FIBER OPTICS

Fundamental research in glass science, optics and quantum mechanics has matured into a technology that is now driving a communications revolution.

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On looking back to the beginnings of *Physical Review* it is interesting to find that the very first paper[1] in volume 1, number 1, 1893, addressed the "transmission spectra of certain substances in the infrared." The article, authored by Ernest Nichols, included quartz and glass as materials of interest. The same volume offers a review[2] of Nikola Tesla's book *Light and Other High-Frequency Phenomena.* It is therefore fitting that this celebration of the 100th anniversary of *Physical Review* includes a discussion of a technology that is based on fundamental principles of physics addressed in the journal's first issue and countless numbers of later issues and that has profoundly transformed the telecommunications infrastructure of our society.

The study of fiber optics owes much to the vision of Charles Kao (then at Standard Telecommunications Labs in England), who recognized 27 years ago[3] that silica-based waveguides, consisting of a core of high-refractive-index glass surrounded by a cladding with a lower refractive index, offered a practical way to transmit light by total internal reflection. Today the field has grown far beyond that vision of a passive communications channel. Research on fibers for active devices such as amplifiers and lasers is now leading to a new class of optical devices. (See figure 1.)

All dielectrics, whether crystalline or amorphous, have an "optic window" of relative transparency to electromagnetic radiation. This window lies between the phonon (and multiphonon) absorption bands at lower energies and the electron (and exciton) absorption characteristics at higher energies. In glasses the losses within this optic window are dominated by scattering from static fluctuations of the refractive index and by absorption by impurities and structural defects. In 1970 came the important milestone at the Corning Glass Works[4] in which researchers fabricated silica fiber with a loss as low as 20 dB/km (that is, 1% transmission through 1 km of fiber). At that time it was impossible to imagine how rapidly silica fiber technology would evolve. In 1978 AT&T demonstrated the first fiber communications system, and since that time several million miles of fiber have been installed around the world, both on land and

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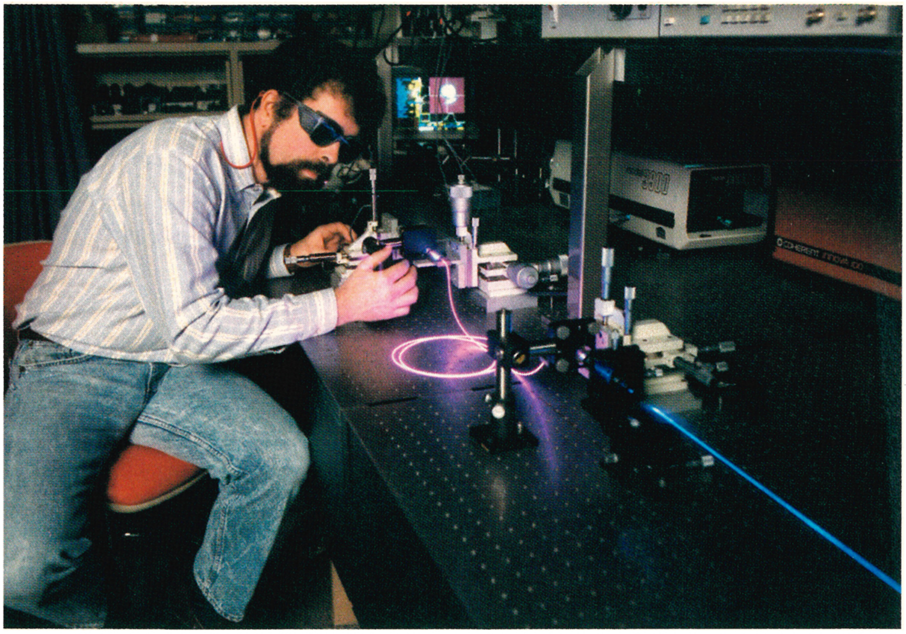


Fiber upconversion laser in a thulium-doped fluoride fiber is used by optics researcher Steve Grubb (then at Amoco) to upconvert laser light from 1.12 μm in the infrared (appearing pink in the photo) to 0.48 μm (blue). The fiber laser converts 200 mW of pump light from a diode-pumped Nd:YAG laser to 50 mW of blue light. Doped optical fibers have a wide and expanding range of applications. **Figure 1**

undersea. Low-cost fiber processing techniques have reduced losses almost to the theoretical limit of 0.15 dB/km (for wavelengths near 1.55 μm), which is set by scattering from density fluctuations in the fiber core. Residual losses are attributed to defects in the silica glass network, the germanium dopant in the fiber core (used to raise the refractive index) and H_2 or OH contaminants.

