CHAPTER III: OPTICAL FIBER FOR COMMUNICATIONS

I. Introduction

The focus of this case is the invention and subsequent development of a method for making optical fibers that within 20 years displaced copper wire as the transmission medium of choice for most commercial applications in telecommunications systems and computer networks worldwide. Optical fibers about the size of a human hair can carry several orders of magnitude more information than copper wires many times larger in diameter, and they are stronger, lighter, and cheaper. In addition, the signal-carrying load of already installed optical fiber cables can be readily increased as signal-processing technologies improve. The invention came out of the interactions of physicists and electrical engineers extending electromagnetic waveguide theory and practice into the optical region, and materials scientists and engineers working to create clad-glass fibers with a minimum of defects and impurities that attenuate (i.e., scatter or absorb) a light signal.

The potential of optical communications had long been known, but efforts to find a suitable channel did not become serious until the invention of a powerful light source, the laser, in 1960. In addition to perfecting the laser itself (solid-state lasers that were reliable and long-lived at room temperature were not commercially available until the late 1970s), the biggest barrier to optical communications was the lack of a suitable transmission medium. Sending laser signals through the air only works at very short distances or when atmospheric conditions are clear. It appeared at the time (circa 1960) that the only practical means of optical transmission would be evacuated or gas-filled tubes lined with mirrors or lenses, whose expense and inability to make sharp turns would limit their use to high-volume long-distance trunk lines between metropolitan areas.

Although light-guiding optical fibers had been developed for medical endoscopes, instrument panel lighting, and other uses in the 1950s and 1960s, the clearest existing fibers could carry detectable light only a few meters. In the mid-1960s, the target was to reduce attenuation to 20 decibels per kilometer (dB/km) or less, which was nearly two orders of magnitude less than attenuation in the clearest optical glass available at that time. An attenuation of 20 dB (99 percent) over a kilometer meant that signal regenerators or repeaters could be placed about one kilometer apart, making optical fibers potentially competitive with copper transmission lines. The breakthrough occurred at Corning Glass in 1970, where researchers adapted chemical vapor deposition techniques for making bulk fused silica to making high-silica fibers that had the required physical and chemical characteristics.

The first fiber was still far from suitable for mass production and commercial use, however, and major improvements were made by the original inventors and others, notably Bell Laboratories, during an intensive period of research and development before optical fibers went into mass production in the early 1980s. R&D on optical fibers accelerated rapidly after the initial demonstration that low-loss fibers were feasible, resulting in a long period of continuous improvements in materials and especially in fabrication techniques and processes that led to maturation of the technology in the mid- to late-1980s. The innovation process was strongly driven by technological competition among firms in the U.S. and abroad (especially Great Britain, Japan, and Holland). The initial focus on reducing sources of light loss in the fibers was broadened to include improvements in the strength and durability of the fibers and in related technologies, especially fiber coating, splicing, and cabling techniques and cable connectors.

A major bottleneck limiting faster transmission for at least a decade after the breakthrough at Corning in 1970 was not the fiber itself, but the component devices that hang on the ends. For example, although it was recognized from the beginning that single-mode fibers would have the largest bandwidth, the cores of single-mode fibers were too small for efficient splicing and coupling into early lasers. Accordingly, the main emphasis during the 1973 to 1980 period was the development of multi-mode fibers. Their large cores were easier to splice and couple with existing lasers, and were also suitable for coupling with light-emitting diodes (LEDs), which were much more reliable and cheaper. At the same time, there were intensive and ultimately successful efforts to develop reliable semiconductor lasers that were not only small enough to work with single-mode fibers, but that worked at the longer wavelengths at which attenuation in optical fibers was lowest. An additional concern was the ability to splice small core, single-mode fibers with low loss and high reliability in a field situation. The coupling from laser to fiber could be accomplished in a more controlled situation than could field splicing, so research during this period also emphasized these and other kinds of problems associated with actual conditions during installation and maintenance of commercial lines (Schwartz interview, 1997).

After the Corning research team demonstrated the first optical fiber with loss less than 20 dB/km, there ensued a long period of continuous improvements and adaptations to the concurrent developments in lasers and other components of fiber optic communications systems. By 1984, attenuation had dropped to 0.20 dB/km in mass-produced fibers (0.16 dB/km in the laboratory), two orders of magnitude better than the first experimental fibers. The lower attenuation was due in part to improved fabrication techniques that reduced impurities, but it also stemmed from the development of supporting technologies (e.g., lasers, detectors, and other components) that operated at higher frequencies where intrinsic loss in silica fibers was lowest. Simultaneously, there were numerous improvements in the manufacturing process–e.g., in yields, deposition rates, preform size, draw rates, and size tolerances–that resulted in much higher production rates, lower unit costs, and better quality.

Field trials of fiber-optic telephone systems began in 1976. Corning and Western Electric opened full-scale production plants in 1980, the same year that the first sea trial of a commercial optical fiber cable was undertaken. The field trials were very successful, and fiber-optic cables began to go into regular service. AT&T’s fiber-optic cable system between Washington, DC, and New York entered service in 1983. By 1982, component development (e.g., lasers, detectors, couplers) and splicing techniques had proceeded to the point that telephone companies began to switch from multi-mode to higher performance single-mode fibers. Production lengths of commercial fiber increased from 2 km in 1982 to 25 km in 1987, while at the same time the price per meter fell six-fold. A fiber-optic cable could carry the same information as a copper wire cable four times larger and eight times heavier. By the end of 1988, more than 10 million kilometers of fiber were installed, and more than 90 percent of long distance telephone traffic in North America was carried on optical fibers. TAT-8, the first transatlantic optical fiber cable, was laid in 1988. The following box lists key events in the evolution of optical communications.[1]

Chronology of Key Events in Optical Communications

1841 Daniel Colladon demonstrated light-guiding in water jets in Geneva.

1854 British physicist John Tyndall shows that light is guided by a bending water jet and published the results in the Proceedings of the Royal Society.

1864 Scottish physicist James Clerk Maxwell predicts the existence of electromagnetic waves, only part of which was visible as light.

1880 Alexander Graham Bell invents the Photophone, using the optical effects of selenium.

1910 Hondros and Debye extend Maxwell’s equations to dielectric waveguides.

1937 Alec H. Reeves, ITT, invents digital pulse-code modulation.

1940s Corning scientists develop flame hydrolysis method/vapor deposition technique of making pure bulk silica (SiO_2).

1949-1954 Dutch group headed by Abraham C. S. van Heel, Technical University of Delft, develops technique of cladding fibers to improve total internal reflection at the surface of the core fiber.

1956 University of Michigan undergraduate Lawrence E. Curtiss makes the first glass-clad fiber by the rod-in-tube method as part of a project to make an improved endoscope.

1958 A paper by Arthur Schawlow, Bell Labs, and Charles Townes, Columbia U., presented the theoretical principles of the laser.

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[1] See also Hecht, 1998, and Keck, 1992.

May 1960 Theodore Maiman, Hughes Aircraft Co., demonstrated the first laser, using a synthetic ruby.

December 1960 Ali Javan and coworkers at MIT demonstrated the first operating gas (helium-neon) laser.

1961 Elias Snitzer, American Optical, wrote pioneering papers on theoretical and observed mode behavior in cylindrical dielectric waveguides.

1962 Research groups at GE, IBM, and Lincoln Laboratory at MIT demonstrated semiconductor lasers using gallium arsenide (GaAs).

January 1966 Charles Kao and George Hockham publish “landmark” paper arguing that the high losses of light characteristic of existing glass fibers were caused by minute impurities in the glass (e.g., transition metal ions and water) and did not result from intrinsic limits of the glass itself.

May 1970 Robert D. Maurer and Peter C. Schultz of Corning Glass apply for patent on an optical waveguide using fused silica for both core and cladding, the former doped with titania to make the index of refraction higher in the core, issued May 2, 1972, Patent No. 3,659,915. On the same day, Donald B. Keck and Schultz apply for patent on the inside vapor deposition method of producing optical waveguide fibers, issued Jan. 16, 1973, Patent No. 3,711,262.

June 1970 Morton B. Panish and Izuo Hayashi, Bell Labs, demonstrate a gallium arsenide (GaAs) semiconductor laser that could operate continuously at room temperature near 850 nanometers. Zhores Alferov and colleagues in Leningrad simultaneously invented a continuous wave laser.

December 1970 Charles Burrus, Bell Labs, published first small-area, high-radiance LED that was cheaper and much more reliable than lasers for the next decade.

May 1974 Bill French and William Tasker, Bell Labs, report attenuation of less than 2dB/km, the lowest level yet reported. MODIFIED

July 1974 John B MacChesney and colleagues at Bell Laboratories provide a detailed description of a commercially viable inside process(MCVD) for mass producing optical fiber.

1975 First commercial continuous-wave semiconductor laser operating at room temperature.

1976 Corning sued ITT for selling the U.S. government fibers made by Corning's method of optical fiber manufacture, the first in a series of patent infringement suits in which Corning prevailed over the next 15 years.

1976 AT&T carries out a realistic optical fiber system experiment in Atlanta Ga. with 144 multimode fibers in 12 fiber ribbons placed in a cable that was installed in conduit and spliced in a manhole. A repeater spacing of 7 km was demonstrated.

April 1977 GTE announced first use of optical fibers in regular service.

May 1977 AT&T began full operation of a trial optical fiber trunk system connecting two Chicago telephone switching offices a mile apart and an office building a half-mile from one of the switching stations. The system, which operated at 45 Mbs, carried voice, data, and video signals.

January 1979 Corning began production of optical waveguides in the world's first full-scale manufacturing facility in Wilmington, NC.

May 1980 AT&T installs and operates first standard commercial optical fiber system at 45 Mb/s using multimode fibers in Smyrna, GA.

1980 AT&T announced plan to build 611-mile fiber-optic network between Cambridge, Mass., and Washington, DC, using multi-mode fiber.

1980 First sea trial of a commercial fiber-optic telephone cable system, in Loch Fyne, Scotland, by Standard Telephones and Cables and British Telecom International.

February 1983 AT&T opened up the 372-mile network between NY and Washington, using 30,000 miles of optical fiber.

1984 AT&T fiber-optic cable entered service in Boston-Washington corridor.

1984 Corning sued to block Sumitomo from making fiber in the U.S. that infringed on Corning patents. After Corning won in October 1987, Sumitomo was ordered to stop production in the U.S. and paid Corning $25 million.

1988 First transatlantic optical fiber cable was laid, with amplifiers about 40 miles apart.

1991 TAT-9 laid from North America to Europe and UK–565 Mb/s, 80,000 telephone channels.

1994 First marine cables with all-optical amplifiers were laid, connecting Florida and U.S. Virgin Islands.

1995 AT&T Submarine Systems and KDD installed a fiber-optic network across the Pacific Ocean.

1997 Completion of FLAG (fiber-optic link around the globe), a 27,300 km fiber-optic cable system linking Great Britain and Japan, consisting of two 5.3 Gb/s optical-fiber pairs.

II. Defining the Boundaries of the Innovation

An optical communications system has three key components: light source, medium or channel, and detector.[2] The innovation that is the subject of this case study is the medium, the optical fiber that has become the standard transmission channel in telecommunications systems since the early 1980s, barely 10 years after the first low-loss optical fiber was invented in 1970 and 20 years after the first laser was demonstrated in 1960. Optical fibers are made of high-silica glass that is extremely clear to laser light at visible to near infrared wavelengths (roughly from 0.6 to 1.6 micrometers or microns), made with special materials and processes developed for the purpose in the 1966-1977 period.[3]

This case details how a method of making low-loss optical fiber for use was discovered in 1970 and subsequently developed into a commercially successful product–fiber-optic cable that by 1983 had replaced copper wire and coaxial cables and microwave and satellite relays as the transmission medium of choice in most long haul telecommunication systems applications. Other components of a working fiber-optic communication system had to be invented and developed as well, such as reliable and long-lived semiconductor lasers, modulators, amplifiers, and detectors, but their story is not told here except when advances in components affected optical fiber technology. The case study does *not* address concurrent developments necessary for the success of optical communications except as they affect the development of optical fibers. Thus the case does not discuss light sources and detectors, except to note that solid-state lasers were developed that could operate for many years at room temperature and at the longer wavelengths where fibers have their lowest intrinsic losses. Other developments not addressed include modulators needed to encode the laser signals, amplifiers needed to regenerate the signal over long distances, switches, and so forth. Nor does the case include cabling (e.g., the combination of empirical studies and analyses (e.g., cut-and-try experimentation followed by analytical modeling to explain the results and guide the next design choice.) The case does, however, address certain

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[2] A system of any significant length also requires repeaters or amplifiers, which consist of sets of detectors and lasers that regenerate the signal when it becomes weak and sends it on.

[3] A micrometer or micron is one-millionth of a meter.

developments affecting transmission properties of the fibers per se, including splicing and protective coatings.

III. The Evolution of Optical Fiber for Communication

Background

When the laser was first demonstrated in 1960, it was immediately recognized as an excellent light source for an optical communications system, assuming that technical development could make it reliable, long-lived, and affordable. Laser light is powerful, nearly monochromatic (i.e., single frequency), coherent (i.e., its light waves travel in phase), and highly directional. Most importantly, light waves are very short (about a millionth of a millimeter). Therefore they correspond to very high frequencies in the electromagnetic spectrum, hence light waves can carry much more information than the electrical pulses used in telephone wires, microwave radio relays, or even the millimeter-waveguide systems then under development in communications laboratories as the next generation in communications systems.[4] Information is carried by modulating the signal waves according to a code, for example, the 0s and 1s (bits) of binary code. Optical waves have a frequency 10^5 (ten thousand) times higher than the high frequency radio waves used in the best coaxial telephone cables, and so their bit rate can be much higher.[5]

Communications companies around the world were constantly on the lookout for higher capacity technologies, because they expected demand to grow strongly for the foreseeable future (not to mention the additional capacity the introduction of AT&T's Picturephone in the 1970s was expected to require).[6] Bell Laboratories, for example, investigated the potential of optical communications in 1945 and again in 1951, and concluded that there was no light source powerful and coherent enough to justify an R&D effort at that time (Fox and Kaminow, 1984:274). Instead, Bell and other telephone enterprises, such as the British Post Office's telecommunications branch, expected to develop millimeter-waveguide systems and put them into service in the 1970s along with satellite communications, supplementing the existing wire, coaxial cable, and microwave radio-relay systems. Like microwave radio, millimeter-waveguide systems were an extension of World War II radar development (Buderi, 1996). Although ultimately proved technically feasible in a field test in 1974, it was clear early on that the stringent degree of circularity and straightness needed in a millimeter waveguide transmission system would make it very difficult and expensive to build and maintain.

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[4] Busignies (1972) describes and compares the capacities of alternative transmission systems, including coaxial cable, microwave relay, communication satellites, millimeter waveguides, and early optical fibers

[5] Frequencies of optical signals are about 3×10^{14} Hz, compared with $3\text{-}10 \times 10^{11}$ Hz for millimeter waveguides, $4\text{-}11 \times 10^9$ Hz for microwave radio-relay systems, and about 10^9 Hz for the highest capacity coaxial cable systems.

[6] Bloom (1973) summarized the forecasts.

> However, the work was far from in vain and left a legacy for the future. The knowledge gained in the devices and techniques for high-speed digital systems was invaluable when attention turned to the light-wave medium. The insights gathered on the behavior of multimode guided-wave propagation were important elements in the successful development of low-loss optical fibers (O'Neill, 1985:647).

