Birth and Growth of the Fiber-Optic Communications Industry

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Fiber-optic communications was born at a time when the telecommunications industry had grown cautious and conservative after making telephone service ubiquitous in the United States and widely available in other developed countries. The backbones of the long-distance telephone network were chains of microwave relay towers, which engineers had planned to replace by buried pipelines carrying millimeter waves in the 60-GHz range, starting in the 1970s. Bell Telephone Laboratories were quick to begin research on optical communications after the invention of the laser, but they spent the 1960s studying beam transmission through buried hollow confocal waveguides, expecting laser communications to be the next generation after the millimeter waveguide, on a technology timetable spanning decades.

Corning's invention of the low-loss fiber in 1970 changed all that. Bell abandoned the hollow optical guide in 1972 and never put any millimeter waveguide into commercial service after completing a field test in the mid-1970s. But telephone engineers remained wary of installing fiber without exhaustive tests and field trials. Bell engineers developed and exhaustively tested the first generation of fiber-optic systems, based on multimode graded-index fibers transmitting 45 Mb/s at 850 nm over spans of 10 km, connecting local telephone central offices. Deployment began slowly in the late 1970s, and soon a second fiber window opened at 1300 nm, allowing a doubling of speed and transmission distance. In 1980, AT&T announced plans to extend multimode fiber into its long-haul network, by laying a 144-fiber cable between Boston and Washington with repeaters spaced every 7 km along an existing right of way.

Yet by then change was accelerating in the no-longer stodgy telecommunications industry. Two crucial choices in system design and the breakup of AT&T were about to launch the modern fiber-optic communications industry. In 1980, Bell Labs announced that the next generation of transoceanic telephone cables would use single-mode fiber instead of the copper coaxial cables used since the first transatlantic phone cable in 1956. In 1982, the upstart MCI Communications picked single-mode fiber as the backbone of its new North American long-distance phone network, replacing the microwave towers that gave the company its original name, Microwave Communications Inc. That same year, AT&T agreed to divest its seven regional telephone companies to focus on long-distance service, computing, and communications hardware.

The submarine fiber decision was a bold bet on a new technology based on desperation. Regulators had barred AT&T from operating communication satellites since the mid-1960s. Coax had reached its practical limit for intercontinental cables. Only single-mode fiber transmitting at 1310 nm could transmit 280 Mb/s through 50-km spans stretching more than 6000 km across the Atlantic. AT&T and its partners British Telecom and France Telecom set a target of 1988 for installing TAT-8, the first transatlantic fiber cable. More submarine fiber cables would follow.

In 1982, MCI went looking for new technology to upgrade its long-distance phone network. Visits to British Telecom Research Labs and Japanese equipment makers convinced them that single-mode fiber transmitting 400 Mb/s at 1310 nm was ready for installation. AT&T and Sprint soon followed, with Sprint ads promoting the new fiber technology by claiming that callers could hear a pin drop over it.

Fueled by the breakup of AT&T and intense competition for long-distance telephone service, fiber sales boomed as new long-haul networks were installed, then slumped briefly after their completion.

The switch to single-mode fiber opened the room to further system improvements. By 1987, terrestrial long-distance backbone systems were carrying 800 Mb/s, and systems able to transmit 1.7 Gb/s were in development. Long-distance traffic increased as competition reduced long-distance rates, and developers pushed for the next transmission milestone of 2.5 Gb/s. Telecommunications was becoming an important part of the laser and optics market, pushing development of products including diode lasers, receivers, and optical connectors.

Fiber optics had shifted the telephone industry into overdrive. Two more technological revolutions in their early stages in the late 1980s would soon shift telecommunications to warp speed. One came from the optical world, the fiber amplifier. The other came from telecommunications—the Internet.