We are indeed fortunate that a material as simple and abundant as silica combines all the features of low loss, high mechanical strength and chemical stability. (Are the parallel revolutions in silica and silicon technology coincidental?) With outside diameters of about 120 μm, the tiny strands of glass are surprisingly flexible and strong. Glass is vulnerable to damage and stress-accelerated corrosion, but application of a protective polymer coating provides long-term mechanical and chemical stability. Polymer science has played an essential role in the fiber success story.

Early developments of fiber optic communication required a number of advances in material research and semiconductor laser development. While I will not dwell on this early work, the net achievement of this first generation of research and development is a worldwide network of optical fiber that provides low-cost, wide-bandwidth communications. Optical fiber now carries most long-distance telecommunication, and the bandwidth–distance product is doubling annually. (See figure 2.) Optical fibers are finding new applications in medicine, environmental sensing, and the aerospace and automotive industries, to name a few.

For long-distance communication it is necessary to compensate for the residual loss in the fiber by regenerating the signal typically every 30–100 km (depending on the data rate). This is currently done by detecting the optical signal (that is, converting it to an electrical signal), followed by amplification and pulse shaping, and finally driving a laser to retransmit the regenerated signal over the next leg of fiber. The electronics needed for this procedure is the bottleneck of the fiber network. The bandwidth of such repeaters is typically much less than 10 gigabits (10^{10} bits) per second, while the full bandwidth of the optical fiber is in the multiterabit (10^{12} bit) per second range. One could increase the communication bandwidth of electronically repeated systems by sending several wavelengths along the same fiber, but each wavelength would require its own set of repeaters. That would be an expensive solution!

Erbium-doped fiber amplifiers

The emergence[5] of the erbium-doped fiber amplifier in 1987 greatly changed this picture. Elias Snitzer and coworkers (then at American Optical Corporation) studied[6] the doping of glasses and fibers to make optical amplifiers and lasers in the 1960s, but it was the 1987 work, by groups led by David Payne (University of Southampton) and Emmanuel Desurvire (then at AT&T Bell Labs), that started the current wave of research and development. It took only a few months for the importance of the erbium amplifier to be recognized. Despite initial skepticism (after all, rare earth ion spectroscopy was popular in the 1960s!), progress in erbium amplifier development was so rapid as to convert even the most devoted semiconductor amplifier researcher. This invention is now revolutionizing telecommunication network design and marks the beginning of an exciting new phase of optical fiber research and development.

The fiber amplifier is a very simple device. (See figure 3.) The core of the fiber is doped with erbium ions (less than 0.1%) during fiber fabrication. The amplifier is pumped at either 1.48 μm or 0.98 μm with a commercially available semiconductor diode laser coupled into the amplifier with a wavelength multiplexer, which is a fiber device that sends light of two different wavelengths into a single fiber. Signal light near 1.55 μm is amplified by stimulated emission of the excited erbium ions as it passes through the fiber. (See figure 4.) A gain of over a thousandfold is readily achieved with pump powers of about 50 mW.

Erbium fiber amplifiers offer amplification independent of polarization in a wavelength range (1.53–1.56 μm) that lies in the region of lowest loss in optical fibers. One can splice these amplifiers directly into the transmission fiber. The noncrystalline environment and the long lifetimes of the excited states of the erbium ions cause linewidth broadening, allowing many wavelength channels to be simultaneously amplified without cross talk. The optical amplifier removes the electronic bottleneck and makes for a transmission line that is data-rate transparent, broadband and lossless over a 4-THz bandwidth! Multichannel operation at several different wavelengths is now commercially feasible, and this has increased the need for tunable semiconductor laser sources (which are used to create the optical signals in the first place).

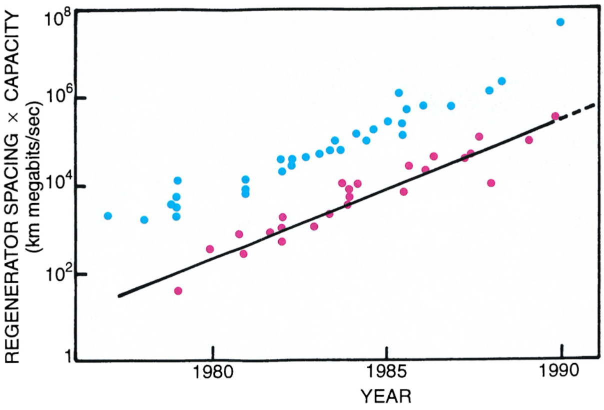
Erbium-doped fiber design and performance continue to improve. The conversion from the pump to the amplified signal can be highly efficient. (Over 75% efficiency is achievable.) Reliability studies and theoretical modeling reinforce confidence in the long-term performance of these new devices. The first transatlantic installation of an all-optical amplified system, which will be almost 6000 km long, is scheduled for operation in 1995, followed by a transpacific system 9000 km long in 1996.