And, it will be shown, many of the people who worked on millimeter waveguides went on to work on the development of optical fibers in the United States and Great Britain.

As work continued on the laser in the early 1960s, laboratories for communications R&D around the world began to investigate the other key components of a working communications system in addition to the signal source, namely, the signal-carrying medium or channel and the receiver. Receivers in the form of photodiodes already existed and were commercially available. The big barrier was lack of a suitable channel to carry the laser signal. The alternatives included atmospheric transmission, beam waveguides (hollow tubes with mirrors or lenses), and glass or plastic fiber waveguides.

<u>Atmospheric Transmission</u>. Optical transmission through the open atmosphere was thoroughly investigated because, after all, the atmosphere is free and there are applications where connecting cables or tubes are not possible or desirable (e.g., satellite–ground communications, battlefield operations). NASA funded substantial academic and industrial research on atmospheric optical communications because of its interest in satellite communications, which turned out not to be practical.[7] Researchers at Bell Laboratories finally concluded that atmospheric optical transmission would not be practical because of severe losses from fog, rain, and snow, except for short special-purpose links of a few hundred meters or "fair weather" applications (Chynoweth and Miller, 1979:4).

The National Science Foundation began to support some of the university researchers previously funded by NASA as part of its problem-oriented Optical Communication Systems Program in the early 1970s. NSF-supported work included practical demonstrations of short-link systems (for example, connecting buildings at the University of Colorado with the computer center) and theoretical research on information theory and quantum limits on receiver design. Although the atmospheric communications systems funded by NSF demonstrated that such systems were feasible for certain uses, they could not achieve the level of reliability needed for commercial use. Most of the campus-based atmospheric systems were eventually replaced by fiber optic cables, because they have superior bandwidth.

<u>Beam Waveguides</u>. In 1962-1963, as the problems and limits of the millimeter waveguide became apparent (and because of the lack of a reliable solid-state amplifier at that time), research groups

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[7] Much of the NASA-supported work is reported in a special issue on optical communications of *Proceedings of the IEEE* (Vol. 58, October 1970), which was based on a conference sponsored by NASA and MIT in 1958. NASA still uses microwaves to communicate with its satellites (and uses optical systems for satellite-to-satellite communications where there is virtually no atmosphere).

at Bell Telephone Laboratories and ITT's Standard Telecommunications Laboratories Ltd. (STL) in Britain shifted their attention to optical communications (Hecht, 1997:8-10,9-1). One approach was to use a "light pipe," a hollow tube with a mirrored surface inside to reflect the light beam, but the attenuation or loss of light was too great, especially if the tube was bent, a problem even for point-to-point communications given the curvature of the earth.

Researchers at Bell Laboratories investigated the use of a "confocal lens" system to guide the light beam down a tube (Kompfner, 1965). A series of glass lenses could keep the beam focused and help bend it around curves. Although the loss of light by each lens due to absorption and scattering might be small, it turned out that the number of lenses needed in real-world conditions (due to the curvature and irregular shape of the earth) added up and the losses required too many amplifiers. In addition, the lenses had to be tied to some sort of sensors and servomechanism system that shifted them to adjust to thermal changes affecting the light beam. Bell's answer was the invention of the gas lens, in which the light rays could be bent with little loss by thermal or density gradients.

Although beam waveguides proved technically feasible in a field experiment, the physical tolerances were extremely close, and the beam was plagued by thermal fluctuations even though the tube was buried in the ground. Like the millimeter waveguide, it was obviously going to be very difficult and costly to build and maintain. At best it was only going to be competitive in uses involving the equivalent of a million voice circuits or more (Chynoweth and Miller, 1979:5).

Optical Fiber. Using glass fibers to transmit light was not a new or untried idea in 1960. British physicist John Tyndall showed that light is guided by a bending water jet in 1854, a demonstration of total internal reflection of light from a boundary with a medium of lower refractive index that is the "underpinning" of optical fibers (Keck, 1992: xviii).[8] In the 1950s, university groups in Britain, The Netherlands, and the United States worked on the development of transparent plastic and glass fibers to use as medical endoscopes (Hecht, 1997:Chs. 5-6). The idea of cladding the core fiber with a material of slightly lower refractive index to increase the internal reflection of light came out of that work (van Heel, 1954).[9] Soon after (1956), Larry Curtiss, a graduate student at the University of Michigan, created the first clad-glass fiber as part of an endoscope development project. He had been coating optical glass rods from Corning with plastic, with poor results. Curtiss then obtained a glass tube with a lower refractive index than the Corning rods, heated the tube until it collapsed on one of the Corning rods, and drew it into a fiber. It performed well, much better than plastic-clad fibers, and became the basis for the first working fiber-optic endoscope and several patents filed in 1957.

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[8] Tyndall is usually credited with the discovery, probably because he published the results in English, but Daniel Colladon demonstrated light bending in water jets in 1841.

[9] The idea was suggested to van Heel in 1951 by Brian O'Brien, then head of the Institute of Optics at the University of Rochester, but O'Brien did not follow up (Hecht, 1998a:Ch. 5).

Meanwhile, Will Hicks at American Optical was developing bundles of optical fibers as imagers and as “faceplates” that collect the image from curved tubes on to a flat surface (the military funded the R&D because it wanted to connect image-intensifier tubes in a series to enable soldiers to see better in dim light) (Hecht, 1997:6-14). Hicks drew finer and finer fibers to increase the detail in the images transmitted by the fiber bundles and began to encounter strange light patterns and colors in individual fibers. Hicks was not trained in electromagnetic theory, and he did not realize he had created single-mode fibers and was perhaps the first person to observe waveguide modes in the visible part of the spectrum (Hecht, 1997:7-13). Soon after, Elias Snitzer, a young physicist familiar with electromagnetic theory, was hired by American Optical when, at his employment interview, he recognized the patterns as waveguide modes. He spent several years working out the mode theory for cylindrical dielectric single-mode waveguides. The two articles he published in 1961 were relied on by the later inventors of the first low-loss fiber (Keck, 1992: xix).

Despite this progress, using optical fibers as the transmission channel for communications did not seem at all promising. The British were the first to investigate it seriously as an alternative to the millimeter waveguide. Although they tried the light pipe and confocal lens systems, such systems would not be very useful in small and built-up Britain, even if their problems could be overcome. Therefore, British researchers were not as put off by the initial finding that attenuation in high-quality optical glass was about 1,000 dB/km, a loss much higher than the 20 dB/km deemed necessary to compete with existing telephone systems in terms of amplifier spacing.

The attenuation problem was substantial, because the amount of light remaining falls logarithmically with distance. A loss of 20 dB/km means that one percent of the light remains; a loss of 1,000 dB/km means that only one part in 10^{100} remains, a vanishingly small amount. The high loss (half the remaining light every meter) was acceptable for endoscopes, faceplates, instrument-panel lighting, and other uses requiring short distances. Most laboratories found the challenge of increasing the clarity of glass so many orders of magnitude too daunting, which is why they tried hollow tubes as transmission channels first.

Antoni E. Karbowiak, who had shifted from heading STL’s millimeter-waveguide project to heading the optical systems group in 1962, attributed the problems with confocal lens waveguides to interference and other complications arising from multiple modes (Hecht, 1997:Ch.9). He was familiar with dielectric microwave guides and decided to try to develop a single-mode dielectric optical waveguide, despite the difference in wavelength (several millimeters vs. a thousandth of a millimeter). Karbowiak asked two young engineers, Charles Kao and George Hockham, to find materials clear enough to make low-loss optical waveguides, work they continued after Karbowiak left STL in 1964.

Kao and Hockham knew from electromagnetic theory that the best design for an optical fiber would be single-mode waveguide with a very small core and thick cladding that had a refractive index about one percent lower than the core. The problem was that the material for the core (and also the cladding because a significant amount of the optical power would travel in the latter) had to be much clearer than existing optical glasses. Jeff Hecht (1997:Ch.9) emphasizes that Kao approached the problem differently than other researchers. Instead of merely asking what attenuation rates were, he asked what the intrinsic limits of glass were on absorption and scattering of glass were if all impurities, such as transition metal ions (especially iron and copper) and water, were removed. Kao found there was little knowledge in the literature or among the experts he consulted, although an earlier study by Corning's Robert D. Maurer indicated that intrinsic scattering from thermal fluctuations in the density and composition of glass as it cooled could be as low as one dB/km at a wavelength of one micrometer (μm) and even lower at longer wavelengths.[10] In addition to their theoretical work, Kao and Hockham conducted some empirical investigations of their own on attenuation in different materials, finding losses as low as 0.2 dB/m (200 dB/km) in bulk fused silica between 0.8 and 0.9 micrometers. They concluded in a paper published in the proceedings of the British Institution of Electrical Engineers in 1966 that if a suitably low-loss material could be developed, a cladded optical fiber could be an important new medium for communications because it would have a larger information capacity and be made of cheaper materials than existing coaxial and radio systems. Most importantly, they saw no fundamental barrier to achieving a low-loss fiber (Kao and Hockham, 1966:1158).

> The crucial material problem appears to be one which is difficult but not impossible. Certainly, the required loss figure of around 20 dB/km is much higher than the lower limit of the loss figure imposed by fundamental mechanisms.

Although most researchers were skeptical, the British Post Office (BPO) along with the British Ministry of Defence began to support work on low-loss fibers at BPO's own laboratory, the University of Southampton, and STL and other companies.[11] BPO also announced its goals–losses less than 20 dB/km , bandwidths of 100 Mbit/sec or more, and low cost–early in 1966, and quoted them to all interested parties, including Corning's UK associate, Electrosil, and William Shaver, a scientist Corning sent around the world looking for opportunities.

Kao continued his attempt to show that low-loss glass was possible. He developed an instrument that could measure losses less than 20 dB/km. He tested samples of bulk fused silica from Corning and Schott and found losses as low as 5 dB/km (Jones and Kao, 1969). That result caused laboratories around the world, including Bell, to begin a serious optical fiber R&D program, if they did not have one already (Hecht, 1997:10-10).

To recap the situation at the end of the 1960s, the laser had been invented and was immediately recognized as the missing light source needed for practical development of optical

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[10] An effect that was exploited by developing lasers with longer wavelengths to help reach the low attenuation rates achieved later (less than 0.2 dB/km at 1.55 μm in 1984, compared with 16 dB/km at 0.633 μm in the original low-loss fiber developed by Corning in 1970).

[11] BP's research laboratory was able to mount a fairly large effort because management consultants had told BPO that its telephone division should be investing more in research (Hecht, 1997:10-6). BPO management boosted the research budget by £12 million pounds, which undoubtedly enabled BPO to launch a bigger effort in optical fiber than otherwise, because it was seen at the time as a high-risk project with payoffs several decades in the future.

communications. It was powerful, highly directional, and worked at a single frequency. It was also very amenable to digital coding. Moreover, although the early lasers were far from suitable for practical use in the field, the first semiconductor lasers were developed by 1963 and the outlook for eventually developing continuous wave lasers that worked for long periods at room temperature was good. Indeed, room-temperature semiconductor lasers were demonstrated just a few months after the first low-loss fiber was made.

AT&T and other telephone companies were always looking for higher capacity systems than the existing ones using radio and microwave signals. They were expecting demand to grow strongly, at least 10 percent a year, and perhaps more if the Picturephone took off in the 1970s. An optical communications system looked very attractive because it could carry enormous amounts of information. Bell Laboratories considered optical communications to be the eventual follow-on to its next generation system, millimeter waveguides, perhaps by the end of the century.

Assuming lasers and other components could be perfected, the showstopper was lack of a good transmission channel. Optical signals are very susceptible to degradation by poor weather and air pollution, and sending laser beams through hollow pipes was going to be difficult and expensive at best. In theory, clad-glass fibers were excellent optical waveguides, but the clearest fibers were still far too opaque to carry detectable light more than a few meters. The British were the first to undertake a serious and sustained investigation of optical fibers for communications, probably because the alternatives, millimeter waveguides and light pipes, were not well suited to their needs.

STL, aware of BPO’s telephone system needs, assigned several engineers to look into optical transmission channels. They conducted a detailed review of what was known theoretically and empirically about material and electromagnetic aspects of optical fibers and did enough experimental work of their own on materials and waveguide models to indicate that optical fibers would probably work and the low-loss materials needed could be developed. After publishing their results with the conclusion that there did not seem to be fundamental obstacles to achieving low-loss optical fibers in 1966, STL researchers continued their basic investigations on materials. They reported in 1968 and 1969 that attenuation in some materials, such as bulk fused silica, was substantially less than believed, and communications laboratories around the world geared up their R&D on optical fibers.

Breakthrough

Everyone was aware from Kao’s work that pure silica (SiO_2) was the clearest glass system, but only one research laboratory–Corning’s–elected to work with it. Everyone else adopted the strategy of purifying compound silicate glasses. The reasons are easy to understand. Pure silica is very difficult to handle because it has to be worked at extremely high melting temperatures (1600 to 1800º C).[12] Compound glasses, made for example by mixing soda and lime with silica, were developed to lower melting temperatures (600-900º C) and make glass easier to work with. The process of drawing fibers was well known from fiberglass manufacturing. Another problem with pure silica was its low refractive index. There was no known material with the lower refractive index required for the cladding.

It turned out to be possible to make low-loss fibers with compound glass. The British and Bell Laboratories did it eventually. The British used an innovative double-crucible (actually a crucible within a crucible) apparatus to draw the core and cladding simultaneously. But by then Corning invented a different process for making optical fibers using chemical vapor deposition techniques rather than melting. The Corning process was more difficult than conventional glassmaking but it became the basis for the standard production of all optical fibers (Midwinter and Guo, 1992:3). It proved far superior in reducing loss and optimizing other performance characteristics (e.g., refractive index profile). It also turned out that it could be scaled up to mass-production levels that greatly lowered its cost while preserving its performance.

William Shaver, Corning's traveling scientist, mentioned BPO's interest in optical fiber to Corning's research director, who asked Robert D. Maurer to look into the possibilities (Hecht, 1997:10-3). Maurer came to Corning in 1952 after earning a Ph.D. in low-temperature physics from MIT, and became manager of the fundamental physics research group in 1963. He had done the basic work on light scattering in glasses that Kao and Hockham used to conclude that the intrinsic limit on attenuation due to scattering was no more than 1 dB/km at 1 µm. More recently, Maurer had been looking into materials for electronic applications, lasers, and opto-electronic devices. That research would have made him aware that techniques for making extremely pure starting materials for making semiconductors (e.g., $SiCl_4$) were in commercial use that could also be used to make pure or doped silica. Although he did not follow the literature on waveguide behavior (for example, the Corning library did not subscribe to the journal with the Kao and Hockham article), he attended laser conferences where he encountered Eli Snitzer. Snitzer, like Maurer, was trying to make lasers by doping glass with europium (a rare earth), and he introduced Maurer to the waveguide view of optical fibers (Hecht, 1997:11-3).

Maurer decided to work with pure silica.[13] Many observers have attributed this in part to his "contrarian" nature, but Maurer's decision suited Corning's position and business strategy. Corning's small size would handicap it in competing head-to-head with the likes of AT&T, ITT, and other big companies in what was likely to be a lengthy brute-force effort to purify compound glasses. Corning's R&D strategy was to look for technological "big hits" or "home runs" that create markets the company could dominate for years, much as light bulbs, fiber glass, Pyrex and Corning Ware, and television bulbs had done before (Morone, 1997:130-136). Besides, Corning

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[12] And Corning had the only furnace in the world that could heat glass high enough to work silica (Hecht, 1997:11-5).