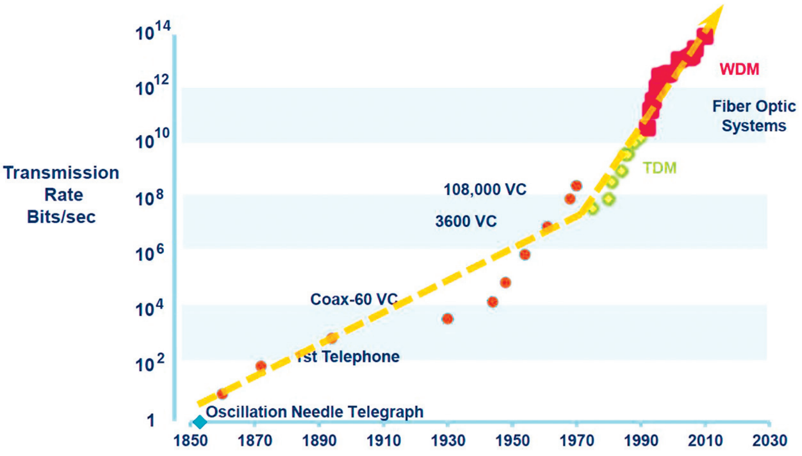
Even in the late 1980s, the bulk of telecommunications traffic consisted of telephone conversations. (Cable television networks carried analog signals and were separate from the usual world of telecommunications.) Telephony was a mature industry, with traffic volume growing about 10% a year. Fiber traffic was increasing faster than that because fiber was displacing older technologies including microwave relays and geosynchronous communication satellites. Telecommunications networks also carried some digital data, but the overall volume was small.

The ideas that laid the groundwork for the Internet date back to the late 1960s. Universities began installing terminals so students and faculty could access mainframe computers, ARPANET began operations to connect universities, and telephone companies envisioned linking home users to mainframes through telephone wiring. Special terminals were hooked to television screens for early home information services called videotex. But those data services attracted few customers, and data traffic remained limited until the spread of personal computers in the 1980s.

The first personal computer modems sent 300 bits/s through phone lines, a number that soon rose to 1200 bits/s. Initially the Internet was limited to academic and government users, so other PC users accessed private networks such as CompuServe and America Online, but private Internet accounts became available by 1990. The World Wide Web was launched in 1991 at the European Center for Nuclear Research (CERN) and initially grew slowly. But in 1994 the number of servers soared from 500 to 10,000, and the data floodgates were loosed. Digital traffic soared.

By good fortune, the global fiber-optic backbone network was already in place as data traffic started to soar. Construction expenses are a major part of network costs, so multi-fiber cables were laid that in the mid-1980s were thought to be adequate to support many years of normal traffic growth. That kept the "Information Superhighway" from becoming a global traffic jam as data traffic took off.

The impact of fiber is evident in Fig. 1, a chart presented by Donald Keck during his 2011 CLEO plenary talk. Diverse new technologies had increased data transmission rates since 1850. Fiber optics became the dominant technology after 1980 and is responsible for the change in slope of the data-rate growth.



▶ **Fig. 1.** Increase in the data transmission rate from 1850 to 2011 in response to diverse technologies. Fiber optics became the dominant technology after 1980. Note the change in slope around that time. (Courtesy of Corning Incorporated.)

Even more fortunately, Internet traffic was growing in phase with the development of a vital new optical technology, the optical fiber amplifier. Early efforts to develop all-optical amplifiers focused on semiconductor sources, because they could be easily matched to signal wavelengths, but experiments in the middle to late 1980s found high noise levels. Attention turned to fiber amplifiers after David Payne demonstrated the first erbium-doped fiber amplifier in 1987. (See Digonnet's chapter on p. 195.)

Elias Snitzer had demonstrated a neodymium-doped optical amplifier at American Optical in 1964, but it had not caught on because it required flashlamp pumping. Erbium was the right material at the right time. Its gain band fell in the 1550-nm window where optical fibers have minimum attenuation. Within a couple of years, British Telecom Labs had identified a diode-laser pump band at 980 nm and Snitzer, then at Polaroid, had found another at 1480 nm. By 1989, diode-pumped fiber amplifiers looked like good replacements for cumbersome electro-optic repeaters.

