Erbium-Doped Fiber Amplifier: From Flashlamps and Crystal Fibers to 10-Tb/s Communication

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The deployment of the world's optical telecommunication network starting in the 1980s was a major change of paradigm in modern society that enabled the Information Age. From a technical standpoint, of the many technologies without which this colossal achievement would have never seen the light of day—from frequency-stable laser sources to efficient low-noise detectors, division wavelength multiplexers, optical filters, and low-noise high-speed electronics—perhaps none was as decisive and challenging as the fiber-optic amplifier (FOA) in general, and the erbium-doped fiber amplifier (EDFA) in particular. Like the optical fiber itself, the EDFA had no good alternative; had it not existed, no other component would have been available, then or now, to perform its vital function as nearly perfectly as it does.

The basic idea of transmitting data encoded on light carried by optical fibers dates back to at least the 1960s. Early incarnations of optical communication links used electronic repeaters that periodically detected, amplified, and remodulated the traveling light signals. Such repeaters worked adequately for high-speed communications over planetary distances, but they required power and costly high-speed electronics. By then the potential of replacing them with optical amplifiers, devices that would amplify the modulated signals without the need for electronics, had already been formulated. Optical amplifiers already existed, and they offered, at least on paper, multiple advantages, including an unprecedented bandwidth in the multiterahertz range. Yet it took nearly three decades of gradually intensifying research in numerous laboratories around the world to turn this concept into a reality, which involved, among other things, developing a practical optical amplifier utilizing a fiber as the gain medium.

From the start, the development of FOAs was riddled with challenges. To be successful in a communication network, an amplifier had to meet tough criteria. It had to provide a high, nearly wavelength independent gain over a broad spectral range while also incorporating an efficient means of mixing the excitation source with the incoming signal, being internally energy efficient, preserving the single-mode character of the trunk fiber, and inducing negligible crosstalk between channels. In later years other requirements were added to this list that further complicated the task. In retrospect, it is easy to trivialize the now well-known solutions to these problems. But back in the 1970s and 1980s when these problems were being tackled, there was nothing obvious about them, and, as in other scientific pursuits, many potential solutions were proposed, tested, and discarded.

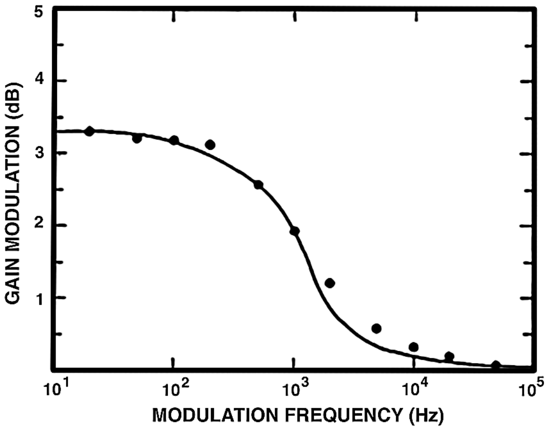
The first report of amplification in a fiber appeared in a famous article published in 1964 by Charles Koester and Elias Snitzer in The Optical Society's (OSA's) *Applied Optics*, just four years after the demonstration of the first laser [1]. This historic amplifier consisted in a 1-m Nd-doped glass fiber coiled around a pulsed flashlamp and end-probed with 1.06-μm pulses. This visionary device already contained several of the key elements of modern FOAs, including a clad glass fiber doped with a trivalent rare earth, an optical pump, and means of reducing reflections from the fiber ends to avoid lasing. It provided a small-signal gain as large as 47 dB, which is remarkable considering that it came out so early in the history of modern photonics. For his many contributions to the fields of FOAs and lasers, Elias Snitzer was awarded the OSA's Charles H. Townes Award in 1991 and the John Tyndall Award in 1994.

Like almost all the laser devices of the time, this fiber amplifier was side-pumped: the pump was incident on the fiber transversally. This made the device bulky, inefficient, and ultimately impractical. The concept of a fiber amplifier in which the pump is end-coupled into the fiber emerged years later as part of efforts carried out at Stanford University to develop a compact fiber amplifier. This work involved end-pumping Nd-doped crystal fibers with an argon-ion laser. This work demonstrated that end-pumping could produce sizeable gain (~5 dB) from a very short fiber (~cm).

The second key improvement was the introduction of the wavelength-division-multiplexing (WDM) coupler to mix the pump and the signal and end-couple them simultaneously into the gain fiber. The advantages of this technique were overwhelming: it made it possible to efficiently inject, with a compact and mechanically stable device, both the pump and the signal into the gain medium. It took several years before it was adopted, in part because commercial WDM couplers were almost nonexistent. It is now the standard technique used in the vast majority of FOAs.

Another concept critical to the performance of FOAs in general, and bench-tested first with EDFAs, is that they should use a single-mode fiber. Although in recent years new findings have suggested that the data transmission capacity could be increased by using multimode fibers, in current telecommunication links a single-mode FOA offers two key advantages, namely, a higher gain per unit pump power due to the higher pump intensity and the elimination of modal coupling, which would otherwise induce time-dependent losses at the trunk fiber/FOA interfaces.