[13] This account is based mostly on 1997 interviews with Keck and Shultz and on Hecht (1997), supplemented by Duke (1983), Magaziner and Patinkin (1989), and Morone (1997).

already had a great deal of experience with silica. It was the world's leading maker of pure and doped silica mirrors for astronomy telescopes and spy satellites, windows for spacecraft, and ultrasonic equipment for the Navy. Maurer recognized that if Corning could make optical fibers from silica rather than compound glasses, it would have a special advantage in the market.

After some preliminary information gathering and experimentation by Maurer and an MIT graduate student working at Corning for the summer, Maurer decided to assemble a team. He borrowed Peter Schultz, who received his Ph.D. in ceramics from Rutgers in 1967, from Corning's glass chemistry department, and recruited Donald B. Keck, who had just received a Ph.D. in physics from Michigan State.[14] Schultz was the materials expert. He was working on ways to improve Corning's methods of making pure and doped bulk silica. Keck's lead assignment was to develop techniques for coupling light into the fibers and measure their attenuation, dispersion, and other characteristics (Keck interview, 1997). Maurer continued to work on the physics aspects.[15]

Schultz and Keck began with rod-in-tube experiments. In the 1930s, Corning scientist Frank Hyde had invented a chemical vapor deposition process for making virtually pure bulk silica for telescope mirrors. In the early 1940s, Martin Nordberg, another Corning scientist, had improved on the process by adding titanium dioxide as a dopant, which virtually eliminated thermal expansion. Schultz and Keck drilled the tubes from the purest boules of fused silica Corning made at its Canton plant, and the cores from boules of doped silica, to achieve the difference in refractive index needed to make the clad-fiber design work. They took the assembly to the lab of another Corning scientist with the furnace that could heat the silica until hair-thin filaments could be drawn. But the results were poor. They could not avoid creating bubbles and other imperfections at the boundary between the core rod and the cladding tube that scattered a lot of light.

After a lot of experimentation and brainstorming, Keck thought of sputtering doped silica inside a thick tube. Sputtering is a vapor deposition technique used in making layers of materials in semiconductor chips. Schultz suggested using the "soot" or flame hydrolysis method invented at Corning to make bulk silica to coat the inside of the pure silica tube with titanium-doped silica. Hyde had realized that burning the vapor of the liquid silicon tetrachloride ($SiCl_4$) in the flame of an oxy-hydrogen torch would produce a fine white power or soot of extremely pure silica. If the vapor is fed continuously into the flame, the soot accretes steadily until it forms a large boule. If the boule is heated to near the melting point, it sinters or fuses into a very clear glass. Nordberg showed that the vapors of $SiCl_4$ and $TiCl_4$ could be mixed before burning to create doped silica.

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[14] Schultz had an NSF graduate fellowship (Schultz interview, 1997). His thesis advisor did NASA-funded research on fused silica. His dissertation project was development of a glass doped with iron and lithium for computer memories (Hecht, 1997:11-5). Keck was a research assistant on his thesis adviser's NSF-funded project in molecular spectroscopy. His thesis was in spectroscopy, but his interest in electromagnetic theory had been stimulated by an inspiring professor (Keck interview, 1997).

[15] Other physicists at or recruited by Corning made important contributions to the theory behind the empirical results, including Felix Kapron and Robert Olshansky (Keck interview, 1997).

Schultz had been trying to improve those processes just before he was tapped for the optical fiber project.

Recall that Jones and Kao (1969) determined that bulk fused silica has an attenuation of about 5 dB/km. This is due to several factors that were also key in making low-loss fibers. The process of building up and sintering the soot produces few inhomogeneities that scatter light. The chloride vapors used as the starting materials are pure because they are distilled. The vapor pressure of $SiCl_4$ is much higher than those of unwanted impurities such as iron, copper, and water, and they are left behind. In fact, ultra pure chloride liquids made by multiple distillation steps were already commercially available for semiconductor manufacturing. Chemical vapor deposition had several additional advantages in making optical fibers. It minimized the imperfections at the core-cladding boundary. It would be easier to use the technique to make the small core needed to make single-mode fiber.

Maurer liked the new approach, because it furthered his goal of “creating a product the competition couldn’t easily match” (Magaziner and Patinkin, 1989:273).

> To achieve that, he felt, it wasn’t enough for the product itself to be unique; you also had to come up with a unique way of making it. Maurer instantly saw that Schultz and Keck’s idea would do that. It would give Corning a patented manufacturing process.

Schultz and Keck borrowed a shop vacuum to deposit the soot down the length of the tube the first time. Their equipment soon became more sophisticated, but it was slow going. The initial fibers absorbed a lot of light. The group proceeded empirically, because there was little experimental knowledge and less theory to predict what would happen if they tried this or that. The process did not follow the linear model. Rather, the experimental results drove the research to explain what had happened and why. Hecht describes the process (1997:11-8):

> They carried out a series of experiments, making preforms, and drawing fibers from them in various ways. They carefully measured the properties of the fibers to see what happened as they changed things. Between experiments, Keck and Schultz analyzed their findings and devised the next round of trials. It was a pattern common to every lab trying to make low-loss fibers: design an experiment, perform it, measure the results, deduce what happened, then design a new experiment.

In the spring of 1970, after months of experiments, the group finally figured out how to adjust the materials and the process to achieve a fiber with an attenuation of 16 dB/km. On May 11, 1970, Maurer and Schultz applied for patent on the product (Patent No. 3,659,915, issued May 2, 1972). On the same day, Keck and Schultz applied for a patent on the process (Patent No. 3,711,262, issued January 16, 1973). The “915” patent argued that the invention was a completely new and novel approach because of the type of material used: substantially pure fused silica rather than the soft and easily worked compound glasses normally used in the production of optical waveguides. The “262” patent argued that the method of applying a film of material with the optical and physical qualities desired for the core inside a tube of materials with desired qualities for the cladding was a new invention that produced low-loss optical fibers.

Maurer et al. wrote a paper for an international conference on trunk telecommunications by guided waves held in London at the end of September 1970 (a revised version was published in *Applied Physics Letters*) (Kapron et al., 1970). Maurer didn't want to reveal how the low-loss fiber had been made. The papers were ostensibly about radiation losses in some recently made optical fibers and only mentioned in passing that total loss in one fiber was less than 20 dB/km. Moreover, Schultz was not listed as an author, to obscure further that silica had been used. Maurer still got the basic message through. The news shocked the other laboratories, none of which was close to making a low-loss fiber.

In addition to the Corning breakthrough, another key event in 1970 was the demonstration of a semiconductor laser that could operate continuously at room temperature by Morton B. Panish and Izuo Hayashi of Bell Laboratories (Hayashi et al., 1970).[16] Although lasers that could meet telephone system standards for ruggedness and reliability were not developed until the late 1970s, these two advances in 1970–-low-loss optical fiber and room-temperature semiconductor lasers-–may have prevented the implementation of millimeter-waveguide systems. If millimeter waveguides had been built, they might have put off the development of optical fibers for many years (Keck interview, 1997). The London conference at which Maurer announced the Corning invention was mostly devoted to millimeter-waveguide systems, which at long last were ready for testing in the field. At the final session, Harold Barlow, one of the leaders in the development of millimeter waveguides, asked which technology would come next, the millimeter waveguide or optical fiber? When someone from the BPO said the millimeter waveguide, because it was ready, one of the BPO optical fiber researchers said: "I'm quite happy for you to lay the waveguides, and we will come along later and fill them with optical fibers" (quoted in Hecht, 1997:11-13). As it turned out, the millimeter waveguides were not built, in part because optical fibers and other components of a working communications system developed very quickly, with successful field tests beginning in 1976.

In 1970, however, Corning's fiber was still a long way from being ready for mass production and field use. As already noted, titanium dioxide made them too brittle. There were many more problems to solve: how to couple light sources into very small cores, how to splice the fibers, how to keep them from breaking, how to make them into cables, and how to connect the cables. In addition to the making optical fibers into practical transmission channels, many advances had to be made in the other components of a communications systems: lasers, modulators, amplifiers, switches, receivers, etc. Progress in the other components affected fiber development in various ways, especially as advances in laser technology made it desirable to design fibers that work at longer wavelengths (where attenuation and signal dispersion are lowest).

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[16] It turned out that Soviet scientists led by Zhores Alferov had developed a continuous wave solid-state laser at the same time, a development that was reported in an obscure Russian-language journal.

Commercial Development

> *Fiber optics went much faster from research to use than any big project ever before.* Charles Burrus, Bell Laboratories, quoted in Bell, 1978:102.

By the early 1980s, optical fiber was being manufactured in large volumes for commercial use, after successful field tests in the 1976-1980 period. Bell Laboratories improved the Corning chemical vapor deposition process by adding a external heat source to speed and improve the deposition of soot for the core on the inside of the silica tube and making other adjustments. Philips, a Dutch company, developed the use of microwave-driven plasma heating to increase the deposition and sintering of soot inside the tube. Meanwhile, after replacing titanium as the core dopant with germanium (GeO_2), which did not require the heat treatment that made the fiber brittle, Corning switched to an outside vapor deposition (OVD) process. OVD is more difficult to manage than inside vapor deposition, but it promised to be cheaper when (and if) production built up to hundreds of thousands of kilometers a year.

The major production processes described below are variations of the chemical vapor deposition method (Midwinter and Guo, 1992:4):

> In each, the key factor is that the glass is formed directly by oxidation of vapour that has been produced from multiple distilled liquid starting material that, as a result, is extremely pure and in particular has very low levels of water and transition metal ions.

<u>Inside Vapor Deposition (IVD)</u>.[17] Although the original Corning process was not used for long, even by Corning, a basic description of it here will make the steps taken to bring optical fiber into mass production easier to understand. A fused silica tube with an outside diameter of 3/4 inch, an inside diameter of 1/4 inch, and length of 5 inches was held in a lathe. Oxygen was bubbled through a tank containing a mixture of liquid silicon tetrachloride ($SiCl_4$) and titanium tetrachloride ($TiCl_4$). The $SiCl_4$ and $TiCl_4$ vapors carried in the stream of oxygen were passed through the center of a gas-oxygen flame which hydrolyzed them to form tiny glass particles, or a white soot. The particles were each about 95 percent SiO and 5 percent TiO by weight. The stream of doped soot was deposited on the inside of the tube by directing it in one end of the tube, while a slight vacuum was applied at the other end to increase the uniformity of the soot layer along the length of the tube. The tube was then heated until the soot sintered into a glassy layer about 1.5 to 2 microns thick. The assembly was heated further until it collapsed into a solid rod, called a preform. The preform was then mounted in a fiber-pulling tower. The tip was heated until it was soft enough to be drawn into a thin fiber. The ratio of the core diameter to the

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[17] The description of IVD is based on the descriptions in the original U.S. patents. Peter Schultz sometimes used the term "inside vapor phase oxidation," perhaps to emphasize that vapor phase oxidation is the common element of all the major production systems, although the vapor composition or means of oxidation might vary (see Schultz, 1979).

outside diameter of the preform stays the same as the preform is pulled into a fiber of smaller and smaller diameter. The fiber Corning patented was about 100 microns thick with a core about 3 microns across. The fiber was then heated about three hours in an oxygen atmosphere to restore the valence of the titania to its low-loss state. The cladding had a refractive index about 0.5 percent lower than the core, and the fiber carried a single light mode with an attenuation in the signal of about 16 dB/km.

The development of the first low-loss optical fiber drew primarily on two bodies of knowledge. One was knowledge Corning had gained from decades of working with silica. That knowledge was based on experience. There was little extant theory about why the materials used in making optical fibers behaved as they did during fabrication.[18] The second body of knowledge was electromagnetic theory. It was used, for example, to estimate the size of the core, the thickness of the cladding, and the difference in refractive index between core and cladding that would be needed to make a fiber that would carry only a single (the HE_{11}) mode. But the amount of doping needed to achieve the desired difference in refractive index and most other questions about how to make the materials do what waveguide theory called for had to be determined empirically.

The invention was carried out (that is, the knowledge bases were applied and extended) by doctoral scientists and engineers recruited by Corning. Corning had long recruited materials science engineers from Rutgers and other leading schools in ceramics, and in fact Schultz was already on board. There were fewer physicists at Corning, and several had to be recruited in the early years, beginning with Keck.

The Corning team made some immediate improvements, the most important being the use of germania (GeO_2) as the core dopant. GeO_2 does not need the heat treatment that TiO_2 does, which in turn avoids the brittleness the heat treatment introduces. Corning researchers also began the long process of finding and eliminating the remaining sources of light absorption. Keck, for example, collaborated with Arthur Tynes of Bell Laboratories in measuring attenuation in sample low-loss optical fibers across the spectrum of wavelengths from 0.6 to 1.06 µm (Keck and Tynes, 1972).

<u>Modified Chemical Vapor Deposition (MCVD)</u>.[19] Although Bell Laboratories had stepped up research on optical fibers after the Jones and Kao article of 1969, they were surprised by the Corning breakthrough a year later. Bell Laboratories was working with compound glasses and a long way from the 20 dB/km target. A. David Pearson at the Murray Hill laboratory was directed to expand his group and effort (Hecht, 1997:11-16). Although Pearson and others could guess

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[18] Maurer (1973) reviewed the empirical and theoretical literature. Most of it was industrial. Few articles by university researchers were cited.

[19] The descriptions of MCVD and the other major optical fiber production processes below are based on the following reviews: Schultz, 1979; Nagel et al., 1985; Morrow et al., 1985; Niizeki et al., 1985; VanDewoestine and Morrow, 1986; Nagel, 1988; Keck and Morrow, 1988.

that Corning had used pure silica, they did not know what the process for doping the core was. Although Corning had signed a cross-licensing agreement with AT&T in 1970 to give each company access to each other's electronic materials technologies, this did not cover optical fiber. In any event, Corning did not have to tell Bell Laboratories any more than was in their patents.

When the Bell Laboratories group figured out what the Corning process was, it added several important advances. One was discovering that using boron (B_2O_2) as a dopant lowers the refractive index of silica. They could use borosilicate glass for the cladding, which meant they could use pure silica for the core. That technique was later dropped, however, as the transmission wavelength moved from the initial one of about 0.8-0.9 µm to 1.3 µm and then to 1.55 µm where attenuation was lowest. Bell then turned to using fluorine in the cladding to lower the refractive index and germanium in the core to increase its index slightly (and using dopants in both core and cladding reduces processing temperatures).

One of Bell's major contributions was the "moving hot zone." In 1973, Bell researchers invented the MCVD process, in which a flame was moved down the outside of the tube as the chemical vapors were run through the inside (MacChesney et al., 1974). By studying the thermodynamics of the processes by which the soot was deposited and sintered to form a glass layer inside the tube, they had determined how a moving external heat source could increase the deposition rate substantially, an obviously critical variable in the economics of manufacturing (Bagley et al., 1979). Bell researchers also invented a plasma-enhanced MCVD using a traversing radio-frequency coil to speed the chemical reaction and increase the particle deposition rate (Nagel et al., 1985:35).