What launched the bandwidth revolution was the ability of fiber amplifiers to handle wavelength-division multiplexed signals. The first tests started with only a few wavelengths and a single amplifier; then developers added more wavelengths and additional amplifiers. The good news was that wavelength-division multiplexing (WDM) multiplied capacity by the number of channels that could be squeezed into the transmission band. The bad news was that WDM also multiplied the number of potential complications.

Design of 1310-nm systems was straightforward because it required considering fiber and amplifier performance at only one wavelength. WDM required balancing fiber and amplifier performance across the usable spectrum, as well as dealing with other complications including crosstalk, combining signals at the input, and separating them at the output. All posed optical challenges.

Both erbium-amplifier gain and fiber attenuation vary with wavelength, but communication systems have to deliver the same power at all wavelengths. This meant developing ways to flatten amplifier gain and fiber attenuation along the system.

Chromatic dispersion became a challenge. The 1310-nm window was picked for early single-mode systems because it was the zero-dispersion wavelength. Chromatic dispersion was high enough at 1550 nm to require ways to reduce it. Corning and British Telecom had developed fiber with zero dispersion shifted to 1550 nm in the 1980s, and that technology was used in early optical-amplifier cable systems transmitting at 1550 nm, including the TAT-12/13 transatlantic cable. However, experiments showed a serious problem with WDM in dispersion-shifted fibers. Signals at uniformly spaced wavelengths remain in phase over long distances, causing four-wave mixing and crosstalk exceeding system tolerances.

That problem led Corning to develop non-zero dispersion-shifted fibers, which have enough dispersion at 1550 nm to avoid four-wave mixing. However, the variation in dispersion across the WDM range nonetheless required dispersion management to meet system dispersion tolerances as data rates increased.

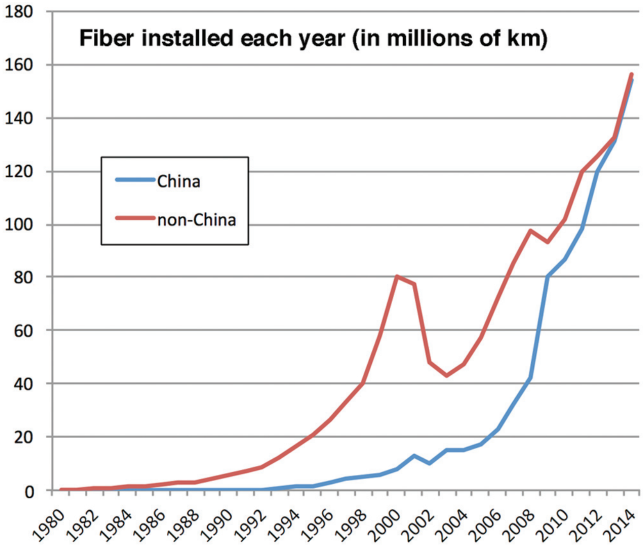
WDM also posed optical challenges. Systems required narrow-line lasers spaced evenly across the spectrum, as well as optics to combine and separate the optical signals at the ends of the fiber. That required new types of optical filters with sharp cutoffs to slice the spectrum into the desired bands. Through the 1990s, the bands grew narrower and narrower as designers sought to squeeze as many channels as possible into the limited gain band of erbium-fiber amplifiers.

WDM, optical amplifiers, and the Internet combined to give the young fiber optics a big boost. In 1990, when the new technologies were still in the lab, Kessler Marketing Intelligence (now part of CRU International) estimated that sales of cable, transceivers, and connectors in the United States were $948 million, up only 2% from the previous year in a slow economy. Sales overseas were comparable, so the whole market was around $2 billion. Global sales of fiber reached 6.74 million kilometers.

