. Notably, this was 23 percent of the applications that had already been granted patent rights by the end of 2007. This discrepancy suggests that patents from these cities appear to take longer to grant, suggesting that the inventions may be more basic in their orientation (Jaffe and Trajtenberg 2002).

As a producer technology, optics may be easily combined with the range of products and processes that are found in large urban areas. A large number of patents overall is attributed to New York City (see Table 3), accounting for 908 patents and applications, even though this city does not immediately come to mind when one considers optics science. The diverse industrial base of New York City and the agglomeration of research institutions located there appear to create necessary prerequisites for general-purpose inventions to be applied to multiple fields. Similarly, Los Angeles, the second-largest city in the United States, ranks high, with 667 optics patents and applications. Although Los Angeles is another geographic area that is not typically associated with optical science, Scott and Soja (1998) discussed the development of a diverse industrial agglomeration

Table 3

Where Optical Science Invention Takes Place: Metropolitan Statistical Areas (MSAs) with the Largest Number of Patents and the Highest Patent Production per Employee

MSA	Total Patents and Applications,[a] 2004–2007	Number of Granted Patents,[b] 2004–2007	Percentage of Granted Patents,[b] 2004–2007	Patent Rank	Employment Rank	Total Patents and Applications[a] per 10,000 Employees[c]
San Jose–Sunnyvale–Santa Clara, California, MSA	2,615	614	23.5	1	32	28.70
Boise City–Nampa, Idaho, MSA	1,848	168	9.1	2	85	65.98
San Francisco–Oakland–Fremont, California, MSA	1,280	266	20.8	3	11	6.23
New York–Northern New Jersey–Long Island, New York–New Jersey–Pennsylvania, MSA	908	181	19.9	4	1	1.07
Boston–Cambridge–Quincy, Massachusetts–New Hampshire, MSA	818	123	15.0	5	9	3.34
Portland–Vancouver–Beaverton, Oregon–Washington, MSA	801	173	21.6	6	26	7.66
Dallas–Fort Worth–Arlington, Texas, MSA	694	113	16.4	7	5	2.38
Los Angeles–Long Beach–Santa Ana, California, MSA	667	130	19.5	8	2	1.15
Phoenix–Mesa–Scottsdale, Arizona, MSA	631	183	28.9	9	13	3.28
Poughkeepsie–Newburgh–Middletown, New York, MSA	574	129	22.5	10	89	21.64
Austin–Round Rock, Texas, MSA	525	71	13.6	11	39	7.15
Minneapolis–St. Paul–Bloomington, Minnesota–Wisconsin, MSA	372	80	21.6	12	14	2.04
Burlington–South Burlington, Vermont, MSA	344	88	25.6	13	177	28.75
Corvallis, Oregon, MSA	268	41	15.3	14	351	67.13
Rochester, New York, MSA	242	52	21.6	15	49	4.63
Chicago–Naperville–Joliet, Illinois–Indiana–Wisconsin, MSA	212	50	23.5	16	3	0.46
San Diego–Carlsbad–San Marcos, California, MSA	211	60	28.4	17	16	1.47

[a] The data were compiled by the application date.
[b] Patents that were applied for between 2004 and 2007 and were granted by the end of 2007.
[c] Total number of patents and applications that were filed between 2004 and 2007, normalized by annual 2006 employment.

in southern California. Optics seemingly would be adaptable to the diverse and vibrant industrial activity located in the second largest MSA in the United States.

Another area that is generally recognized as a technology hub is Boston, with a total of 818 optics inventions. Smaller cities, such as Portland, Oregon (with 801 patents and applications), Dallas (694), Phoenix (631), and Austin (525), represent places that have been described as part of America's geographic Gunbelt, accounting for a strong presence of federal research and development (R&D) support and defense contracting (Markusen, Hall, Campbell, and Deitrick 1991). From the list, Phoenix is perhaps the best-known center of optical science, and Poughkeepsie (574) is perhaps the least known. Poughkeepsie is located in the Hudson River Valley, midway between New York City and Albany, and is the location of IBM's main R&D facility. It is not only a place with one of the greatest number of filed applications and granted patents in optics during 2004 to 2007, but it is also on a list of the five places with the highest level of patents and applications per employee (21.64).