<u>Plasma-activated Chemical Vapor Deposition (PCVD)</u>. PCVD was invented at Philips Research Laboratories, West Germany, and developed there and at Philips Glass Division, The Netherlands. It was an inside vapor deposition process modified so that the chemical vapors are reacted within the tube by a microwave-generated plasma rather than a gas-oxygen torch (Corning) or traversing outside flame (Bell). One advantage of PCVD was high deposition efficiency. Another was reduction of OH by using fluorine as the carrier gas. PCVD fibers performed well, but process economics were limited by low deposition rates and short tube lengths (preforms could only produce 30 km lengths of fiber) (Keck and Morrow, 1988). Philips later left the optical fiber manufacturing business, after losing a patent case brought by Corning against its U.S. subsidiary .

<u>Outside Vapor Deposition (OVD)</u>. Even as other laboratories were figuring out how Corning made the first low-loss fiber, Corning was developing a variation of the original process that eventually became its main production method (U.S. Patent 3,737,292, filed January 1, 1972 and issued June 5, 1973). As in the IVD process, soot of the desired composition is made by passing halide vapors ($SiCl_4$, $GeCl_4$, etc.) through a flame. In the OVD process, however, the stream of soot particles is directed at a rotating and traversing target rod, where they build up layer by layer into a porous preform cylinder. The material that will become the core is deposited first, followed by the material for the cladding. When the appropriate amounts are deposited, the cylinder is slipped off the target rod. The cylinder is then dried, to eliminate the water introduced by the

flame hydrolysis step, and sintered. The cylinder is bathed in gaseous chlorine (the drying process is enhanced by running the gas through the center hole) as it is fed down through the sintering furnace. The hot zone of the furnace (between 1400 and 1600º C) sinters it into a solid-glass preform. Finally, the preform is then drawn into a fiber at higher temperatures (1800-2200º C).

OVD is more complex and requires more steps than MCVD and other IVD processes, because it is harder to control the environmental contaminants, such as dust and water, than working within an enclosed tube. Thus special clean room conditions are needed to keep out dust, and an extra step is required to "dry" the preform before it is sintered. Corning also had to figure out how to avoid fracture of the preform at the center hole due to differing thermal expansion coefficients of the doped core and cladding. OVD is economically advantageous in high-volume production, especially in terms of deposition efficiency and rates and preform size. By the late 1980s, Corning was drawing 90-km fibers in production, compared with 40 km with MCVD and 30 km with PCVD (Keck and Morrow, 1988:Tab.3). Longer lengths means lower overall time spent setting up for drawing and for testing, less material waste, and easier cabling (due to less splicing).

Vapor-phase Axial Deposition (VAD). VAD was invented at NTT Laboratories, Japan, and used by the major Japanese producers (NTT, Furukawa Electric, Fujikura Limited, Sumitomo Electric) (Izawa et al., 1977). It is an OVD process in which the soot is applied axially instead of laterally. The burners for the core and cladding are placed at the end of the preform and operate simultaneously. The main advantage of VAD is the large preform size (theoretically, it could operate continuously), and it does not have the center hole left by Corning's OVD process. In the late 1980s the standard production lengths were 100 km (Keck and Morrow, 1988:Tab.3). The biggest challenge was controlling the index profile to achieve high bandwidths.

The first low-loss fiber of 1970, which constituted a "proof-of-concept" (Lambright et al., 1987:II-12), was based on trial-and-error and admittedly crude. The Corning group itself became hopeful that optical fiber might become practical for communications when it made a germanium-doped fiber with an attenuation of 4 dB/km in June 1972. "That's when we knew we really had something," Schultz said later. Marketing studies done by Corning at that time were favorable (Chaffee, 1988:20).

The challenge was to understand and improve the performance characteristics of the fiber while reducing production costs and also respond to developments in the other components of fiber-optic communications system. For example, although single-mode fiber was clearly capable of superior performance, especially in bandwidth, lasers suitable for use in the field were not yet ready (that is, solid-state lasers that could operate continuously at room temperature for long time periods). Reliable and inexpensive light-emitting diodes (LEDs) were available, but it was very difficult to couple enough of their incoherent light into a core only four or five microns across. Attention shifted quickly to making multimode fibers with cores of about 50 microns.

The big problem with multi-mode fibers, because of the large cores, is modal dispersion. Modal dispersion is the spreading of light pulses because photons traveling down the axis of the fiber would arrive before photons that started out at an angle to the axis and thus have a longer, zigzag path to travel). Modal dispersion was solved by developing graded-index fibers.[20] In a graded-index fiber, the index of refraction gradually decreases from the center of the core out to the boundary with the cladding. In this structure, light traveling at an angle to the axis is bent back toward the center by refraction before hitting the core-cladding boundary. Because light travels faster in material with a lower refractive index, the refractive index profile can be adjusted to make a pulse of light arrive at the detector at nearly the same instant.

It turned out that the MCVD deposition process was well-suited for making multimode fiber, because the core could be built up to more than a hundred layers simply by changing the mixture of vapors to adjust the doping level, which allowed close control of the refractive index profile. AT&T and other telephone companies decided to go with multimode fibers early on (in 1972 or 1973), and these subsequently were made by MCVD. The first major long haul operational systems, the New York-Boston link built by AT&T between 1981-1983, used multimode fiber. By that time, however, laser development had advanced to the point that they could be used with single-mode fibers (they were not only long-lived at room temperature, they were reduced to the size of grains of sand). MCI, trying to get a jump on the AT&T breakup, ordered 150,000 km of single-mode fiber from Corning in late 1982. Single-mode fiber was well along in the R&D stage at that point, because Corning researchers had been tracking the development of lasers.[21] They attended national and international conferences on optical fiber telecommunications regularly although they rarely gave papers (Keck interview, 1997):

> From my vantage point, these kinds of meetings are very important to the key players. From industry's perspective, it is extremely valuable to enable you to learn about related fields. It helps you pace your own work.

Corning took a contract from the Navy in 1978-1980 for a design study of single-mode fibers and cables, although it was not yet clear that it would become the main product (Quan interview, 1997). The contract supported theoretical work on optimal single-mode structures and did not involve the technology for making it. It nevertheless put Corning in a better position to respond to MCI's large order in 1982.

The immediate post-invention period focused on reducing attenuation and so was dominated by additional research on materials used in optical fibers in order to understand their characteristics (especially scattering and absorption) and how to modify them (Bagley et al., 1979:168-184). This research was accompanied by the development of techniques for measuring

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[20] Graded-index fiber (Selfoc) was developed first in Japan in the late 1960s, although it was not low-loss fiber or made by using the chemical vapor deposition process.

[21] Advances in splicing techniques and improvements in the control of fiber geometry were crucial to the commercial development of single-mode fiber systems.

scattering and absorption losses in both bulk glasses (Bagley et al., 1979:212-225) and optical fibers (Cohen et al., 1979). The review articles just cited give detailed overviews of the research that had to be done, and research tools developed, to understand the details of the breakthrough in 1970 and achieve the additional order-of-magnitude reduction in attenuation between 1970 and 1985 or so. As one participant summarized it in 1976 (Chynoweth, 1976:29),

> Sufficiently detailed, comprehensive information about such basic quantities as the refractive index and the thermal-expansion coefficient of glass as a function of its composition was lacking ten years ago. This made it very much an empirical matter of seeking the optimum combinations for core and cladding materials....the amount of information in the literature on the actual absorption spectra of ions in various glassy hosts was inadequate. Often, it was not known with any great confidence what concentration levels of impurities could be tolerated in the glasses, or even the valence states in which they occurred. Furthermore, there were few analytical approaches available for measuring trace amounts of impurities in the raw materials and the glasses made from them. One of the spin-offs from this glass program has been an increase in the sophistication of related analytical chemical techniques.

The first fibers were made to go with gallium arsenide (GaAs) lasers. Research was indicating, however, that material dispersion in high-silica fibers would be zero at around 1.3 µm (or even longer wavelengths depending on the waveguide design). Researchers found that lasers made with indium and phosphorus as well as GaAs could be adjusted to operate at longer wavelengths, such as the zero-dispersion point at 1.3 µm. This opened up a second “window” in the late 1970s.[22] For a few years, Corning even made a “double window” fiber that could operate at both wavelengths, making it possible for telephone companies to switch to the second window at a later date when they were ready to replace 0.8 µm lasers with 1.3 µm lasers and detectors.

As optical fiber processing improved to the point that impurities were virtually eliminated, it became evident that the lowest attenuation would occur in a third window at about 1.55 µm. The focus shifted to making advances in optical fiber processing that would shift the zero-dispersion point to that wavelength. Simultaneously, lasers and detectors were developed to operate at 1.55 µm. As those systems began to go into production in the mid-1980s, attenuation fell to 0.16 dB/km in the laboratory and 0.20 dB/km in commercially produced fibers, permitting spacing amplifiers at 100 km or more, a development driven by requirements for undersea cables.[23]

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[22] Meanwhile, NTT and other Japanese companies were showing demonstrating low losses at longer wavelengths in fibers in which OH was greatly reduced.

[23] In the 1990s, all optical amplifiers consisting of optical fibers doped with the rare earth erbium have been introduced.

Early on, there were intensive investigations of fiber strength and fiber splicing, much of which was conducted at Bell Labs and shared with Corning (Schwartz interview, 1997). As for strength, pristine high-silica fibers are extremely strong, stronger than steel fibers of the same diameter, but their propensity to fracture grows quickly with any surface damage. Corning (under defense contracts) and other laboratories proceeded empirically and soon discovered that coating the fiber immediately preserved fiber strength (Maurer, 1975).[24] Research continued both on the fundamental understanding of fiber fracture and on better coatings and more economical processes for applying them. Early cabling efforts were also largely empirical but were guided by analysis. Designs were focused on controlling the strain seen by optical fibers to prevent damage in installation and via static fatigue. Analytic studies by Gloge and others at Bell Labs focused on the control of microbending loss by geometry, materials, and fiber design (Schwartz interview, 1997).

Crucial to the commercial application of optical fibers was the development of methods to fabricate the fibers without introducing mechanical flaws and the development of suitable in-line coating so that the fibers could be safely taken up on spools. The coating also had to provide the physical protection needed to allow the packaging of fibers into cables and to allow for handling of the fibers in the field in splicing operations. This work, carried out from 1972 to 1975, laid the groundwork for the Atlanta System experiment in 1976 and the Chicago field trial in 1977 (Schwartz interview, 1997). During the late 1970s and early 1980s, research contributed to great improvements in the manufacturing process, especially in deposition yields and rates, preform size, draw rates, and size tolerances, resulting in much higher production rates, lower unit costs, and better quality in the fibers and easier cabling. Each of the companies conducted extensive research programs to understand each step in their fabrication process and make changes and adjustments to improve fiber performance or to improve process efficiency. Scientists at Bell Laboratories, for example, studied the vapor oxidation process, how soot particles were deposited on the tube wall (which turned out to be a process called thermophoresis), and the sintering process (Nagel et al., 1985). The results were used to increase deposition rates by adjusting vapor composition, flow, and the heating process. For example, Bell scientists worked out a combination of radio frequency plasma heating to react the vapors, downstream external cooling to enhance thermophoretic movement of soot to the tube wall, and external flame heating to sinter the deposited material into clear glass. When they found out that optimum reaction temperatures softened the tube, they figured out how to pressurize and rotate the tube to keep its profile round. Similar activities went on at Corning and other fiber producers.

During most of the time period covered, optical fiber research was conducted primarily by the companies involved. Corning, in the tradition of glass companies, did not publish much about its work. Bell Laboratories published much more but even its reports did not provide the detail other companies could use directly without doing the same research themselves.

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[24] There were also DOD-funded studies of radiation effects on optical fibers (e.g., Maurer et al., 1973).

U.S. companies did not look to universities for research. The universities were not involved in much research on fibers in the late 1960s and, in the initial period, the companies were reluctant to share the information the universities would need to start programs. The large companies (AT&T and Corning) were also leery about taking federal funding for research on optical fiber fabrication, because they did not want to share the rights to any discoveries which they felt they make on their own. That view began to change in the 1980s as the patent battles subsided and fiber optics industry matured and faced substantial challenges from abroad, especially Japan. Several reports assessed the fiber optics industry and identified research needs. A 1984 report warned that the U.S. lead in fiber-optics R&D was being challenged by other governments that were targeting funding on fiber optics development and graduating more engineers (U.S. Department of Commerce, 1984:45-47). A 1988 report by the National Research Council (NRC), commissioned by NSF and the Navy and Air Force research offices, concluded that the Japanese had achieved a position of technical excellence in photonic technology and were ahead of the U.S. in a number of areas of opto-electronics. The only major example of U.S. leadership was in optical fibers, where there was “an excellent coupling between research and development and manufacturing” (NRC, 1988:65-66). The NRC report identified a number of technologies needing further research. They included “coherent communication systems, components for wavelength-division multiplexing, low-noise avalanche photodiodes, optical amplifiers, external modulators, fibers with low loss and low dispersion over extended bandwidths, and practical integrated optics technologies.” The NRC recommended that industry establish one or more joint industry-university-national laboratory research centers and the federal government provide “stable, basic research funding with an increased emphasis at the interface of research and development,” including materials research. NSF involvement in stepped up efforts to support research on photonics materials and devices in the 1980s, including engineering research centers and materials research groups, are described in Section IV. Industry also became more involved in university research centers.

Influence of intellectual property rights

The box below lists eleven important early patents in fiber optics fabrication. The patents were identified through the literature describing the evolution of the innovation (e.g., Hecht, 1997a; Morone; 1997, Magaziner and Patinkin, 1989; and IGI Consulting, 1988) and through our interviews with contributors. It is sometimes instructive to examine the “other references” section of patents as a possible indication of the patent’s reliance on fundamental research. Because such references are included at the preference of either the inventor or the patent attorney, and not systematically, such data are unreliable. Nonetheless, in some cases some interesting observations can be made. In this case, only a few references are cited in the patents. The Corning patent on a germania-doped waveguide (1973) cites a 1961 Armed Services Technical Report from the Armour Research Foundation, and an article by W.S.C. Chang in the 1971 issue of *Applied Optics* on guided waves in germanium thin films.[25] The only other citations appear in Bell

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[25] Chang, at Washington University, was later to become an NSF grantee in optical communication.

Laboratories' patent on the modified CVD process; citations include a 1966 textbook on chemical vapor deposition, two articles in the journal *J. El. Soc.*, 1964 and 1970 on CVD processes, and a conference paper by Bell Labs' MacChesney. Although far from conclusive, this suggests that the technology's dependence on academic research was slight. This tentative suggestion will receive further support in later sections of the case.

KEY EARLY OPTICAL FIBER WAVEGUIDE PATENTS

Corning:

Robert D. Maurer and Peter C. Schultz, Fused silica optical waveguide, U.S. patent 3,659,915, May 2, 1972. Filed 5-11-70. [The original product patent.]

Donald B. Keck and Peter C. Schultz, Method of producing optical waveguide fibers, U.S. patent 3,711,262, Jan. 16, 1973. Filed 5-11-70. [The original process patent.]

DB Keck, PC Schultz, Frank Zimar, Method of forming optical waveguide fibers, U.S. Patent 3,737,292, June 5, 1973. Filed 1-3-72. [Outside vapor deposition (OVD) or ìsootî process, with core doped with material such as Titania or Germania.]

Larry L. Carpenter, Method of forming light focusing fiber waveguide, U.S. Patent 3,823,995, July 16, 1974. Filed 3-30-72. [First low-loss graded-index fibers, made by depositing layers of progressively lower refractive index to form the core, using either inside or outside vapor deposition.]

Robert D. Maurer and Peter C. Schultz, Germania containing optical waveguide, U.S. Patent 3,884,550, May 20, 1975. Filed 1-4-73. [Replaced titanium dioxide with germania.]