While it might seem from this discussion that fiber amplifiers offer a potentially unlimited upgrade to already installed optical systems, new limits are evident. First, amplified spontaneous emission adds noise to the system. To minimize amplified spontaneous emission it is important to continue to reduce the loss of the transmission fiber and so minimize the number of amplifiers required. Second, much of the installed terrestrial fiber was designed for operation near 1.3 μm, because of the availability of 1.3-μm transmitters at the time of initial installation. This fiber has significant chromatic dispersion at 1.55 μm, causing pulse broadening, which limits the rate at which one can transmit data over long distances. Conceptually the simplest solution to this problem is to design a fiber amplifier for 1.3-μm light. This wavelength falls outside the erbium gain spectrum, but trivalent praseodymium ions have an optical transition in the right spectral region. In silica-based glasses, excited Pr^{3+} ions relax too rapidly via nonradiative processes for practical use. Heavy metal fluoride glasses and chalcogenide glasses involving the elements sulfur or selenium are appropriate hosts, however, because their lower phonon energy spectra lead to longer Pr^{3+} excited-state lifetimes and more efficient radiative recombination. Researchers have fabricated fiber amplifiers from Pr^{3+}-doped fluoride glasses[7] with respectable gain, but the pump power required is still relatively high. Further research on different materials is required for efficient 1.3-μm amplification.

An alternate solution to upgrading the installed 1.3-μm-based network is to equalize the dispersion at each optical amplifier with special dispersion-compensating fiber having large negative dispersion. A number of such fiber designs have been fabricated, exhibiting negative dispersions up to 30 times[8] the (positive) dispersion of conventional transmission fiber and equalizing the dispersion over the entire wavelength range of interest. Designs with about −5 times the conventional dispersion are commercially available.

Nonlinearity

An important new limit to long-distance transmission is caused by optical nonlinearity of the silica fiber. Although nonlinearities of silica are extremely small, and one never had to consider them in the past because electronic repeaters reshaped the pulses, long optical interaction lengths without regeneration and higher average optical powers make even these small nonlinearities significant. Nonlinearities result in pulse broadening and cross talk between channels. A number of systems studies have been carried out on nonlinearities such as stimulated Brillouin scattering, stimulated Raman scattering, self-phase modulation, cross-phase modulation and four-photon mixing. Even at power levels as low as a few milliwatts one must now take these nonlinearities into account in designing a system. Despite these limitations, testbeds have demonstrated excellent performance at 5 Gb/sec over 9000 km.



Fiber optic communications systems have increased exponentially in capacity and distance over the last decade. Commercial implementation (red) of new systems has followed the first research results (blue) by about four years. **Figure 2**

Physicists have, however, yet another trump card to play. It turns out that a solution to Maxwell's equation in a lossless, single-mode optical fiber including the nonlinear term and chromatic dispersion is nondispersive in both the time domain *and* the frequency domain.[9] The stable solution of this type for the optical pulse, called a "soliton," is $u(z,t) = \mathrm{sech}(t)\exp(iz/2)$, where $u(z,t)$ is the envelope of the pulse, z is the distance of propagation, and t is the elapsed time (both suitably normalized). If one launches such a pulse, with a correctly chosen width-to-peak-power relationship, into an ideal lossless fiber, it will propagate without change over arbitrarily long distances. Physically a pulse of this kind will maintain its shape because the chromatic dispersion and nonlinearity effects cancel each other out. Linn Mollenauer, Rogers Stolen and James Gordon at AT&T Bell Labs[10] demonstrated soliton propagation in fibers experimentally in 1980.