Although the total amount of innovation activity matters, another criterion for identifying the hubs of innovation is a productivity-type measure of the number of optics patents normalized by the total employment in an MSA. Table 3 also presents the ratio of patents per 10,000 employees. Considering the most productive places in optics invention distinguishes five places. Corvallis leads the list of the most patent-productive cities, with 67.1 patents and applications per 10,000 employees, mainly because of its small size—40,000 employees in 2006. Four other geographies are among the most productive places in optical science, ranging in their employment from 911,000 employees in San Jose, with 28.7 patents per 10,000 employees, to 120,000 in Burlington, with 28.8 normalized patents. Two other metropolitan areas, Poughkeepsie and Boise City, are similar in size (265,000 and 280,000, respectively) but differ significantly in patent production, with 21.6 in Poughkeepsie and 66.0 in Boise City per 10,000 employees. Both latter geographies represent smaller metropolitan areas and are not known as national centers of innovation or production.

The devil is in the details and requires examining the entities in places that generate the most optical patents (see Table 4). For example, Boise City, the headquarters of Micron Technology, is a technological leader in image-capturing applications and the production of computer memory components, modules, and development solutions that fuel the most advanced digital products. Micron Technology was started in Boise as a semiconductor company by four Idaho natives in 1978 (Mayer forthcoming). The technical founders had previously worked at Mostek Corporation in Dallas and returned to their prior residence to start their new firm (Mayer forthcoming). The firm entered a niche in memory semiconductors just as other American firms were exiting that market. It had an initial public offering in 1984. Today, with 693 granted patents, Micron has been the leading national company in optics patents at least during the past 4 years. Its net sales for 2007 were $5.69 billion, and the company currently employs 22,600 people worldwide, about half of them located in Boise. Mayer (forthcoming) documented the optics firms that have spun out of Micron. In addition, Boise City houses more than 4,000 employees of Hewlett-Packard Company—also one of the top patenting companies in optics (8th, with 104 patents granted during 2004–2007).

Optics in each city has a story that may be examined in a detailed case study. For example, Poughkeepsie's optics industry builds upon the historical presence of IBM—the largest employer in the area in the 1980s. IBM describes itself as a multinational computer technology corporation that specializes in leading chip technologies and research on innovative technologies that produce leading-edge solutions, ranging from mainframe computers to nanotechnology. Headquartered in Armonk, New York, it employs 355,766

Table 4

Prominent Patenting Entities in Optics in Metropolitan Statistical Areas (MSAs)