Robert D. DeLuca, Method of making optical waveguides, U.S. Patent 3,933,454, Jan. 1976. [OVD using gaseous chlorine drying in the zone sintering process, instead of methane flame, which left too much water.]

AT&T Bell Laboratories:

John B. MacChesney and PB OíConnor, Optical fiber fabrication and resultant product, U.S. Patent No. 4,217,027, August 12, 1980 [Modified CVD process, in which particles are deposited and fused in one step, resulting in a two-order-of-magnitude increase in fabrication rate]

JW Fleming, Jr., John B. MacChesney, and PB OíConnor, Optical fiber fabrication by a plasma generator, U.S. Patent No. 4,331,462, May 25, 1982. Filed 4-25-80. [Plasma enhanced MCVD, a process improvement leading to deposition rates 20 times higher than initial studies, due to better understanding of the process mechanisms.]

NTT Laboratories, Japan:

Tatsuo Izawa, T Miyashita, and F Hanawa, Continuous fabrication of high silica fiber preform, U.S. Patent 4,062,665 (1977). [Vapor axial deposition (VAD) process.]

Philips Research Laboratories, West Germany, and Philips Glass Division, The Netherlands:

U.S. Patent 4,145,456. March 20, 1979. Reissued (No. 30,635) June 2, 1981. [Plasma-activated chemical vapor deposition (PCVD) process, assigned to U.S. Philips Corporation.]

Vitreous State Laboratory, Catholic University:

Pedro B. Macedo and Theodore A. Litovitz, Method of producing optical waveguide fibers, U.S. Patent 3,938,974 (1976). [Phase-separable glass method that was made by Pilkington Ltd. and other companies.]

Corning fiercely and successfully defended its product and process patents on the first low-loss optical fiber and subsequent improvements against domestic and foreign rivals. Corning was in court continuously from 1976 until 1990, when the patents began to expire, winning eight times against seven defendants. Corning clearly saw patent rights as key to protecting their market share. Although Corning was very successful in its patent infringement suits, process patents are often weak protection in a fast-changing technology. Corning also signed a cross-licensing agreement with AT&T in 1970, which gave Signetics, a Corning subsidiary making integrated circuits, access to valuable AT&T semiconductor technology. A subsequent patent-licensing agreement in 1975 gave AT&T access to Corning’s newly invented optical fiber technology. In other words, Corning did not have any patent protection at all against its largest potential customer and competitor. AT&T made it clear that it intended to develop and manufacture its own optical fiber (Magaziner and Patinkin, 1989:275). Corning therefore adopted a strategy that was relatively new for it: continuous technological innovation and improvement to outperform all competitors in cost and quality (Morone, 1997:Ch.4).

The dual strategy–strong patent defense and vigorous technological innovation–put Corning in a position to capture much of the non-AT&T market that emerged after the AT&T breakup. MCI ordered 150,000 km of single-mode optical fiber from Corning in January 1983, and GTE, Sprint, and US Telcom soon followed with 100,000 km orders each (Chaffee, 1988). In all, Corning invested $100 million in R&D over the 17 years it took for a market to develop (1966-1883) (Morone, 1997:185). U.S. sales of single-mode fiber increased rapidly from 199 km in 1980 to 14,520 km in 1982, and to 114,700 km in 1983, 95 percent of it made by Corning or its licensees (IGI Consulting, 1988:23).

Corning's patent protection strategy was very important–it made the potential competitors other than AT&T pay Corning royalties for what Schultz-Keck-Maurer invented. But the cross-license may have been even more important. It required Corning to adopt a much more aggressive approach to R&D on optical fibers and production improvements than they would have made if protected just by patents. Corning could not rely on its patents alone to maintain a competitive edge; Western Electric could and would make all the fiber that AT&T, which accounted for 80% of the telephone market, needed. Corning soon abandoned the original process Keck et al. had invented, the inside chemical vapor deposition (IVD) process, which is what most of the other companies, including Bell Labs, ended up using, with some substantial modifications. Corning went to the outside vapor deposition process (OVP) and also made aggressive marketing decisions. Corning managers ripped out the production machinery every 18 months in their plant in the early years–far ahead of market pressures–so that, when potential customers were looking around, Corning would always be competitive or ahead of AT&T and other companies in quality and price (see Magaziner, 1989, and Morone, 1997). OVP was more complex than IVP, but Corning figured if they could master the problems through aggressive R&D, the mass production economics would be better, and they were right. For Corning, the economic curve crossed over in 1981, which is basically when mass production began (Keck interview, 1997). That meant that, instead of relying for income on royalties from ITT, Sumitomo , and other licensees for using IVP, Corning sought to participate in the market outside AT&T for fiber. This was much more lucrative; Corning reaped not only the royalties but also a larger profit because, thanks to OVP, they enjoyed lower production costs.

IV. The Role of the National Science Foundation

To document systematically the role of the National Science Foundation in each of these cases of innovation, SRI employed the following strategies:

- Identify key contributors to the innovation and determine, via interviews and the NSF awards database, whether they have received support from NSF during their academic training or during the development of the innovation.
- Identify publications that represent significant contributions to the innovation and determine whether the research reported was supported by NSF.
- Examine references to the scholarly literature made in key patents to determine potential links to academic research or researchers supported by NSF.
- Use keyword searches of the NSF awards database to identify the profile of NSF support for research related to the innovation.

This section reports on the results of these strategies in the case of optical fiber. We begin with a description of the institutional homes and sources of support for key contributors to optical fiber, and follow with the profile of support for the broader field of optical communication using data from the awards database.

Support for Key Contributors to Optical Fiber

In 1975 and again in 1980, the IEEE Press published a volume of reprints on optical fiber technology. The first was edited by Detlef Gloge of Bell Laboratories and the second by Charles Kao of ITT. The volumes were “aimed at providing a comprehensive survey of the key developments” in the field over the time frames covered. Selection of papers was made “mainly on the basis of subject coverage and illustrative examples, with an additional criterion of a high standard of scholarship” (Kao, 1980: vii). The first volume contained 53 papers covering the pre-1976 period, and the second 35 papers covering 1976-1980. To the extent that these papers represent the major scholarly contributions to the development of optical fiber technology to 1980, the institutional affiliations of the authors and the source of support for their research are of interest. The fact that both are edited by major figures in the development of optical fiber in industry may indicate that the selection is biased toward industry contributors, but other data in this case study support the conclusion that these tables illustrate: the major advances in fiber optic material and material processing were made in industry, at least during the first ten years following the Corning breakthrough. The tables also illustrate the disproportionate contribution of Bell Labs researchers to the literature, in part because of the Labs’ tradition of encouraging open publication of research results.

Table 1: Institutional Affiliation and Sources of Support, Optical Fiber Research Contributions to 1976 Published in Gloge, ed. (1975)

Affiliation	Number of papers*	Acknowledgment
Bell Labs	28	none
Corning Glass	1	none
CSIRO (Australia)	1	none
SRC (United Kingdom)	2	none
Jenaer Glaserk Schott & Gen.	3	none
Western Company	1	none
Bell Labs	1	NATO-CRN (Italian) Fellowship
Plessey Telecom Research	1	none
Nippon Electric/Nippon Glass	2	none
University of Southampton	2	UK Science Council/Pirelli General
Standard Telecom Lab (UK)	1	British Post Office
Catholic University	1	Office of Naval Research
University College London	1	British Post Office
Corning	1	ONR Contract N00014-73-C-0293
Naval Electronics Labs	1	none
Corning/Army Electronics Command	1	none

Naval Research Lab	1	none
Bell Labs/Nippon Glass	1	none

* number of papers can exceed 53 due to multiple sources of support

Table 2: Institutional Affiliation and Sources of Support, Optical Fiber Research Contributions, 1976-1980, Published in Kao, ed. (1980)

Affiliation	Number of papers*	Acknowledgment
Bell Labs	9	none
Corning Glass	4	none
Naval Research Lab	1	thanks to NSF program manager
Nippon Telephone and Telegraph	4	none
Western Electric	1	none
Standard Telecom Labs	2	none
Hughes Research/Bell Labs	1	none
Fujikura Cable Works/NTT	1	none
University of Massachusetts	1	Material Research Lab, U. of Mass.
Naval Research Lab	1	Defense Nuclear Agency/Naval Air Systems Command
Bell-Northern Research	1	none
University College London	1	UK Science Research Council/UK Ministry of Defence
Naval Research Lab	1	none

Rockwell	1	Air Force Avionics Lab/NASA
AEG (Germany)	1	none
Bell-Northern	1	Canadian Dept. of Communication
ITT	1	Army Electronics Command
British Post Office	1	none
Sumitomo Electric	1	none

*number of papers can exceed 36 due to multiple sources of support.

In 1979 and again in 1988, research directors at Bell Labs published comprehensive reviews of recent research in optical fiber communications: *Optical Fiber Communication* and *Optical Fiber Telecommunications II*, the first edited by Stewart Miller and Alan Chynoweth , and the second by Miller and Ivan Kaminow. Chapter authors in both volumes are from industry, but NSF grantees in academia are cited in the chapters on light sources, detectors, integrated optics and electro-optic devices, and receiver design (Shyh Wang, Berkeley; Amon Yariv, Caltech; JT Boyd, U. of Cincinnati; Clifford Fonstad, MIT; JM Ballantyne, Cornell; Gregory Stillman and Wolfe, U of Illinois; William S.C. Chang, Washington, U.; Carl Helstrom, UCSD; and Theodor Tamir, Polytechnic Institute of NY). Of course, this is not necessarily an indication of the amount of influence these grantees had on the work described, only that appropriate recognition was being given.

NSF Support for Optical Fiber Research, Education, and other Activities

The NSF awards database offers an opportunity to trace NSF support for particular technical fields over time. The problem is that as of 1997 only project titles, not abstracts, were available for all NSF awards. This is a crude way to identify relevant projects, principal investigators, and performing institutions. One reason is that principal investigators, not NSF, decide how to title their projects, so use of technical terms is not consistent within fields or over time. Second, as fields develop and change, new terminology is employed. The result is that any keyword search of the awards database yields only a general picture of the Foundation’s support profile.

In the case of optical fiber, the most fruitful (i.e., inclusive) keywords were “optical communication.” It is instructive to present the results of searches of the database using “optical fiber” as well as “optical communications.” Figure 1 shows the profile of support for “optical fiber” from 1976, the time of the first award using these terms, to 1990. The accompanying table (Table 1) shows the titles of these awards. Compare these results with those obtained using "optical communication:" Figure 2 and Table 2. It is clear from both tables that NSF did not target optical fiber as a material

Figure 1

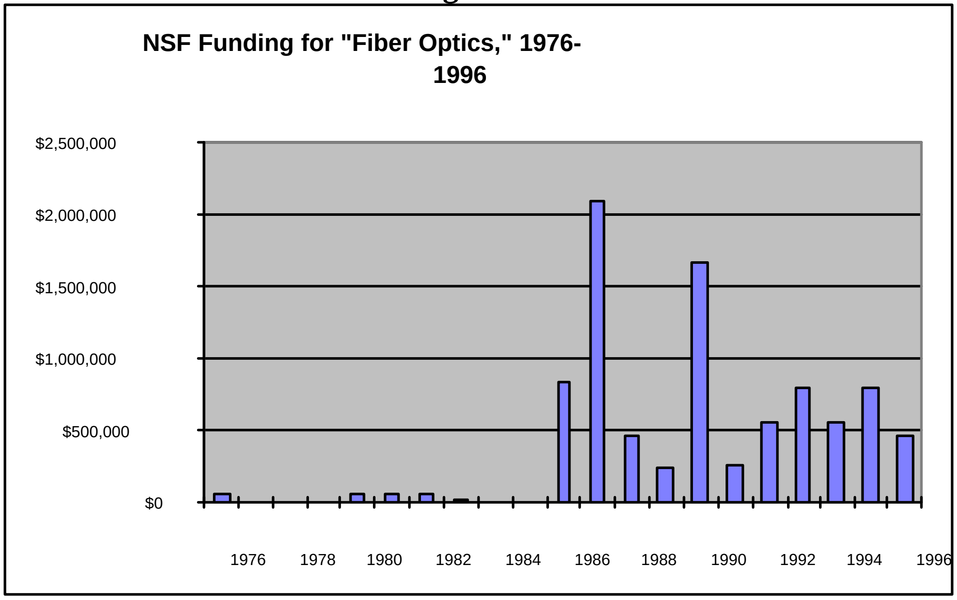

Table 1: Projects Related to "Fiber Optics," 1976-1990

Start Year	TITLE
1976	Rays and Beams -- Applications to Optical Resonators, Optical Fibers, Integrated Optics and Microwave Acoustics
1980	Fiber Optics Experiments For Undergraduate Engineers
1980	Research Initiation -- Fm Optical Fiber Communications
1981	Fiber Optics Concepts and Applications
1981	Fiber Optic Laboratory Improvement
1982	Fiber Optic Communications Systems For Student Laboratories
1982	Research Initiation: Integrated Optical Components For Coherent High Data Rate Optical Fiber Communication Systems

1982	Topic No. 8: Feasibility Investigation For an Electrostatically Bonded Fiber Optic Coupler
1983	Wavelength Division Multi/Demultiplexer System and Mult- Fiber Cable Connectors For Fiber Optics Communications
1986	High Energy Laser Heating of Optical Fiber Preforms: Thermophoretic Deposition and Collapse
1986	Magnetostatic Interaction of Guided Optical Wave & Magnetostatic Surface Waves in Yittrium Iron Garnet-Novel MSW/Fiber Optic Devices for Lightwave Communication
1986	High Speed Fiber Optics Local Networks for Integrated Traffic; U.S.-Italy Program
1986	Optical Fiber Interferometer to Study Surface Charges Produced by Triboelectric Forces
1986	High Energy Laser Heating of Optical Fiber Preforms: Thermophoretic Deposition and Collapse
1986	Presidential Young Investigator Award: Nonlinear Optical Studies of GaAs Heterostructures and Optical Fibers
1986	Automated Optical Fiber Analysis System for Fiber-Optics Laboratory
1987	Berry's Phase of Solitons in Optical Fibers
1987	Expedited Award for Novel Research: Berry's Phase of Photons In Optical Fibers: Quantal Aspects
1987	Rapid Sampling of Fluorescence Using Laser/Fiber Optics
1987	Presidential Young Investigator Award: Nonlinear Phenomena in Optical Fibers and Semiconductor Lasers
1987	Gigabit-Rate Adaptive Fiber Optics Local Area Networks
1987	Fiber Optic Quantum Communications
1988	Optical Fiber Preforms: Study of the Outside Vapor Deposition Process
1988	Optical Fiber Device Research

1988	Research Initiation: Multi-Channel Wavelength-Division- Multiplexed Technique in a Soliton-Based Optical Fiber Communication System
1989	Instrumentation for Undergraduate Optical Fiber Projects
1989	Optoelectronics and Fiber Optics Laboratory Upgrade
1989	High Temperature Superconducting Films on Optical Fiber Coated by a Pulsed Laser Deposition Technique
1989	A Fiber Optics Instructional Laboratory
1990	Study of Cross-Phase Modulation in Optical Fibers
1990	Photoelectronic Detectors Lasers and Fiber Optics: A Technologically Current Approach to the Study of Optics
1990	Fundamental Deposition Processes in Optical Fiber Manufacturing
1990	An Undergraduate Fiber Optics Telecommunications Laboratory
1990	U.S.-Italy Cooperative Research: Integrated Voice, Data and Video Communications on High Speed, Fiber Optics Networks
1990	Fundamental Deposition Processes in Optical Fiber Manufacturing
1990	Group II Fluoride Coated Scintillating Optical Fibers
1990	Architectures for Multichannel Optical Fiber Communication Using Arrays of Surface Normal Devices
1990	No Silica Based Optical Fibers
1990	Improving the Laser Electro-Optics/Fiber Optics Curriculum Through the Acquisition of an Ultraviolet Pulsed Laser System
1990	Undergraduate Lasers, Fiber Optics, and Photonics Laboratory