For several years research on optical soliton propagation in fibers continued with little attention from optical systems designers, but the invention of the optical fiber amplifier has made long-distance soliton propagation a practical reality. In recent experiments solitons have retained their precise pulse shapes over thousands of kilometers. Furthermore, experiments with two wavelength channels showed that solitons of different wavelengths can pass through each other without changing shape. In these experiments the limits on distance and bit rate (per channel) were set by amplified spontaneous emission from the erbium amplifiers. The amplified spontaneous emission frequency modulates the signal frequencies via the nonlinearity, resulting in a distribution of pulse arrival times ("jitter"). This is known as the Gordon–Haus effect,[11] after Gordon and Hermann Haus (MIT). This jitter can be reduced by using a guiding frequency filter, which guides the pulse in the frequency domain. The improvement is limited, however, by the need for more amplification (to compensate for the loss caused by the insertion of the filter), which in turn leads to more amplified spontaneous emission.

A major advance[12] in 1992 overcame this limit and allowed error-free propagation of solitons over a distance of 20 000 km at a bit rate of 10 Gb/sec and over 13 000 km at 20 Gb/sec using two wavelength channels each at 10 Gb/sec. Mollenauer and coworkers achieved this breakthrough by using a sliding frequency filter in which the guiding filter frequency is slightly shifted after each amplification step. This concept creates a transmission line that is transparent to solitons, which can adjust to the frequency shift, but opaque to amplified spontaneous emission noise, which cannot adjust. Since this discovery has overcome the previous limitations of the Gordon–Haus effect, more research is now necessary to establish the new fundamental limit for soliton transmission! Solitons, with all of their advantages, are expected to find their way into commercial systems before the end of the decade.

Fiber lasers

Until recently the term "optical fiber components" implied fused-fiber couplers, splitters and multiplexers, fiber Fabry–Perot structures, polarization controllers and so on. Most of these devices are commercially available. A new family of passive fiber devices was made possible by the discovery[13] that ultraviolet light absorbed in the core of germanium-doped silica fiber (conventional transmission fiber) changes the refractive index of the glass. We do not yet understand the detailed microscopic mechanisms, although germanium defect centers play an essential role. The effect has much practical significance, because the induced index changes are large ($\Delta n \gtrsim 10^{-2}$) and substantially permanent. By illuminating the optical fiber from the side with interfering excimer laser beams at 257 nm, one can record phase gratings directly into the core of the fiber.[14] One can use such a grating to modify the transmission of light propagating in the fiber at a well-defined wavelength.

A number of interesting devices based on grating filters and grating reflectors have now been fabricated. Of particular interest for communications is the fiber laser, which consists of a short length of erbium-doped amplifier fiber containing two reflection gratings to define the resonator. Researchers have demonstrated[15] stable, single-mode lasers about 2 cm long operating near 1.53 μm. Because the gratings transmit the pump laser wavelength (0.98 μm or 1.48 μm), the same semiconductor laser can pump the fiber laser and a tandem fiber amplifier for high power output. These lasers cannot be directly modulated like semiconductor source lasers and thus require external $LiNbO_3$ modulators. However, the precision with which the wavelength can be set and their reduced temperature sensitivity make these lasers attractive candidates for communications, if they are found to satisfy long-term reliability requirements.

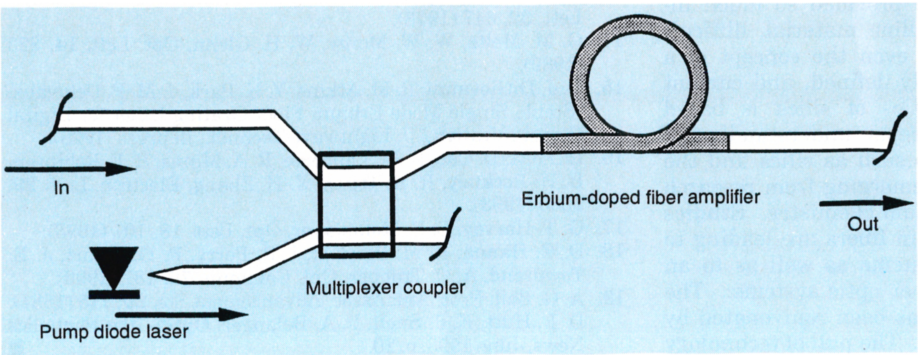
In a broader context the field of fiber lasers is now undergoing rapid growth. Recent achievements include:

▷ fiber lasers emitting up to 5 watts of power at 1.06 μm pumped with GaAs diode laser arrays[16]