MSA	Total Number of Patenting Entities	Mean Patents per Patenting Entity	Percentage of University Patents	Largest Patentor (Percentage)	Entity Name	Second-Largest Patentor (Percentage)	Entity Name
Austin–Round Rock, Texas, MSA	33	3,06	0.0	29.7	FreeScale	12.9	Advanced Micro Devices
Boise City–Nampa, Idaho, MSA	6	29,50		97.2	Micron Technology		
Boston–Cambridge–Quincy, Massachusetts–New Hampshire, MSA	81	2,22	13.7	8.9	MIT	5.6	Applied Materials
Burlington–South Burlington, Vermont, MSA	8	15,63	0.8	86.4	IBM	6.4	Micron Technology
Chicago–Naperville–Joliet, Illinois–Indiana–Wisconsin, MSA	28	2,29	4.8	9.4	Molex Incorporated	7.8	Panduit
						7.8	Motorola
						7.8	Cabot Microelectronics
Corvallis, Oregon, MSA	4	17,25	4.3	50.7	Micron Technology	43.5	Hewlett-Packard
Dallas–Fort Worth–Arlington, Texas, MSA	31	4,42	1.4	58.4	Texas Instruments	5.8	National Semiconductor
Los Angeles–Long Beach–Santa Ana, California, MSA	75	2,41	10.5	7.7	Luxtera	7.2	HRL Laboratories
Minneapolis–St. Paul–Bloomington, Minnesota–Wisconsin, MSA	27	3,81	3.0	29.1	3M	26.2	ADC Telecommunications
New York–Northern New Jersey–Long Island, New York–New Jersey–Pennsylvania, MSA	62	5,05	1.2	50.8	IBM	8.3	Lucent Technologies
Phoenix–Mesa–Scottsdale, Arizona, MSA	33	5,76	1.0	31.1	Intel	21.6	FreeScale
Portland–Vancouver–Beaverton, Oregon–Washington, MSA	27	7,41	0.5	44.0	Intel	25.5	Sharp Laboratories
Poughkeepsie–Newburgh–Middletown, New York, MSA	13	18,00	0.4	76.1	IBM	10.7	Advanced Micro Devices
Rochester, New York, MSA	15	3,80	7.1	42.1	Eastman Kodak	17.5	Xerox
San Diego–Carlsbad–San Marcos, California, MSA	36	2,75	1.0	32.3	Luxtera	11.1	U.S. Navy
San Francisco–Oakland–Fremont, California, MSA	157	3,58	3.2	12.3	Applied Materials	5.2	Advanced Micro Devices
San Jose–Sunnyvale–Santa Clara, California, MSA	189	4,59	2.6	11.1	Applied Materials	9.1	Advanced Micro Devices

worldwide, with revenue of $98.8 billion in 2007 (IBM 2008). According to IBM (2006), the corporation "earned 2,941 patents last year [2005], more than any other company—the 13th consecutive year [that] IBM has led the nation's patent production." IBM is the second-most-prominent inventing entity in optical sciences and employs 11,500 in the Poughkeepsie region (Dutchess County Economic Development Corporation 2008). Advanced Micro Devices is still patenting while headquartered elsewhere. Philips Semiconductor became NXP in 2006 and closed the branch plant in Fishkill, New York, in 2008.

Corvallis, traditionally recognized as a high-patenting place in the country, is home to Oregon State University, as well as the printer cartridge manufacturing and prototyping facility of Hewlett-Packard Corporation. In fact, Corvallis is noted as the birthplace of computer ink-jet printing technology—an optical application developed by Hewlett-Packard in 1984 (Hewlett-Packard 2009). According to the Community Profile for the City of Corvallis (2007, 2-2), "In 2004, the Harvard Business Review ranked Corvallis 15th . . . in its Creativity Index, which looks at Technology, Talent, and Tolerance. In 2005, Expansion Management selected Corvallis as a 'Five-Star Knowledge Worker Metro Area,' the highest rating achievable, and in 2006 Corvallis was named number two on the National Science Foundation's list for percentage of scientists in the population." Burlington, a college town that has attracted industrial R&D, is home to the University of Vermont. IBM, for example, has a facility there with 6,000 employees, and IDX Systems, a provider of software, services, and technologies for health-care provider organizations, employs 750.

Table 4 presents details on the patenting entities within each MSA. The second column shows the total number of organizations that were granted patents. For example, Austin had 33 distinct patenting entities, while San Jose had 189. Large companies, even though our defining criteria eliminated their influence by excluding them from our definition of the industry, were later included in the list of all companies patenting within the patent profile of optics and appear as prominent in most cities. For example, IBM is the most prominent inventing entity in Burlington, Poughkeepsie, and New York City, while Intel is most prominent in Phoenix and Portland.

In general, the larger the number of entities, the more likely it is that small- and medium-sized firms are active in the city. For example, Corvallis, while making our list of prominent places, has four patenting entities, and the two most prominent, Micron and Hewlett-Packard, account for almost 95 percent of the patents generated there. For comparison, the third column of Table 4 lists the mean number of patents per patenting entity, with a smaller number indicating that activity is more evenly distributed.