Figure 2

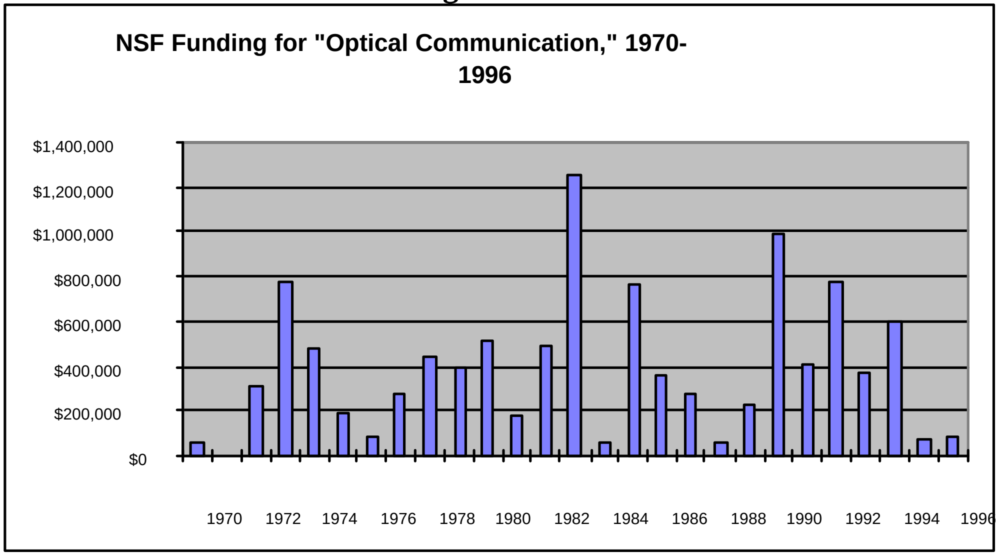

Table 2: NSF Project Titles Related to "Optical Communications," 1970-1980

Start Year	Project Title
1970	Optimum Methods of Optical Communication Through Atmospheric Turbulence
1972	METAL-OXIDE-METAL DIODES IN OPTICAL COMMUNICATION SYSTEMS
1972	Metal-Oxide-Metal Diodes in Optical Communication Systems
1972	COMMUNICATION THEORY FOR OPTICAL COMMUNICATION SYSTEMS
1972	WORKSHOP IN OPTICAL COMMUNICATION SYSTEMS
1972	APPLICATION OF SIGNAL DETECTION THEORY TO OPTICAL COMMUNICATION
1972	INTEGRATED OPTICS IN OPTICAL COMMUNICATION SYSTEMS
1972	COHERENT OPTICAL DEVICES FOR COMMUNICATIONS
1973	VISIBLE AND INFRARED OPTICAL COMMUNICATION IN THE ATMOSPHERE

1973	Optical Communication Based on Photoelectron Arrival Times
1973	OPTICAL COMMUNICATION BASED ON PHOTOELECTRON ARRIVAL TIMES
1973	DIVERSITY TECHNIQUES IN ATMOSPHERIC OPTICAL COMMUNICATION SYSTEMS
1973	Diversity Techniques in Atmospheric Optical Communication Systems
1973	Optical Communication Devices
1973	OPTICAL COMMUNICATION DEVICES
1974	OPTICAL COMMUNICATIONS BASED UPON PHOTOELECTRON ARRIVAL TIMES
1974	Optical Communication Systems For Improved Low Visibility Communication
1974	OPTICAL COMMUNICATION SYSTEMS FOR IMPROVED LOW VISIBILITY COMMUNICATION
1974	DIVERSITY TECHNIQUES IN ATMOSPHERIC OPTICAL COMMUNICATION SYSTEMS
1975	Research Initiation - Analysis of Sequential Detection and Estimation in Optical Communications
1975	Workshop on Optical Communications Through the Atmosphere, Beaverton, Oregon, Summer, 1975
1975	Optical Pulse Communication Through Finite Atmospheric Turbulence
1975	Coherent Optical Devices For Communication
1975	Guided-Wave Acoustooptic and Electrooptic Interactions And Devices in Optical Communications Systems
1975	Thin Film Bragg Devices For Integrated Optical Communication Systems
1976	Visible and Infrared Optical Communication in the Atmosphere

1977	Integrated Optical Silicon Devices For Applications to Optical Communications and Optical Signal Processing
1977	Integrated Optical Communications For Multiprocessor Computers
1977	Quantum Detection and Estimation Theory With Application To Optical Communications
1978	Metal-Insulator-Metal Diodes For Optical Communications
1978	Guided-Wave Acoustooptic and Electrooptic Devices in Wideband Optical Communication and Signal Processing Systems
1978	Optical Communication Devices
1978	Laboratory in Optical Communications
1979	An Investigation of Optical Communication Systems For Improved Low-Visibility Communication
1979	Diversity Arrays For Optical Communications Through the Atmosphere
1979	Photon-Counting Optical Communications in the Presence of Dead Time
1980	Devices For High-Rate Optical Communications
1980	Research Initiation -- Fm Optical Fiber Communications
1980	Industry/University Cooperative Research Program: Avalanche Photodiodes Using Quaternary Alloys For Fiber Optical Communication Systems
1980	Guided Wave Acoustooptic/Electrooptic Devices in Wideband Optical Communication and Signal Processing Systems

or its processing as areas for priority funding prior to the mid-1980s. Instead, NSF supported the related areas of opto-electronics and photonics, the components essential for the functioning of an optical communications system. Also apparent are awards for laboratory development and instructional materials in optical communication systems. Between 1970 and 1996 NSF spent just over $10 million on the areas of research, education, and infrastructure support. During the period of greatest interest in this case, 1970-80, these awards were clearly in the opto-electronics area, at least regarding technology itself as opposed to education and training. The award titles show that most awards dealt with communication systems or opto-electronic devices for use in such systems. Only until the late 1980s do a few awards related to the processing of optical fiber begin to appear.

A report by the Congressional Office of Technology Assessment in 1985 summarized the situation in the U.S. concerning research on fiber optic communication (U.S. Congress, 1985). The report noted that most research and development was at that time being performed in industry, with Bell Labs, Corning, and ITT leading the way. Longer-term research was being supported by NSF at universities, but its focus was on

> advancing theoretical knowledge in areas such as laser technology, the development of pioneering optic and optoelectronic integrated systems and bistable optical switching devices, research into infrared lasers and detectors, and the application of integrated optical interface circuits in local area networks at gigabit (billions of bits) per second data rates. Another $300,000 of NSF funding is available for upgrading university laboratory equipment (U.S. Congress, 1985: 72).

For example, through its Industry/University Cooperative Research Program, NSF provided a planning grant to the University of Arizona's Optical Sciences Center in 1984. Most of the research at this center focused on physics and materials science with potential applications to optical logic circuitry and optical computers. Under another NSF program, Industry/University Cooperative Research Projects, Bell Labs and Arizona worked on high speed optical switching devices. OTA estimated that the Department of Defense was spending $12.6 million on the development of cables and connectors, light sources and detectors, radiation effects exploration, and on sensor and communications applications. NSF and the academic community, and for the most part federal mission agencies, left the early development of optical fiber materials and their manufacturing processes to industry.

<u>Specific NSF Research Support</u>. NSF, through the Optical Communication Systems (OCS) program within the Division of Engineering, funded device research at California Institute of Technology, Carnegie-Mellon, Cornell, Rice, MIT, University of Arizona, UC-Berkeley, UC-San Diego, University of Cincinnati, University of Illinois, USC, Washington University, and other universities. The program supported systems work at such institutions as Case-Western, Columbia, Johns Hopkins, MIT, Oregon Graduate Center, UC-San Diego, University of Colorado, University of Maryland, and Washington University. Grantees published extensively in both the established journals (e.g., *J. Appl. Phys.*, *Appl. Phys. Lett.*, *IEEE Tran. Microwave Theory and Tech.*, *IEEE J. Quantum Electron.*, *Appl. Opt.*) and the new journals in the rapidly growing field of optical or “lightwave” communications (e.g., *Optics Comm.*, *Journal of Lightwave Technology*). Grantees and former trainees also wrote or edited basic textbooks: Yariv, *Introduction to Optical Electronics* (1971), Yariv and Yeh, *Optical Waves in Crystals* (1984); Robert G. Hunsperger, *Integrated Optics: Theory and Technology* (Third Ed., 1991);Tamir, ed., *Integrated Optics* (1975; Second Ed., 1979).

OCS grantees made regular presentations of their work in progress at the relevant national and international meetings (e.g., the biennial IEEE-Optical Society of America topical meetings on integrated optics that began in 1972 and on optical fiber communications that started in 1975). NSF grantees and former graduate research assistants who gave papers at the January 1974 topical meeting on integrated optics included Jay H. Harris, University of Washington; William S. C. Chang, Washington U.; Gregory E. Stillman and Ivars Melngailis, MIT, Elsa Garmire, a Yariv student then at Standard Telecommunications Laboratories, later on the faculty and head of the Center for Laser Studies at USC; Chenming Hu, MIT; John R. Whinnery, Berkeley; Amnon Yariv, Caltech; Shyh Wang, Berkeley; Richard Shubert, a Jay Harris student then at Rockwell International; C Yeh, UCLA; Joseph M. Ballantyne and Chung Tang, Cornell; and Theodor Tamir, Polytechnic Institute of New York.[26]

Perhaps the most important contributions the OCS device grantees made were in the development of distributed feedback semiconductor lasers (Whinnery, 1997a), but they also contributed to integrated opto-electronic devices, nanofabrication techniques, signal detection theory, and fiber optic local area networks. In the laser area, for example, although the basic scientific principles underlying solid-state thin-film lasers were the same as those for bulk lasers, those trying to develop semiconductor lasers for use in optical communication systems had to overcome some practical problems (Tang, 1974:471). One problem was coming up with a less bulky feedback structure than the external mirror reflectors used in laboratory-based lasers. Shyh Wang (Berkeley), Amnon Yariv (Caltech), and Chung Tang (Cornell) worked on distributed feedback and distributed Bragg-reflector lasers.

In the integrated optics area, Amnon Yariv and his group at Caltech started a systematic effort in 1971 to explore the feasibility of integrated opto-electronic circuits (analogous to electronic integrated circuits) and were the first to demonstrate several types of such devices. For example, Yariv's group was the first to integrate a laser and transistor on the same semiconductor substrate (Ury et al., 1979). In the same year, the group was the first to integrate an optical repeater on a GaAs/GaAlAs system, combining detection, current amplification, and retransmitting laser powered by the amplified signal current (Yust et al. 1979). They also demonstrated a distributed feedback laser on a GaAlAs system (Yen et al., 1973).[27]

It should also be noted that integrated optics research did not meet early expectations because, it turns out, no single semiconductor substrate allows optimum performance by the various types of devices it would be desirable to integrate, especially optical devices on the one hand and electrical on the other. As one researcher explained in 1991: "The design and fabrication of a large scale OIC (optical integrated circuit) with a bandwidth to match that of an

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[26] Not all the work presented in the papers was supported by NSF.

[27] "The principle of distributed feedback is properly credited to Kogelnik and Shank at Bell Labs, who demonstrated it with dye lasers. Others, including Yariv, Wang and Tang extended it to semiconductor lasers." (Whinnery, personal communication, 12/9/97).

optical fiber, while feasible in principle, probably will require many years of technology development. However, practical applications of OICs have already been accomplished, and the future is promising" (Hunsperger, 1991:7). Whinnery (1997a and personal communication, 12/9/97) is less sanguine: "Progress has been very slow. It did not turn out to have the same curve as the development of integrated electronics. Chips with three or four functions from the list of generators, modulators, detectors, amplifiers and switches have been made, but it is difficult to find a material optimum for the functions to be combined, or to fabricate a chip with a combination of materials. This is compared with the thousands of transistors on an IC chip. Large numbers of quantum dot lasers can be made on a single chip, but of course this does not satisfy all of the functional needs."

The early diagnosis that the opto-electronic devices would be the bottleneck in achieving the high bandwidth potential of optical wavelengths has turned out to be true. The achievement of terabit per second transmission rates in 1996 was achieved by developing optical fibers (rather than thin-film devices) into powerful amplifiers. It turns out that optical fibers doped with the rare earth erbium act like lasers operating at a wavelength interval that straddles the wavelength of lowest attenuation in optical fibers (1.55 µm). That wavelength interval–1.53 to 1.56 µm–corresponds to a bandwidth of about 3 Terahertz, which in turn permits the use of wavelength-division multiplexing. The two technologies together allow terabit-per-second transmission in the laboratory and promise operational systems of 100 Gb/s in the near future. One supporting technology based on integrated optics would be commercial waveguides with multiple lasers operating at different wavelengths (a six-laser version was achieved in the laboratory in 1977) (Hunsperger, 1991:7).

NSF, along with NASA and the Air Force, supported research on the development of short-haul atmospheric optical communication systems that might have better performance in urban areas and lower costs than other systems. MIT researchers built a system linking the main campus in Cambridge with the Lincoln Laboratory some 10 km. away to test the limits of atmospheric laser systems. A group at the University of Colorado built a system linking the main computer center with other buildings and found that the system was very reliable at distances up to a mile in all kinds of weather, and inexpensive. A few such systems still exist because they are reliable and cheap, but most have converted to fiber-optic cable networks because of the greater bandwidth. Some of the systems theorists supported by OCS eventually turned their attention to local area network theory.

Trained Personnel. A number of graduate students who went on to distinguished research careers in academia and industry were supported by NSF's OCS program(Whinnery, 1997b). We have already noted that Richard Shubert, Jay Harris' student at the University of Washington and coauthor of the 1968 paper that inspired Yariv to create a program in integrated optics at Caltech, went to Rockwell International (Shubert, 1974). A Yariv student, Robert G. Hunsperger, worked at Hughes Research Laboratories, and is now a professor at the University of Delaware.

A look at the program at Berkeley, albeit a relatively large and successful one, illustrates this aspect of the program's impact (Whinnery, 1997b). Whinnery began a program in quantum electronics (i.e., lasers) in the mid-1960s. His colleagues included Steven Schwarz, a new professor who had just received a Ph.D. from Caltech, and Shyh Wang, who had worked on masers. Later, Kenneth Gustafson became the fourth faculty member in the group. They were funded by NSF and DOD's Joint Services Electronics Program. Initially there were about nine or ten graduate students and up to 24 at a time later. Some students ended up at Bell Laboratories, including Erich Ippen (now on the MIT faculty), David Auston (now provost of Rice University), Ronald V. Schmidt (now executive VP and chief technical officer, Bay Networks), ____ Wood, and Charles V. Shank (director of Lawrence Berkeley Laboratory). Martin Highboom went to IBM, William Clark and Marvin Klein to Hughes, and John Buck to Georgia Tech. Auston, Ippen, and Shank are members of the National Academy of Sciences, and those three plus Schmidt are members of the National Academy of Engineering (Whinnery himself is a member of both academies). Three or four graduates of the program went on to receive the quantum electronics award.