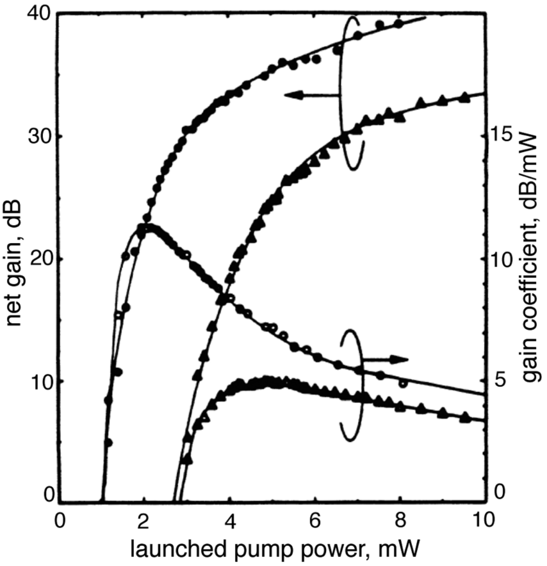
It was known as early as the 1980s that the third communication window, centered around 1550 nm, was the most promising candidate for long-haul fiber links, because in this spectral range both the loss and dispersion of conventional single-mode silica fibers are minimum. Trivalent erbium ions (Er^{3+}) in a variety of amorphous and crystalline hosts had also long been known to provide gain in this wavelength range, so this ion was a natural candidate. David Payne, who would receive the OSA's John Tyndall Award in 1994 for his pioneering work on EDFAs, and his team at the University of Southampton were first to demonstrate this potential experimentally with the report of the first EDFA in 1987 [2,3]. This was followed later the same year by a similar paper from Bell Laboratories. These milestone publications provided experimental proof that single-pass gains exceeding 20 dB were readily attainable in single-mode Er-doped fibers (EDFs) end-pumped with the best laser wavelengths available at the time, namely, 670 nm and 514.5 nm. Another key property that made Er^{3+} so attractive is that the lifetime of its 1550-nm transition is unusually long (~5–10 ms); hence the population inversion and the gain essentially do not respond dynamically at the very high modulation frequencies of the signals (unlike semiconductor amplifiers). The important consequence is that the crosstalk between signals being amplified simultaneously in an EDFA can be exceedingly small (see Fig. 1) [4], a crucial property for communications.



▲ **Fig. 1.** Measured crosstalk between two channels, characterized by the peak-to-peak gain variation induced in a first signal (channel A) by a second signal (channel B) sinusoidally modulated at frequency *f*. [C. R. Giles, E. Desurvire, and J. R. Simpson, Opt. Lett. **14**, 880–882 (1989)].

The EDFA seemed to be a great candidate, but several issues, some perceived to be critical by the communication community, made it difficult to be accepted right away. In fact, it took nearly another decade of detailed engineering and the development of several parallel technologies (diode lasers and fused WDM couplers, in particular) to make this device a reality.

To be practical, the EDFA had to be pumped with a semiconductor laser. Over time several pump sources and wavelengths were investigated. This battle was one of the most technically challenging and interesting in the history of the EDFA. The proliferation of inexpensive GaAs diode lasers in the 800-nm range in the electronic products of the late 1980s led to substantial research on 800-nm pumping, in particular at British Telecom Research Laboratories. However, they found that the gain efficiency was low. The reason was later identified as the unfortunate presence of excited-state absorption around 800 nm in Er^{3+}, a limitation that could not be sufficiently reduced by adjusting the pump wavelength or the glass composition.



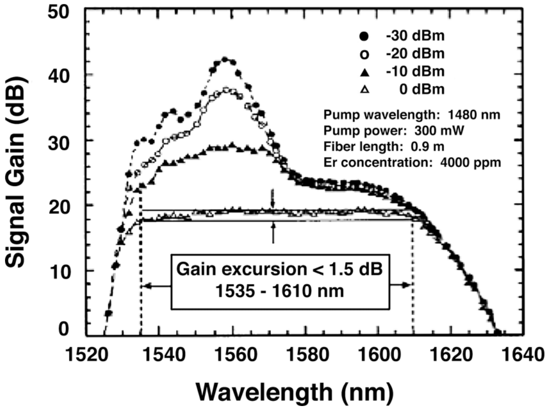
▲ Fig. 2. Measured gain and gain coefficient in an EDFA pumped at 980 nm and 1480 nm. Circles, 980 nm; triangles, 1480 nm. (Reproduced with permission of the Institution of Engineering and Technology.)