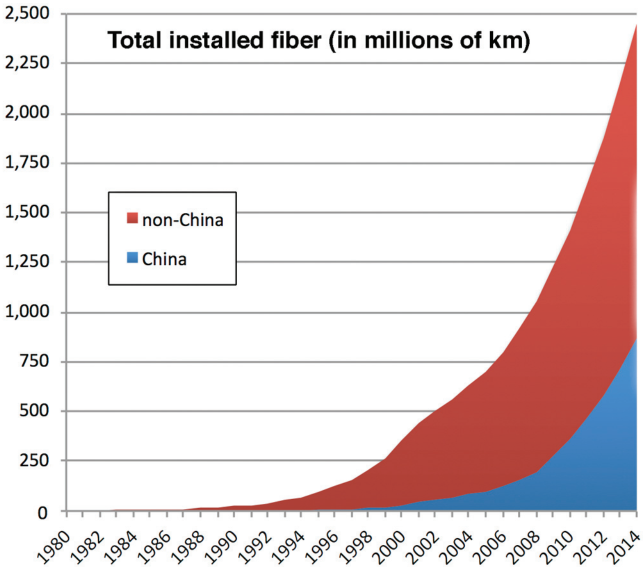
By 1995, when the optical amplifier/WDM revolution was in full swing, the company estimated the global fiber-optic component market at $7.1 billion, with global fiber sales more than tripling to 22.87 million kilometers. The web was in takeoff mode, and as the number of servers soared, Internet traffic may have been doubling every three months, although few reliable numbers are available. Long-distance and international calling had grown with a decline in phone rates. Phone lines were humming with faxes carrying documents that would have been sent by express carrier or mail in 1990.

That growth was a welcome boost for optics as a whole. The wind-down of Ronald Reagan's Strategic Defense Initiative had left many optickers out of work in 1990. Telecommunications companies in need of optics specialists hired some of them. Others went to work for fast-growing firms building components or instruments for the fiber market, or started their own companies. Figure 2 shows CRU's data on fiber sales in millions of kilometers, with Chinese sales tracked separately, from 1980 to 2013. The trend in 1995 was clearly upward.

At the postdeadline session of OFC 1996, a team from Fujitsu Laboratories in Japan reported sending a record 1.1 Tb/s through 150 km of fiber, transmitting 20 Gb/s on each of 55 channels, with erbium-fiber amplifiers on both transmitter and receiver ends. Two other teams reported reaching 1 Tb/s over shorter distances by other means, one from AT&T Research and Bell Laboratories and the second from NTT. Fiber had become the key to delivering high bandwidth to a telecommunications industry convinced that you could never have enough bandwidth. The future looked bright.



▲ Fig. 2. Total length (in millions of kilometers) of the optical fiber installed each year from 1980 through 2013, divided between China and the rest of the world. (Courtesy of CRU International, http://www.crugroup.com.)



▲ Fig. 3. Cumulative installations of communications fiber around the world from 1980 through 2013. (Courtesy of CRU International, http://www.crugroup.com.)

In fact, as Fig. 2 shows, the light would dim after the bubble burst in 2001. Sales outside of China, little affected by the bubble, dropped from a peak of 80 million kilometers in 2000 to a low of 43 million kilometers in 2003. But then the light brightened. CRU International reports that growth returned outside of China, reaching 128 million kilometers in 2013. China's aggressive modernization program brought its fiber sale to 123 million kilometers in 2013, just short of the rest of the world combined. All told, as shown in Fig. 3, CRU says that cumulative global installation of optical fiber for communications through 2013 exceeds a staggering 2.1 billion kilometers. Optics now connects the world as the backbone of the global telecommunications network.

Acknowledgment

Part of this material is adapted, with permission, from Jeff Hecht, *City of Light: The Story of Fiber Optics* (Oxford, 2004).