Optical communications was a fast-growing field beginning in the late 1960s, and no doubt a number of graduate students supported by NSF fellowships or research assistantships on NSF grants outside the OCS program went into research positions in industry and government and faculty positions and made important contributions in optical communications. Donald B. Keck, one of the inventors of the first low-loss optical fiber at Corning, was supported as a Ph.D. student at Michigan State by an NSF grant for research in molecular spectroscopy awarded to his thesis advisor, Clarence D. Hause. Peter Schultz, a co-inventor, had an NSF engineering fellowship to support his Ph.D. work in ceramics at Rutgers.

Research Infrastructure. The list of NSF awards for activities related to optical communications shows a number of workshops. These workshops were intended to promote communication among researchers in academia and industry and to identify priorities for research. By 1978, industry accounted for more than a third of the participants in the meetings, which consisted of formal presentations of NSF-supported research-in-progress and informal interaction between academic and industry researchers.

An initial workshop to explore the need for a coordinated program on optical communication systems was held for two days in January 1972 at the University of Maryland. The workshop was largely pro forma: NSF had been requesting funding from Congress for such a program for two years and it had been endorsed by the advisory committee for engineering in its annual report for 1971. In fact, four grants had already been made (NSF, 1972b:28). In his opening remarks, NSF Program Manager Elias Schutzman indicated that NSF thought it "desirable to encourage greater cooperation not only among the grantees, but between the grantees and industry" and hoped "this meeting may be the beginning of new cooperative research efforts in optical communications" (NSF, 1972a:vi). A workshop report was published to inform university researchers about the problems and challenges from industrial and governmental perspectives as well as the more familiar perspective of fundamental research (NSF, 1972a).

There were 41 participants, 24 from universities, 10 from industrial labs (Bell Labs, IBM, RCA, Hughes, Zenith), and seven from government agencies and labs (NSF, NASA, Air Force, Navy).

There were two groups of researchers at the workshop, one of university researchers working in areas that the Division of Engineering had supported previously that could be included in OCS–e.g., electromagnetic radiation, circuits, opto-electronics, devices, and computer and network theory (NSF, 1970:41). For example, the division had supported pioneering work on "thin-film optics," that is, the use of thin films of semiconductor materials to guide light and form the basis for miniaturized optical devices (semiconductor lasers, modulators, couplers, and switches) that would be needed in optical communication systems. Researchers with early NSF grants included Jay Harris, professor of electrical engineering, University of Washington, John Whinnery, Kenneth Gustafson, and Shyh Wang, professors of electrical engineering, UC-Berkeley, Yariv Amnon, California Institute of Technology, and Chung Tang and Joseph Ballantyne, professors of electrical engineering, Cornell University. Yariv later said a 1968 article by Harris (Shubert and Harris, 1968), although it was looking at data-processing applications, made him realize that gallium arsenide could be used for both optical devices such as lasers and as a base material for electronic devices, thus making possible integration of desired combinations of such devices on a single chip (Yariv, 1984).

The other group represented university and industrial researchers who had been supported by NASA and DOD to study optical systems for communication with and between satellites and between aircraft, aircraft and ground stations, and aircraft and satellites.[28] Presumably, the inclusion of this group had something to do with the use of "dropout funding" to launch new programs in the division, such as OCS. It also had to do with the fact that the problems posed by signal attenuation from weather conditions and turbulence were driving fundamental work by university researchers in quantum communication and statistical communication theory, for example, quantum limits on signal detection. The academic researchers included Carl W Helstrom, professor of applied physics, UC-San Diego, Hermann A. Haus and Robert S. Kennedy, professors of electrical engineering, MIT, Fred Davidson, Johns Hopkins, and Robert O. Harger, professor of electrical engineering, University of Maryland.

Given the composition of the group, it is not too surprising that "it was clear that support should be concentrated in two major areas": (1) research on optical communication devices and (2) research on atmospheric optical communications systems. The rationales were (NSF, 1973b):

> The device research, with particular emphasis on integrated optics, is important since ultimate success for optical communications depends upon the discovery of modulators, detectors, couplers, amplifiers, and other functional components that can take advantage of the wide bandwidth.

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[28] The October 1970 special issue on optical communications of *Proceedings of the IEEE* reports much of this work.

> The use of the atmospheric channel is attractive, since it is free, can accommodate many users, and it is not being investigated to any degree by others in industry or mission-oriented agencies for earth-bound communications.

In the device area, Schutzman (and many others at that time) had the same idea that led to the integrated electronic chip: “it would be desirable to make multiple devices on a single piece of silicon, in order to be able to make interconnection between devices as part of the manufacturing process, and thus reduce size, weight, etc., as well as cost per active element” (Noyce, 1959).

Following this initial workshop, NSF organized regular “grantee-user meetings on optical communication systems” so that grantees could share information about results and research in progress with each other and potential users in industry and government, review the research agenda, and issue a proceedings to inform others about progress, problems, and opportunities. The first grantee-user meeting was held at Rice University in September 1972, after which they were held twice a year through 1975 and annually thereafter at various universities. Proceedings were published for each, consisting largely of abstracts of the research presentations, but early meetings had plenary discussions of research problems and needs from the perspective of industry and government that were summarized in the proceedings.[29] Some 16 meetings were held over a 13-year period, 1973-1984. The number of academic participants/grantees was about 30 in the early meetings, grew to 50 in the late 1970s, and returned to 30 in the last meeting in 1984.[30] There were typically a dozen representatives from government, including several program directors from NSF, a half dozen researchers from the Army, Navy and Air Force, and a few department-level representatives (Commerce, DOD).

There was strong industrial participation throughout the grantee-user meetings. A quarter of the participants in the early meetings were from industrial laboratories. The percentage increased to more than a third in the later meetings. The large laboratories were well represented (Bell Labs, Hughes, Sylvania, GTE, IBM, Xerox), but an increasing number of small opto-electronics and fiber optics firms came in the later years (Electro Optical Systems, General Optronics, Valtec, Spectra-Physics, Lasertron, Lightwave Technologies, Linkabit, Plescor Optronics).

In sum, optical fiber companies regularly attended the various series of meetings and conferences on optical fiber communications and on integrated optics and the biennial glass congresses to monitor the latest research results (Keck interview, 1997), mostly applied and from

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[29] For example, there were presentations by Frank E. Goodwin, Hughes Research Laboratories (Device research needs as seen from a systems point of view), Solomon J. Buchsbaum, Bell Laboratories (The future of optical communication systems and special problems), and Israel Warshaw, NSF (Mechanisms for university-industry cooperation in research), as well as by an academic researcher (Robert S. Kennedy, MIT, Some problems of interest to the communication theorist and device physicist) at the second grantee-user meeting held in May 1973. The presentations and summary of the discussions of them were published in the proceedings (NSF, 1973c:5-35).

[30] The number and composition of the participants were sampled from the proceedings for the second, tenth, and sixteenth meetings.

industrial R&D but some more basic and academic in origin. According to Corning's Keck, such meetings are very important. "From industry's perspective, it is extremely valuable to enable you to learn about related fields. It helps you pace your own work" (Keck interview, 1997). Bell Laboratories' Stewart Miller helped organize the IEEE/OSA topical meeting of optical fiber communications that began in 1975, and he and other Bell Labs researchers and research directors attended the NSF grantee-user meetings on optical communications systems beginning with the organizational meeting in January 1972.

In addition to workshops, NSF made some instrumentation awards related to optical communications. The Berkeley group, for example, received a specialized research equipment grant in FY 1973 for a $50,000 multi-wavelength laser system (NSF, 1973d:84) (NSF had asked for $1.2 million for specialized engineering research equipment required to undertake problem-oriented research programs in FY 1973) (NSF, 1972c). Second, a multi-million dollar National Research and Resource Facility for Sub-Micron Structures was established at Cornell University in 1977, where OCS grantees Chung Tang, Joseph Ballantyne, and their students were located and working on integrated optics. Now called the National Nanofabrication Facility, it has also served as a national user facility for others working on opto-electronic devices. Third, the OCS program awarded some research initiation grants, which supported the research of new members of engineering faculties (four were participants at the fifth grantee-user meeting held November 1974 at the University of Illinois) (NSF, 1974:v).

What NSF Did Not Do

Although NSF had an organized program in optical communication systems, it did not support research relevant to optical fiber development during the 1970s in that or any other formal program. The key researchers at Bell Labs and Corning involved in the development of optical fibers do not recall any NSF activity directly relevant to their work (Schwartz interview, 1997; Keck interview, 1997).

There were several reasons why NSF did not contribute directly to the development of low-loss optical fibers. The main reason was that the universities were not very active in this area, and there was little for NSF to build on. The knowledge and expertise were in the glass industry. The glass companies gladly recruited the graduates of the university science and engineering programs but conducted their research largely in secret for competitive reasons. Corning, for example, relied on a strong in-house research laboratory and did not seek cooperative research arrangements with universities, because it would have involved sharing proprietary technical knowledge. Corning also did not think that university research would be able to have commercial impact: "Academics didn't have the capital investment to do research that would help us. And they wouldn't help us with commercial development" (Quan interview, 1997).

Another factor that may have discouraged special NSF initiatives in optical fiber research was the separation of materials research from the Division of Engineering in 1972, which prevented the close connection between electrical and materials engineering that was characteristic of the industrial research teams working on optical fibers at Corning and Bell. Glass processing was one of the areas considered for an organized problem-oriented research program by the Division of Engineering at the same time as optical communications systems, but it did not proceed past the initial exploratory meeting held in October 1971. Although the meeting found that glass melting, workability, and surfaces needed an infusion of new ideas and techniques, because it was very polluting and "extravagantly" wasteful of energy and a major source of air pollution (NSF, 1972b:36-38), no formal program was adopted. It may have been lost in the shuffle of creating the new Division of Materials Research in early 1972.

A third factor was the great uncertainty about the future practicality of optical fiber in communications at the time NSF was planning the OCS and other focused programs in the 1970-1972 period. For that reason, OCS explored the feasibility of short-haul atmospheric laser communication systems. It was clear, however, that long-term progress in achieving the very high bandwidth at optical frequencies would require innovative new devices, whatever the transmission medium ended up being. At the second grantee-user meeting in May 1973, for example, Frank Goodwin of Hughes Research Laboratories was not sure which transmission medium would become practical, but he argued that digital signaling "depends critically upon the electronic signal processing. At the present, such signal processing is barely within the state of the art. Cost factors must be reduced by three or four orders of magnitude, a requirement which will come about only through extensive product engineering using integrated circuits. ...then the use of optical communication links via both fibers and through the atmosphere will become practical" (NSF, 1973c:18). At the same meeting, Solomon Buchsbaum, of Bell Labs, was more optimistic about the potential of optical fibers but urged better understanding of the basic limitations on all system components (fibers, sources, detectors, etc.). Both Goodwin and Buchsbaum urged that university researchers should not work on problems that industrial labs such as Bell were working on in any case, but take the longer view and explore ideas in which the payoff was not obvious.

NSF contributed to the fundamental science base through its support of investigator-initiated basic research grants, for example, in solid-state physics and on amorphous materials, and that work was occasionally cited in articles reporting optical fiber research. As we saw earlier, the NSF physics program funded a group at Catholic University's Vitreous State Laboratory to study fluctuations in liquids in the 1950s and 1960s (NSF, 1979:16), which went on to develop and patent a method for fabricating graded-index optical fibers that was commercially produced by Pilkington (Macedo and Litovitz, 1976; Simmons et al., 1979).[31] But the fact was that glass science was largely empirical, as Charles Kao found when he decided to investigate the fundamental limits on the clarity of optical glass in the mid-1960s. "He was trained in electromagnetic theory, where elegant formulas precisely predict what experiments should measure. Materials science is largely empirical; specialists make measurements first, then try to explain them. You can calculate the behavior of a waveguide from fundamental laws of physics,

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[31] The optical fiber development work of the Litovitz-Macedo group was funded by the Navy and Air Force and Canadian Wire and Cable Corp., not NSF.

but not the transparency of glass. The quantum-mechanical interactions among atoms are far too complex for that" (Hecht, 1997:9-11). Industry does that kind of research best, and by 1972, Corning and Bell Labs were only the two biggest companies mounting a major effort to make optical fibers workable in telecommunication systems. From Corning's point of view, then, "NSF *should* have been in opto-electronics" (Keck interview, 1997).

Postscript

NSF did eventually become involved in supporting university research relevant to optical fiber research when it created the big research centers programs in the 1980s. Industry also (including Corning) has become more involved in industry-university research ventures.

Industry/University Cooperative Research Centers. These include the Center for Ceramic Research, Rutgers (1982); Center for Communications and Signal Processing, NC State (1982)--no longer funded; Center for Optical Circuitry, University of Arizona (1984); Center for Glass Research at the NY State College of Ceramics at Alfred University, Alfred, NY (1986); and Center for Process Analytical Chemistry, U of Washington (1984), which works with the Center for Glass Research and has a technology focus group in "sensors & fiber optics."

MRGs. One of the first five awards was to a group at RPI to study stability of glass, especially glass used to make optical fibers (NSF Annual Report, 1985).

Industry Involvement in University Research. As noted, in the 1990s, Corning researchers have collaborated much more with academic researchers, as evidenced by co-authored scientific articles. Corning is on the Industrial Advisory Board of the Arizona Center. Keck followed Duncan Moore's work at University of Rochester's Institute of Optics on graded index lenses used in desk copiers because of possible applications in focusing laser light beams into fiber cores (Keck interview, 1997). Keck also follows work on robotic engineering ERC at UC Santa Barbara, because if its possible applications in low-cost manufacturing of optical devices. "Industry relies on NSF to provide people with the core competencies and support work underlying advances that come along only every decade, but who does the nearer term work helpful to industry? ERCs come the closest, and there's not one for photonics or terabit communications. We need one," Keck said.

V. NSF Managerial Actions

As described in the Overview chapter of this report, in the late 1960s NSF began to take a more active approach to fostering research that was relevant to national social and economic goals. One manifestation of this was the establishment of a formal program on optical communication systems (OCS) in the Division of Engineering. In its lifetime, 1971 to the mid-1980s, the OCS program used a set of strategies to focus the attention of some leading scientists and engineers on the theoretical and experimental aspects of optical communications systems and component devices, and to ensure the relevance of academic research to (and hopefully use by) industry. Those strategies included university-industry workshops, special funding, coordinated grants, regular reports on research-in-progress, and faculty development awards.