Much of this research soon focused on two pump wavelengths only, namely, 980 nm from the then-emerging strained GaAlAs laser technology and around 1480 nm from InGaAsP diode lasers. The prevalent thinking was initially that since an EDFA pumped at 1480 nm is nearly a two-level laser system, it should be difficult to invert and exhibit a poor noise performance. The demonstration of the first EDFA pumped at 1.49 μm by Elias Snitzer in 1988 quickly changed this perception. The following year saw the first report of an EDFA pumped at 1480 nm with an InGaAsP diode laser, at NTT Optical Communication Laboratory in Japan. This spectacular result (12.5 dB of gain for 16 mW of absorbed pump power) put the EDFA on a new track by establishing that a packaged FOA was within reach. For a short while pumping at 980 nm was the underdog, in part because it had a higher quantum defect than 1480-nm pumping, hence an expected lower efficiency, and in part because of the lower maturity of the strained GaAlAs technology. But 980-nm pumping nevertheless eventually won. Stimulated emission at 1480 nm turned out to be a serious penalty, which gave a lower pump efficiency and noise performance than with a 980-nm pump. M. Shimizu and his team at NTT illustrated this compromise clearly in a cornerstone paper [5] that compared the gain of an EDFA pumped at either wavelength (Fig. 2). The gain and the gain per unit pump power (11 dB/mW!) were all substantially higher with 980-nm pumping, and the transparency threshold was lower. This new understanding triggered a substantial R&D effort in the semiconductor laser community, which ultimately lead to the commercialization of reliable, high-power, long-lifetime diode lasers at 980 nm.

Many other important engineering issues were addressed through the mid-1990s. Two teams contributed to this major effort more prominently than any other, namely, David Payne's group at the University of Southampton [2,3] and Emmanuel Desurvive, first at the AT&T Bell Laboratories, then at Columbia University and Alcatel in France [6]. Many other substantial contributions came out of academic and industrial laboratories around the world, especially in the U.S., UK, Denmark, Japan, and France.

A significant fraction of the research was consumed by the quest for ever greater gain bandwidth, lower noise, and a gain that is nearly independent of signal polarization, signal power, and number of channels. To increase the bandwidth a number of ingenious solutions were implemented, ranging from hybrid EDFs concatenating fibers of different compositions and slightly offset gain spectra to adjusting the level of inversion to produce preferential gain in the C band (1530–1565 nm) or L band (1565–1625 nm) or designing the EDF so that it does not guide well above 1530 nm to produce efficient gain in the S band (1460–1530 nm). This effort was greatly complicated by the parallel need for a uniform gain (or flat gain spectrum) so that all channels have a similar power and signal-to-noise ratio at the receiver. Here too, clever solutions were conceived, from using passive filters to hybrid EDFAs, gain clamping, and the use of telluride fibers. This last approach produced a gain with a remarkable bandwidth of 80 nm (see Fig. 3) [7]. Later refinements produced EDFAs with a gain flatness well under 1 nm over wide bandwidths [8].

The EDFA rose from the status of research device to stardom remarkably rapidly, a resounding manifestation of its practical importance, exceptional performance, and timeliness. The first commercial EDFA appeared in 1992. By 1998 over 40 companies were selling EDFAs; the count ultimately



▲ **Fig. 3.** Measured gain spectrum of a 0.9-m-long tellurite EDFA at various input-signal power levels. The gain in the 1535–1570-nm range was compressed by using higher-power input signals. [Y. Ohishi, A. Mori, M. Yamada, H. Ono, Y. Nishida, and K. Oikawa, Opt. Lett. **23**, 274–276 (1998)].

peaked above 100. Research on communication systems followed suit, leading to the demonstration of increasingly large and high-performance experimental and deployed systems. As one of many examples illustrating the phenomenal performance of communication links utilizing EDFAs, in a particular experiment a total of 365 signals were simultaneously recirculated 13 times around a ~500-km fiber loop containing ten EDFAs (one every ~50 km). At the output the power imbalance between channels was as low as -7 dB and the bit-error rate only 10^{-13}. This system accomplished a remarkable total optical reach of 6850 km and a total capacity as high as 3.65 Tb/s. Deployed links now exceed 10 Tb/s over even longer distances.

In the early 2000s, following the saturation of the telecommunication industry and the sharp decline in the world's markets, a significant percentage of the optical communication task force redirected its vast technical expertise to other areas of photonics. This concerted effort gave the EDFA and other FOAs a second carrier in spectacular new applications, especially fiber sensors and high-power fiber lasers. Using an FOA to amplify the output of a fiber laser, in a now widely used configuration called the master-oscillator power amplifier (MOPA), turned out to be the most energy-efficient way to produce extremely clean and spectrally pure laser outputs up to enormous power levels. Today, fiber MOPAs are the world's brightest light sources, to a large extent thanks to the superb properties of fiber amplifiers. Yb^{3+}, in particular, rapidly became the workhorse of high-power fiber lasers for its low quantum defect and high quenching-free concentration. Power scaling posed significant challenges, including efficient coupling into the gain fiber of the high required pump powers, wavelength conversion due to stimulated Brillouin and Raman scattering, optical damage, and photodarkening. These challenges were met with a number of clever engineering solutions, including large-mode-area fibers (in which the signal intensity, and hence nonlinear effects and optical damage, are reduced) and acoustic anti-guiding fibers (in which the spatial overlap between acoustic and optical modes, and hence the nonlinearity, are reduced). Commercial fiber lasers utilizing MOPA configurations now offer average powers up to the 100-kW range, a feat that would not have been possible without the superb attributes of FOAs.

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