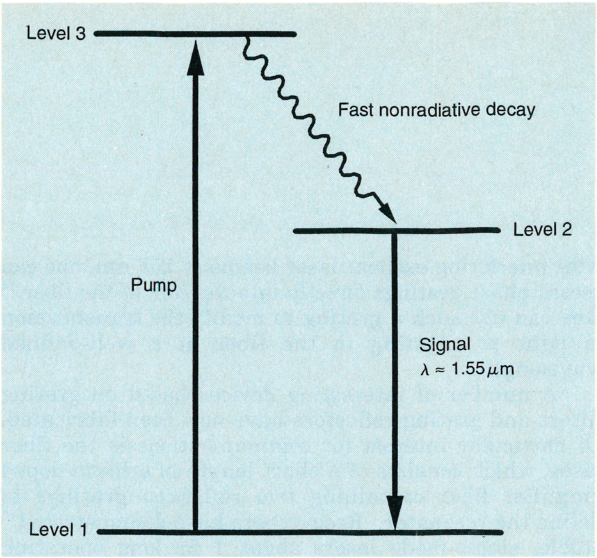
▷ mode-locked fiber ring lasers at 1.55 μm for soliton sources[17]

▷ upconversion lasers (based on fluoride fibers) that efficiently convert infrared lasers to the red, blue and green regions of the visible spectrum for optical storage and display.[18] (Figure 1 shows an upconversion laser emitting in the blue.)

All of these fiber lasers are based on the rare earth ion spectroscopy that was studied extensively some two to three decades ago. Looking back at this early work it is evident that one can expect fiber sources to cover the entire visible and near-infrared spectrum. By doping with more than one impurity and taking advantage of energy transfer, one can achieve considerable flexibility in the choice of pump wavelength. And by using different fiber designs it is possible to efficiently convert pump sources with low-quality beams into lasers with high



Erbium-doped fiber amplifier can be inserted directly into an optical fiber communications line. A semiconductor diode laser pumps the erbium ions into an excited state (see figure 4), and the signal is amplified by stimulated emission as it traverses the amplifier. **Figure 3**



Energy levels of Er^{3+} used by an erbium-doped fiber amplifier. The ions are optically pumped from level 1 to level 3, and the signal is amplified by stimulated emission from level 2 to level 1. The linewidth is broadened to 1.53–1.56 μm, allowing a bandwidth of up to 4 terahertz. **Figure 4**

spectral quality. Because of the simplicity of such devices we can expect a rapid evolution of this field.

Doing it all with fiber?

In relatively few years research has taken fibers from being a passive light transmission medium into roles that were traditionally the domain of compound semiconductors: amplifiers and lasers. All we need for an all-fiber communication system are fiber switches, fiber modulators and fiber isolators. Prototype switches based on fiber nonlinearity are still in an early stage of research. Recent reports of optoelectronic effects in silica glass give some optimism for fiber modulators. One might expect fibers doped appropriately with magnetic ions to provide practical isolators if the problems associated with fiber birefringence can be overcome.

Fiber optic technology and the communications revolution made possible by this technology have their origins in the base of fundamental knowledge developed over many decades: Glass science itself has evolved over centuries. Light-wave propagation in fibers begins with Maxwell. Communication by light dates back to Alexander Graham Bell.[19] Concepts of bound states and modes have their origins in quantum mechanics and Einstein's work on stimulated emission. In most of these cases the motivation of the research work was fundamental knowledge.

As the field of fiber optics has matured, the technology has supplied new challenges to physical theory and experiments: The theoretical prediction of new low-scattering glass compositions has pointed the way to glasses with ultimate losses lower than that of silica. The random structure of the glass network makes the usual spectroscopic probes, which have provided so much insight into the behavior of crystalline material, difficult to interpret in glasses. Indeed, even the concept of a structural defect in glass is poorly defined, and current understanding of defect properties of silica is based largely on empirical studies. Deeper understanding of the structures of network glasses such as silica and the electronic structure of defects is emerging from research on molecular modeling and quantum chemistry. Studies of nonlinear propagation of light in fibers are leading to new concepts for devices and systems as well as to an understanding of the limits of fiber optic systems. The field of rare earth spectroscopy has been rejuvenated by the demand for novel fiber devices. The pull of technology on all these areas of physics is great, and deeper fundamental understanding is likely to reap rewards in improved technology. We are still far from the ultimate limits of fiber communication, and new concepts will be required to make full use of the fiber bandwidth. Optical fiber communication is driving the entire photonics revolution, a vision that was surely beyond the imagination of the founders of this science.

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I am indebted to Alice White, Marsha Grabow, Malcolm Lines and Greg Blonder for helpful suggestions on this article. In addition I am grateful to Donald Keck for information on early fiber developments.

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