The fourth column of Table 4 provides the percentage of university patents, which nationally averages 3 percent across all industries. Boston has the highest percentage, with about 14 percent of optical science patents assigned to universities. Indeed, MIT accounts for about 9 percent of Boston's patents, making it the largest patenting entity in optical science in the city. Universities account for 10.5 percent of the patents in Los Angeles and 7.1 percent in Rochester.

In conclusion, within this one emergent industry, patterns are revealed that suggest three different types of concentrations of inventive activity: small specialized cities dominated by one or a few large companies that anchor the industry, places with inventive activity dominated by a large anchor but with a greater share of other innovative firms, and large cities with diverse innovative environments that specialize in innovation and provide the munificent environment that is likely to encourage invention in a producer industry.

The next section examines places that have self-designated as optics clusters to see how they compare to prominent patenting locations in optics.

Self-Designated Clusters

Optics emerged as an important technology just as the concept of clusters was gaining currency. SPIE maintains a website (http://photonicsclusters.org) that tracks optics and photonic clusters around the world. The website lists seven American optics clusters located in New York (Rochester and central New York), Arizona, New Mexico, Colorado, Florida, and the Carolinas. These clusters are often led by states' economic development efforts or champions of local industries. Each has a unique story that has been told from a variety of perspectives (Florida High Tech Corridor 1999; Catts, Likins, and Wright 1999; Waits 2000). It is interesting to examine how these self-designated clusters compared in terms of inventive activity to the other geographic centers we have identified for the industry.

Table 5 presents a description of each MSA that is included in seven self-designated optics and photonics clusters. For example, the Arizona Optics Cluster consists of the metropolitan areas of Phoenix, Tucson, and Prescott—virtually the entire population base of the state. The second column of Table 5 shows the number of applications submitted during 2004 to 2007. Column 3 lists the percentage of patents that were granted from 2004 to 2007. Only Phoenix and Rochester appear in the 17 largest patenting metropolitan areas in Table 3. If these MSAs are excluded, then, on average, each self-designated cluster submitted only 39 applications and received 16 patents. In comparison, the top 17 patenting MSAs in optics submitted, on average, 765 applications and were granted 148 patents in 2004 to 2007. Self-designated clusters have a fewer number of submitted applications but a higher percentage of granted patents. The shorter, on average, review time in self-designated clusters may suggest that inventors from these places file applications on more incremental types of innovations.

The next two columns of Table 5 show the patent rank and employment rank when considered against all metropolitan areas that are active in optics patenting. These two columns help one better understand the last column's indicator—total patents and applications per 10,000 employees. For example, two places with almost the same ranking in patent numbers—Hickory (North Carolina) (ranked 46) and Palm Bay (Florida) (ranked 42)—have significantly different indicators of patents per employee because of the different sizes of their economies. In particular, Hickory (ranked 137) is a significantly smaller place than Palm Bay (ranked 104) yet yields 3.34 patents per employee compared with 2.92 patents per employee for Palm Bay. Having a higher productivity in patents may not always mean a better patenting rate.

Phoenix and Rochester are the only two metropolitan areas that have significant patenting activity and belong to the self-designated optics clusters (see Tables 3 and 5). The Rochester Regional Photonic Cluster, concentrated in Rochester but also including Buffalo, New York, is anchored at the Institute of Optics at the University of Rochester, and entrepreneurial startups located there have grown to become large brand-name firms, such as Kodak, Bausch & Lomb, and Xerox. The Rochester MSA is ranked 15 in the total development of optics patents and applications and has a productivity of 4.63 patents per 10,000 employees. The other metropolitan area in this cluster, the Buffalo MSA, is ranked only 105 in total patents and has a low 0.15 patents normalized by employment.

The Arizona Optics Cluster is concentrated in Tucson and Phoenix, which covers most of the population of Arizona. It is anchored in Phoenix, which is one of the 17 prominent optics metropolitan areas and is 9th in the total patents and applications in optics submitted from 2004 to 2007. Although the Tucson metropolitan area has a much smaller number of patents, Tucson is one of the top 30 optics patenting MSAs, and because of the smaller size of its economy, it is high in patents per employee (3.97) (see Table 5).