The ideas for problem-oriented research topics came from many sources rather than a comprehensive planning or research agenda-building exercise (Devey, 1997). The selection criteria did not have specific weightings. The presence of an NSF program director interested in putting a program together was therefore a major factor, for example, Warshaw and superhard materials and Gilbert Devey and bioengineering. The optical communication systems (OCS) program was suggested by a new program director, Elias Schutzman, an electrical engineer who had been on the engineering faculty at NYU (Schutzman, 1997).[32]

Schutzman remembers that soon after he arrived in 1969, someone from the director's office was going around asking for ideas for new program initiatives. He suggested optical communications as an area that would benefit from active coordination by NSF and also contribute to the progress in telecommunications technology, an important area of the economy in which the U.S.'s world lead was eroding. NSF mentioned communications systems and theory in its budget request for FY 1971 as an area that would receive more attention if funding were increased, but the division's budget was cut nearly 30 percent.[33]

The situation changed drastically for FY 1972. In the fall of 1970, the administration became concerned about stimulating the economy through increased federal spending, and OMB used the opportunity to effect some changes it wanted at NSF (Lomask, 1976:237-240). In return for ending its institutional development programs and sharply curtailing graduate education support, NSF would receive an increase of $100 million, to be used partly to reorganize and expand its applied research program and partly to pick up the costs of programs and facilities being transferred from DOD under the Mansfield Amendment.[34]

The impact on the Division of Engineering was considerable. The second largest and fastest growing program, engineering materials, was transferred with its budget to the new Division of Materials Research (DMR), which was formed to accommodate the transfer of the dozen materials research laboratories from ARPA and magnet laboratory from the Air Force. The engineering division also lost a number of problem-oriented programs with their budgets and personnel to DMR and to the expanded applied-research program, now called RANN. Those losses were offset, however, by a net increase of $11.3 million (80 percent) over FY 1971, most

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[32] Yariv (1997), in describing Schutzman's champion role, called him "Mr. Optics at NSF."

[33] The division's budget, which was $20.0 million in FY 1970, asked for $24.0 million in FY 1972 but only got $14.1 million.

[34] The Mansfield Amendment, effective October 7, 1970, barred DOD from funding basic research unless clearly related to a military requirement, and called on NSF to support a "larger share" of such basic research (Lomask, 1976:240).

of it designated as “dropout funding,” that is, to be used to pick up some of the engineering PIs dropped by DOD and other agencies (NASA, AEC).

In response to the changes, the division began to remake itself to carry out the expanded goals it had laid out at the November 1970 director’s program review. At the June 1972 director’s program review, division director Frederick Abernathy summarized the situation as follows (NSF, 1972b:1):

> The establishment of new programs, an emphasis on specially organized workshops to highlight the research opportunities in many areas of engineering research, particularly areas of interest to industry, the general emphasis on encouraging university-industry cooperation in research, a major redirection for the Research Initiation Grants Program, are examples of specific actions taken by the Division to make our research programs more responsive to the current and future needs of the country.

The division’s research initiation grant program to launch outstanding new engineering faculty on research careers was revised to allow grantees to spend summers working in a nonacademic research institution. The division also greatly expanded its sponsorship of university-industry workshops to promote interactions, information exchange, and cooperative research among participants from universities, industry, and government. Some were held on new research topics as well as on topics already addressed by the regular grant program. Examples included (NSF, 1972b:8):

- new directions in system science and engineering–theory and practice
- computers in biomedicine
- effects of magnetic fields on communication processes
- industrialized building processes
- engineering software coordination
- lower cost housing problems
- glass processing

The division’s expanded funding also went to start some new organized research programs. One of the new programs was Schutzman’s optical communication systems (OCS) program, which was located in the newly formed Electrical Sciences and Analysis Section (ESAS). In addition to OCS and another focused program in advanced automation, ESAS initially had four large traditional (that is, investigator-initiated) grant programs. In fact, OCS was small compared with the two basic research grant programs relevant to optical communications–”electrical and optical communications” and “devices and waves” ($700,000 vs. $1.6 million and $1.8 million respectively in the FY 1974 budget request). The notion was that that organized areas such as OCS were “special projects where studies by a number of investigators are focused on well defined and coordinated research efforts” (NSF, 1973a).

> These are broad problem areas in which there is a unique opportunity for high impact through intensive coordination of research related to a given area or in which there is a serious void in information required to cope with a particular problems area...because of the fragmented nature of involved industrial groups or the lack of specific responsibility of any government agency (NSF, 1974).

Ambitious plans to enlarge the program substantially from its initial level of about $600,000 a year did not eventuate.[35] The program stayed at about the same level for some years. The program was small relative to other funding sources even in the Division of Engineering. ARPA and the armed services remained major supporters of optical communications even after the Mansfield Amendment, because of its potential applications. For example, the Navy was “planning for major use of fiber optics in ship communications” as early as 1973 (see remarks by D. J. Albares in NSF, 1973c:35). Many of the investigators supported by OCS were also receiving support from these other agencies, and representatives from the services participated regularly in the grantee-user meetings. Bell Laboratories was also running its own very large research program in optical communications but stayed in close touch with the OCS program at NSF, sending its top people in opto-electronics and fiber optic communication systems research and management (but not optical fiber R&D).[36]

VI. Summary and Conclusions

Government, industry, and university roles and relationships

Low-loss optical fibers for communications were invented by industry, based on processes previously developed in industry. Federally-funded science and engineering activities played an indirect role, primarily by helping to train doctoral scientists and engineers who went to work in industrial R&D on optical fibers and related components of fiber-optic communication systems such as lasers, and by supporting basic research at materials engineering centers. Of the three Corning researchers who made the first low-loss optical fiber, one was supported as a doctoral student by a research grant to his thesis adviser from the NSF physics program, and another was supported by a graduate fellowship in engineering from NSF (the third received his Ph.D. in 1952, too early to be supported by NSF). NSF- funded basic research in solid-state physics, ceramics/glass engineering, and other areas was part of the science base in the late 1960s, when the initial R&D on optical fibers was done, but it was too remote for researchers at Corning or Bell Laboratories to identify any specific contributions to optical fibers. One researcher who had

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[35] According to the 1972 director’s program review, “We expect the expenditures in FY 1973 will be $1.2 million, and in FY 1974 $2.4 million” (NSF, 1972b:28). The program was still at the $600,000 level in FY 1976, and NSF asked for “slightly higher” support in FY 1977 (NSF, 1976).

[36] Mauro DiDomenico was an invited speaker at the inaugural workshop in January 1972; Stewart E. Miller was co-chair of the second grantee-user meeting in 1973, and other participants in the 1970s included Enrique A. J. Marcatili, Tingye Li, Sol Buchsbaum, Stewart D. Personick, Ivan P. Kaminow, P. K. Tien.

received basic research grants from NSF to study fluctuations in liquids went on to apply some of that knowledge with grants from DOD to developing a new way to make optical fibers, although that method was not ultimately competitive in the market.

The two most successful optical fiber companies—Corning and AT&T—were not very interested in taking federal R&D contracts, preferring to keep their work proprietary. Corning did accept some Army and Navy contracts in 1972-1975 to study radiation effects and ways to improve mechanical strength (the latter work revealed the need to coat fibers immediately after they were drawn). Corning also took a Navy contract in the late 1970s to conduct a design study of single mode fibers and cables, which helped position Corning for when MCI and other buyers suddenly wanted large amounts of single mode rather than multi-mode after 1980. In each case, however, Corning was careful to avoid giving the government a position in the R&D for fabricating optical fiber. For example, Corning provided the Navy with some fiber for testing as part of the single mode design study, but it was done through a procurement contract so the government would not gain any rights to fiber composition or fabrication technology (Quan interview, 1997).

DOD had been active in supporting early fiber optics R&D in small and start-up firms because of its possible applications in short-distance, noncommunication uses, such as instrument panel lighting and faceplates for radar screens. The Air Force supported the fundamental work on mode propagation in cylindrical dielectric waveguides at American Optical (Snitzer, 1961) used by the Corning team (Keck, 1992:xix). The superiority of fiber optics for military communications led DOD to fund R&D by other companies, such as ITT and Valtec, who would be responsive to DOD's needs (the military market was small from the perspective of AT&T and Corning), but those companies all made doped-core silica fibers by chemical vapor deposition and were successfully sued by Corning for patent infringements.

The universities were not very engaged in research relevant to optical fiber in the 1960s, and the applied research and development work was done in industry. At the time Corning was figuring out how to apply vapor deposition techniques to make low-loss silica fibers, the NSF Division of Engineering was supporting areas of research that might make a contribution to U.S. leadership in civilian technology. The division started the optical communication systems program, among others, deeming it an area in which progress could be made that would be useful to industry. Since the criteria included ripeness of the scientific base and potential for impact, the program emphasized topics that leading academic researchers were already active in, not building a research program from scratch. Industry was not pushing for an NSF program on optical fiber R&D, because it seemed to have such work well in hand. The program thus funded established researchers in quantum electronics and communication theorists; it did not try to stimulate research in fiber optics at that time. Later, NSF became more active in supporting optical physics and engineering, including fiber optics, through its centers programs in the 1980s, but even the most recent major advances in optical communications have continued to come from industry (e.g., erbium-doped optical-fiber amplifiers and wavelength-division multiplexing).

Relationships between fundamental research and technological development

When Kao and Hockham set out in late 1964 to see if glass fibers could be used for optical communications, they found little basic information about the optical behavior of glass materials in the scientific literature and virtually nothing on its fundamental physical limits.[37] Glass experts they visited could not tell them much more. “Mostly, they learned how little people knew about glass absorption” (Hecht, 1997:9-11). What they discovered was that materials science was mostly empirical, with little basic theory to design experiments. A few years later, inspired by Kao and Hockham’s article when Corning researchers Maurer, Keck, and Schultz tackled the problem of using silica to make low-loss fibers, they too proceeded empirically.

This is not to say there was no fundamental research. There was, but it was the need to explain developments that fostered new research rather than the other way around. As a result, a large body of knowledge about optical fiber materials and the processes for making and testing them developed in industry in a short period of time (see reviews by Bagley et al. 1979; Nagel, 1988; and Keck, 1992:Sec.3,4). The research provided better understanding of what was being observed empirically, which industry supported because it helped fine tune the manufacturing process.

In the first 15 or so years (1966-1981) of fiber optic development, industry did not look to universities for knowledge about, or as a place to sponsor research on, optical fibers, although they built up their in-house R&D staffs by hiring doctoral and masters degree recipients from engineering and physics programs in the universities. That pattern changed in the 1980s. Corning, Bell Labs, and other optical fiber companies apparently saw the value of building a broader research base and began to affiliate with universities, first through Industry/University Cooperative Research Centers and then through Engineering Research Centers. The relationship between fundamental research and technology development was much closer in other aspects of fiber-optic communications, especially advances in lasers and network theory. Academic scientists and engineers working in those areas, including some NSF-supported grantees and graduate students, made fundamental contributions, as measured by awards and memberships in prestigious organizations (NAE and NAS).

NSF role

At the time of the original invention of low-loss optical fiber in 1970, NSF was just beginning to expand its original mission of supporting basic research and training to include support of research and training that was more applied in focus. Even as it initiated a program

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[37] One of the few previous studies was one done by Corning’s Maurer (1956), who investigated light scattering in different kinds of glass and developed a formula to describe it. Kao and Hockham (1966) used the formula to predict that intrinsic loss from scattering (caused by random density fluctuations frozen into the glass) would be relatively small (less than 1 dB/km) (Hecht, 1997:9-12). That meant that most of the loss could be attributed to absorption by impurities and imperfections, which could potentially be reduced or eliminated through careful processing.

aimed at contributing to progress in optical communications science and technology, NSF was constrained by two realities. First, it did not want to support work that would otherwise be funded by industry, and industry R&D in optical communications was large and growing. Second, federal mission agencies—DOD and NASA in particular—were already supporting large amounts of R&D in optical communications, and even after the Mansfield Amendment, NSF would only be able to play a secondary role (at least until substantially larger budgets for university-industry research center programs came about in the 1980s). Nevertheless, NSF contributed in several ways.

Education. NSF had doctoral fellowship and traineeship programs for some hundreds of students a year, and through graduate research assistantships funded by its research grants, it supported the graduate work of thousands more in the 1960s. In 1969-1970, about half of all engineering Ph.D.s and 30 percent of all physics Ph.D.s went into industry (those percentages had increased during the decade) (NRC, 1978:82). Not surprisingly, then, NSF supported the graduate education of some of those who contributed to optical fiber and related R&D. We have seen that one of the three original inventors of the first low-loss fiber had had an NSF engineering fellowship in graduate school and another had worked as a graduate assistant on an NSF grant awarded to his thesis adviser. It is likely that a number of recent Ph.D.s whose graduate work was supported by NSF went into the rapidly developing optical communications R&D programs in industry during the 1970s, abetted in part by slowdown in the academic job market of the early 1970s.

Direct Research Support. NSF did not play a noticeable role in funding research relevant to optical fiber (Keck interview, 1997), “consistent with the absence of materials work for fibers in the university programs” (Whinnery, 1997c) and with the reality that the major firms were already pursuing large R&D programs. NSF limited its organized effort to support optical communications research to two areas with strong academic bases—integrated optics and information system theory. Researchers funded by the OCS program contributed to the development of workable semiconductor lasers (but most of the work was supported by industry and DOD) and achieved a number of firsts in building integrated optical circuits (although the hoped for parallel with the developmental curve of electronic integrated circuits did not pan out). Work on the development of atmospheric optical communications systems was made obsolete by optical fiber, which has higher bandwidth and became relatively cheap, but some of the theoretical work turned out to be relevant to telecommunications receiver design and to the design of computer networks.

Knowledge Base. The basic work in electromagnetic theory had been done before NSF existed. NSF funded some basic research on amorphous or noncrystalline materials and on solid-state physics during the 1950s and 1960s. NSF support of research at Catholic University’s Vitreous State Laboratory has already been mentioned. When the head of the team that invented the first low-loss optical fiber published a review article in 1973, however, few of the 59 references were to academic researchers (most were to industrial researchers in the U.S., Great Britain, and Japan) (Maurer, 1973). When another member of the team edited a collection of key papers in optical fiber technology, including the “foundation” papers, again, few academic papers were included and none of the authors was supported by NSF (Keck, 1992).

In the research areas in which NSF chose to establish an active program, NSF-funded work became part of the knowledge base. For example, articles by a number of NSF-funded researchers and former students are cited in a basic overview of optical fiber telecommunications, in chapters concerning semiconductor lasers, detectors, integrated optics, opto-electronic devices, and receiver design (Miller and Kaminow, 1988:Chs. 11,13,14,15,16,18,19).

Research Infrastructure. In 1977, the Division of Engineering created the National Research and Resource Facility for Submicron Structures to assist in universities and industry working on nanofabrication technologies and related fundamental physics and materials problems and on the miniaturization of advanced devices with submicron dimensions, including optical and opto-electronic devices. The facility was located at Cornell in part because several OCS grantees were doing pioneering work in creating opto-electronic devices through state-of-the-art techniques (Ballantyne, 1978).

Supporting Technology. NSF did not play a role in developing supporting technologies relating to optical fiber per se—splicing techniques, connectors, polymer coatings, or cabling. That work was done in industry. (As noted above, NSF did play a role in supporting research relevant to the development of the nonfiber components and devices needed in a fiber-optic communication system.)

Organizational Leadership. The main leadership in optical fiber communications R&D was taken by industry researchers working through the OSA, IEEE, and other professional societies. The most important meetings in terms of sharing information and charting future research directions were the OSA/IEEE topical meetings on Optical Fiber Communications (1975 on) and on Integrated and Guided-Wave Optics (1972 on) organized by Stewart Miller, Bell Labs, and Robert Maurer, Corning (Keck interview, 1997).

NSF played a strong leadership role within the relatively small areas it chose to address formally. An activist program director sought out leading academic researchers and encouraged them to apply for funding that was, although peer-reviewed, set aside specifically for work on optical devices or optical communications systems. Although the program did not grow in accordance with initial plans, NSF sustained the program for 15 years. Finally, the program funded regular industry- university meetings to promote information exchange among grantees and also with researchers in industry.[38] The meetings were well- attended by industry throughout the history of the program.

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[38] The meetings were twice-a-year through 1975 and annual

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