Table 5

Self-Designated U.S. Optics and Photonics Clusters: Activity by Metropolitan Statistical Area (MSA)

MSA	Total Patents and Applications,[a] 2004–2007	Number of Granted Patents,[b] 2004–2007	Percentage of Granted Patents,[b] 2004–2007	Patent Rank	Employment Rank	Total Patents and Applications[a] per 10,000 Employees
Arizona Optics Cluster						
Phoenix–Mesa–Scottsdale, Arizona, MSA	631	183	28.9	9	13	3.28
Tucson, Arizona, MSA	155	49	31.6	22	60	3.97
Prescott, Arizona, MSA	3	0	0.0	146	262	0.43
New Mexico Optics Cluster						
Albuquerque, New Mexico, MSA	73	25	34.1	38	58	1.83
Santa Fe, New Mexico, MSA	8	2	26.6	112	268	1.17
Colorado Photonics Cluster						
Colorado Springs, Colorado, MSA	76	24	31.7	37	82	2.57
Denver–Aurora, Colorado, MSA	63	27	42.5	43	21	0.52
Greeley, Colorado, MSA	20	12	59.7	70	217	2.32
Fort Collins–Loveland, Colorado, MSA	45	12	26.6	51	160	3.30
Florida Photonics Cluster						
Orlando, Florida, MSA	72	31	43.3	39	23	0.66
Palm Bay–Melbourne–Titusville, Florida, MSA	65	35	54.3	42	104	2.92
Deltona–Daytona Beach–Ormond Beach, Florida, MSA	0	0	0.0		128	0
Carolinas MicroOptics Triangle						
Hickory–Lenoir–Morganton, North Carolina, MSA	56	38	68.0	46	137	3.34
Charlotte–Gastonia–Concord, North Carolina—South Carolina, MSA	22	16	73.4	69	36	0.26
Spartanburg, South Carolina, MSA	2	1	50.0	161	169	0.16
Greenville, South Carolina, MSA	12	5	41.7	92	78	0.38
Rochester/Buffalo Regional Photonics Cluster						
Rochester, New York, MSA	242	52	21.6	15	49	4.63
Buffalo–Niagara Falls, New York, MSA	9	2	23.4	105	47	0.15
Central New York Photonics Cluster						
Utica–Rome, New York, MSA	3	2	66.7	144	162	0.22
Syracuse, New York, MSA	19	7	36.8	72	75	0.58
Ithaca, New York, MSA	41	21	51.4	57	270	6.40

[a] The data were compiled by the application date.
[b] Patents that were applied for between 2004 and 2007 and were granted by the end of 2007.

Concentrating on high-technology industries that specialize in electronic and aerospace, Arizona is home not only to Intel, Motorola, and Boeing but also to the large defense companies Honeywell and Raytheon. According to the company's website, Honeywell "is a leading global provider of integrated avionics, engines, systems and service solutions for aircraft manufacturers, airlines, business and general aviation, military, space and airport operations" (Honeywell 2009). Raytheon is the world largest designer and producer of missile systems (Raytheon 2009). On the basis of a web survey, Wiggins's (2008) analysis of 92 Arizona optics and nanotechnology firms indicated that, despite a few large anchor companies in the region, the average size of Arizona optics and nanotechnology firms is about 25 employees, with an average revenue of $45 million per year. Once large firms are eliminated, the average employment for small- and medium-sized optics companies (with fewer than 100 employees) is 13 employees per company, with an average revenue of about $1.7 million. Wiggins (2008) indicated that the optics and nanotechnology industry could be described by 13 different fields of business, and 46 percent of all the respondents mentioning *consulting* as their activity.

Besides Phoenix, Rochester, and Tucson, 4 more metropolitan areas are among the top 50 producers of optics patents. The indicator of relative patent productivity is high only in places with small regional economies, such as Greeley and Fort Collins, Colorado (ranked 217 and 160, respectively, in employment size); Palm Bay, Florida (ranked 104); and Ithaca, New York (ranked 270).

Each of the seven self-designated locations has an anchor company or institution and a motivation for development. There may be a time lag before some of the comparably new optics clusters with strong academic anchors develop. For example, the Florida Photonics Cluster is based on a strong educational base at the University of Central Florida's Center for Research and Education in Optics and Lasers and the University of South Florida (both of which conduct more than $12 million to $15 million in optics research). The young and ambitious Carolinas MicroOptics Triangle is a partnership among Clemson University, the University of North Carolina at Charlotte, and Western Carolina University. However, these places have yet to attract corporate partners that will lead the commercialization of optics innovation.

The self-designation of optics clusters in these seven regions is an attempt to create policy-induced optics clusters that are geographically concentrated. There are myriad advantages to self-identifying as a cluster, including the creation of a larger market for skilled labor and professionals, easier marketing for the attraction of suppliers and customers, developing interregional and state policies, and gaining better access to funding. Analyzing the industry-cluster approach and using, among others, the optics cluster in her case study, Waits (2000, 35) pointed out that Arizona "uses clusters as a tool for better understanding the economy, getting key industry stakeholders together to address common problems, and providing high-value specialized services to key industries." However, the mismatch in the regional distribution of designated academic programs in optics and large corporations suggests that it takes more than self-designation to become a national leader in an emerging technology.

The map in Figure 2 provides a visual comparison of the self-designated optics clusters with the cities that have the largest number of patents and the highest productivity of patents per employee at the level of individual MSAs. The circles overlaying the boundaries of the MSAs reflect the number of patents and applications that were submitted from 2004 to 2007. It is visually obvious that the emerging technology in optical science is not concentrated in self-designated optics and photonics clusters.

There are several observations from this map that can be added to the comparison of the self-designated and top patenting optics regions that have already been discussed (see

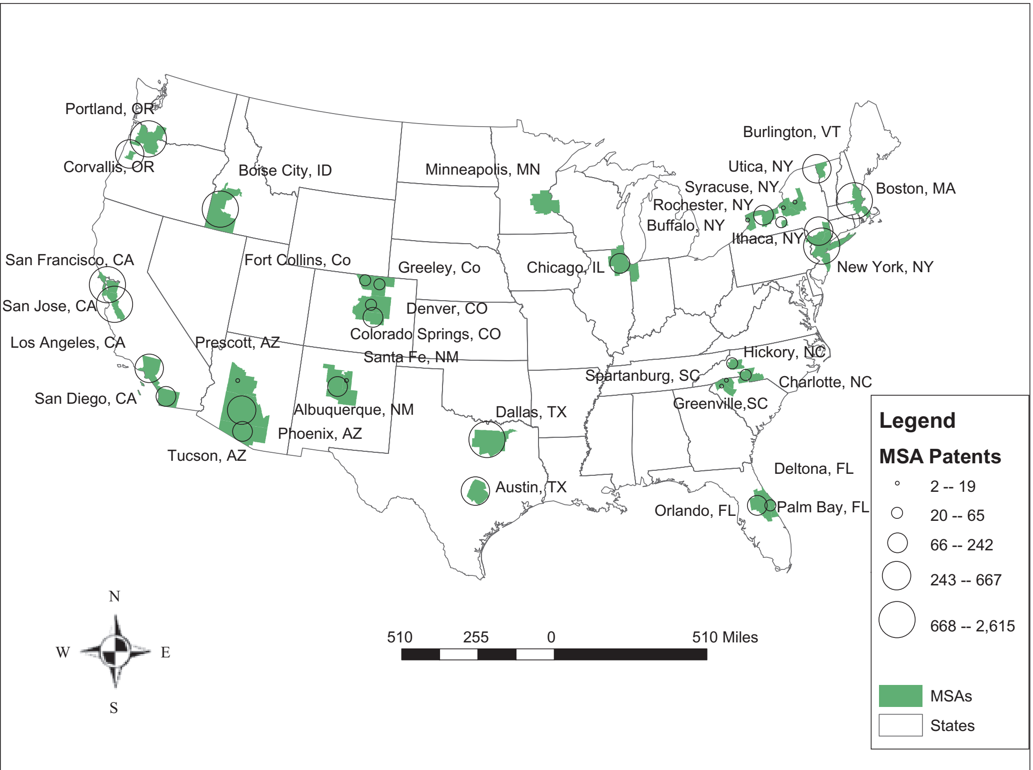

Figure 2. Self-designated and largest producers of optics patents: total number of patents and applications, 2004–2007.

Tables 3 and 5). Among the self-designated optics and photonics clusters, only Arizona's scope of patents may be competitive with the rest of the regions that lead in optics technology. It is not only sizable in the number of patents and applications but also covers a contiguous geographic area and has a strategy in place that recognizes the region as specialized in optics. Even though the scope of patenting activity in Arizona may be comparable to that of Dallas and Austin taken together, the area that is marketed as specialized in optics covers a larger portion of the state, creates an image among companies and professionals, and draws attention to public policies to help sustain it as a cluster.

The New Mexico and Colorado clusters are not prominent when one considers the number of patents. The most likely explanation for their existence is probably their respective state economic development efforts. Detailed case-study analyses are needed to gain a better understanding of the rationale for this designation and to evaluate the success of these optics-clustering strategies to economic development. The efforts of the Florida Photonics Cluster and the Carolina MicroOptics Triangle are not reflected in the optics patenting activity. They may be too new to be considered a success or failure.

In comparison to the self-designated clusters, the top patenting places can be speculatively classified in three categories. The first category accounts for regions that create contiguous geographies and have a high potential to develop optic clusters on the basis of emerging technology. The New York and Poughkeepsie MSAs are a contiguous region with a high number of patents and strong anchor companies and institutions. Similarly, three more regions can be considered by patenting activity as emerging clusters in optics: Los Angeles–San Diego, San Francisco–San Jose, and Portland–Corvallis.

The second group of MSAs includes five other places with high patenting in optics that are large urban areas with high economic diversity and prominent research institutions—Boston, Austin, Dallas, Minneapolis, and Chicago. The optics industry in these cities may be prominent but is not a focal point of the local economy because of these MSAs' diverse economic bases. The last group accounts for Boise City and Burlington, which are small, less economically diversified, and anchored in the industries and technologies of their largest companies. In sum, there are many different ways to anchor the industry in a place, and only time will tell if the self-designated clusters will develop viable industries.

Reflective Conclusions

Despite significant conceptual and practical problems, cluster development has emerged as the most prominent economic development objective during the past decade (Martin and Sunley 2003). Many politically motivated initiatives around the world have attempted to create clusters to create some level of competitive advantage (Amin 1999). Understanding the reasons why new industries emerge and thrive in some places but not in others is a core issue in economic geography. Indeed, studying the genesis and emergence of industrial clusters also requires an understanding of industrial organization, business strategy, and public policy, along with their integration (Braunerhjelm and Feldman 2007). Certainly, this is a complex undertaking, and we hope that with this simple exercise, we will encourage others to look more broadly at the rich context of economic geography.

Knowledge-intensive industries that emerge in multiple scientific fields are difficult to capture using traditional tools of analysis. Standard conventional classification codes, such as SIC and NAICS, describe mature sectors of the economy. The geographic distribution of employment in such industries points to regional centers of production employment, which does not always coincide with a concentration of innovative activity in this industry. Analyses to identify emerging science industries or to understand the evolution of technologies must use different means (Pilkington 2004). Our intention in this article was to provide a comprehensive view of the cutting edge of an emerging science-based industry and to consider the underlying geographic and industrial structure.

Our interest lies in broadening inquiry beyond the usual suspects of biotechnology and nanotechnology. Using the example of optical science, we argued that a science-based membership organization provides another means to define an emerging industry. Industry members of scientific associations, especially if they pay to participate, are a mechanism for identifying science-based industrial activity. OSA provided a list of its member companies for this study that we used to define the optical science industry. Examining OSA companies' patenting activities provided information on the relevant technology space, which allowed us to discern a short list of patent classes that define invention in optical science. This method may be generalized to identify inventive activity in other emerging and rapidly evolving industries and adds a new tool to the regional analysis of technology-based economic development.

Optical science is arguably a young and rapidly evolving platform technology that is based on a cross section of traditional optical science, electrical conductivity, and information and communication technologies (Kodama 1992). Optical science has diffused applications, and a large number of industries use optical science technology as an input. As a producer-goods industry, optical science is likely to be the type of industry that will engender large-scale economic growth (Freeman and Soete 1997). The applications of optics include telecommunication equipment, medical devices, scientific instruments, semiconductors, imaging and reproduction, defense and security, and retail logistics (SPIE 2006). A variety of places are engaged in inventive activity for this one emergent industry.

Moving from the industrial to the geographic description of the optical science industry, we identified different types of regional agglomerations among metropolitan areas that capture the essence of this industry. The first type of geography includes small, specialized metropolitan areas that are dominated by one or a few large companies. Since these places have a small number of patenting entities, the industry cluster may be vulnerable to a downturn in the economic fortune of the prominent entity. The long-term sustainability of these places may depend on economic development policies that encourage the entrepreneurship of displaced workers. Such policies are likely to be more effective if they ease the transition to entrepreneurship before an economic downturn. Another economic development strategy would be to encourage complementary upstream and downstream activities to diversify the local economy.

The second distinct category includes clusters that are driven by one or a small number of anchor companies, along with smaller firms within the same technical specialization. These places also benefit from the presence of local universities. Even if universities are not major centers of patenting, they likely play a role in entrepreneurial spin-offs and the transfer of knowledge through licensing, faculty consulting, and recruiting of students (Hendry, Brown, and Defillippi 2000b). The result is a vibrant ecology of large and small companies located in a region. These regions have typically earned a reputation as a focal place for the industry, especially since these places are smaller cities.

The third type of geography includes large urban agglomerations and places that are known to specialize in innovative activity more generally. Inventive activity in these places may be due to the presence of industries that use the platform technology in various applications. These large, diversified urban centers provide the Jacob's externalities that encourage the integration of an emerging industry with a range of applications. Such cities also have a wealth of universities that may conduct relevant research but most certainly provide the skilled labor that is important for inventive activity.

Studying optical science inventions reveals a geographic distribution that is different from the map of self-identified optics clusters in the United States. Self-designation reflects a policy choice and serves to mobilize resources. Places where the industry is already centered appear to have little need to organize formally and designate as a cluster. The articulation of a cluster may be more wishful thinking or future vision than current reality. The self-designated optics clusters appear to follow a path that is based on university-led technology development, which stands in stark contrast to observed patterns in prominent centers of the optics science industry. Only time will tell if this strategy will be successful.

Overall, these results indicate the importance of an existing industrial structure. Large firms are important to regional ecologies—a fact that is not typically incorporated into considerations of regional dynamics. The large companies not only serve as major hubs of innovative activity, but they also become anchors in small places, providing employment, contributing to the regional tax base, helping create a regional identity, and setting the agenda for regional economic development. They attract or spin off smaller companies that fill the local landscape, bringing additional employment but also providing expertise. Large firms are important to inventive activity. The willingness of large firms to set up branch-plant operations suggests that recruiting these facilities may be a cornerstone of a viable economic development strategy. Rather than harkening back to an older era of smokestack chasing, we suggest that the strategic recruitment of larger firms can significantly contribute to the vitality of the region. Our results suggest that there is certainly more to consider about the complementary relationships among mature industries, emerging industries, small and large firms, and research universities in the development of regional economies.

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