In 1957, a group of scientists—K. Shimoda, H. Takahasi, and C.H. Townes—were studying the statistics of quanta amplifications for applications to maser amplifiers. In their fundamental paper, they reported that:

"...if an abnormal ensemble [of molecules] can be created in which there are more molecules in the upper than in the lower state, a wave packet of photons passing through such an ensemble will be amplified rather than attenuated. This type of phenomenon ...gives promise of allowing construction of amplifiers which are exceptionally free of noise."

From these pioneering times to now—where this basic principle of optical amplification made it possible to demonstrate optical communications at multi-gigabit rates through distances over 2,000km (ref.2) and potentially 10,000km (ref. 3)—a considerable evolution in technology has taken place. Following the invention and development of the first lasers and GaAs laser diodes (1958-1962), the idea of doping glass fibers with rare-earth ions for achieving traveling-wave amplifying devices was soon investigated. In 1963, C.J. Koester and E. Snitzer (himself inventor of glass lasers) obtained 47 dB gain at 1.06 µm wavelength, using a 1m-long neodymium-doped fiber coiled around a flash lamp.

After the demonstration of low-loss single mode fibers by Corning in 1970, nonlinear Raman (SRS) and Brillouin (SBS) scattering were also shown to offer the potential for light amplification (R.H. Stolen and E.P. Ippen, 1972). During the same

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period, J. Stone and C.A. Burrus from AT&T Bell Laboratories studied Nd-doped fiber lasers and realized the first laser-diode pumped device (1974). From this time to 1985, fiber amplifiers based on the optical nonlinearities (SRS, SBS, and four-photon mixing, SFPM) of the silica fiber itself had been the object of sustained research around the world. Using such effects, high gains could be achieved indeed, with the advantage of tunability over the whole infrared transmission window (1.3-1.5 µm), but with the drawbacks of high pump power requirements (1W to 1KW for SRS and SFPM), or narrow gain bandwidth (SBS).

Great attention was also given to semiconductor optical amplifiers, following the advances in laser diode technology. Optical amplifiers were soon perceived as being key elements for non-coherent communication systems: as optical preamplifiers to enhance the signal-to-noise ratio (J.A. Arnaud, 1968) or as optical repeaters for long-haul applications (S.D. Personick, 1973).

In 1985-1986, Southampton University reported a new technique for the fabrication of low-loss rare-earth-doped fibers, leading to a prolific generation of novel fiber laser sources. In particular, the element Erbium, which, in the silica host, exhibits a broad fluorescence line centered near 1.55 µm, was immediately identified as potentially important for applications in optical communications. The advantages of fiber amplifiers include both the low pump thresholds made possible in single mode fiber waveguides and the low splicing loss with conventional fibers. The first Er-doped fiber amplifier (EDFA) was then reported by this group at OFC®/IOOC in 1987: 125dB gain for a 1.53 µm signal was achieved in a 3m long EDFA pumped with 60 mW power at 650 nm. These encouraging results triggered much interest in the research community.

Our team at AT&T Bell Laboratories then investigated the potential of using such devices for high-speed communication by measuring the bit-error-rate of a 2 Gbit/s ASK signal amplified by an EDFA pumped at 514 nm (CLEO® '88). Error-free transmission could easily be achieved, but, furthermore, the gain was found to be independent of the signal polarization, an important advantage over the competing semiconductor amplifier.

The EDFA gain dynamics were studied thereafter, for investigating potential crosstalk limitations. It was found that such gain dynamics were very slow, with gains saturation and recovery times in the 100 µs-1 ms range. A two-channel experiment at 2 Gbits/s under saturation conditions showed indeed negligible crosstalk effects, as we reported at OFC® '90. Such slow gain dynamics property is highly advantageous, as several amplitude-modulated signals could be simultaneously input to the EDFA under saturation conditions without interchannel interference. In contrast with semiconductor amplifiers, the gain dynamics are in the 100 ps-1 ns time range. The same conclusion also applies to the case of frequency-division multiplexed (FDM) signals, which in semiconductors amplifiers suffer from intermodulation distortion effect when the channels are placed in ≤1 GHz frequency spacings.

It became very clear after these results that with such assets, the field of Er-fiber amplifiers was destined grow rapidly. To be really practical, however, the EDFA needed a compact pump source such as a laser diode. In less than two years, this final technological gap was bridged, thanks to considerable research work by various teams around the world in both Er-fiber spectroscopy, for the identification of the most suitable pumping bands, and in semiconductor diode technology to achieve efficient and reliable pump sources.

**Basic physics and characteristics of EDFAs**

A typical absorption spectrum of a silica-based Erbium-doped fiber is shown in Figure 1. The different absorption bands correspond to the energy levels of the 4f electrons of Er3+, the ground level being 1I15/2. In the silica host, all possible transitions between these levels are strongly nonradiative, due to a process of multiphoton decay, except the last transition 1I13/2→1I15/2 which is 100% radiative. This transition exhibits a wide (40 nm) emission spectrum centered around 1.55 µm, which is essentially homogeneously broadened. The 10 ms fluorescence lifetime of the upper laser level 1I13/2 is conducive to a low medium inversion threshold. Such a gain medium, pumped in any of these energy levels, corresponds to a three-level laser system, with the ground level (1I15/2), being the terminal level of the 1.5 µm transition.

Due to the multiplicity of energy levels, pump absorption can also take place from the upper level 1I13/2 (pump excited-state absorption or ESA), which results in a decrease in pumping efficiency. The bottom of Figure 1 shows the spectral regions where pump ESA occurs, which in particular makes the 800 nm pump band unattractive. The two last infrared bands near 980 nm and 1480 nm, which are free from ESA, are compatible with InGaAs and InGaAsP laser diodes. This justifies the interest for these pump wavelengths. The 1480 nm wavelength corresponds to an optimum value; at shorter wavelengths, pump absorption and gain would decrease, while at wavelengths closer to the 1530 nm peak, the laser medium behaves like a two-level system for which no gain could be achieved.

The EDFA gain plotted as a function of launched pump power (near 1.48 µm) is shown in Figure 2, for two signal wavelengths near 1.53 µm and 1.55 µm. The inset, which
represents a typical output spectrum, shows a broad amplified spontaneous emission (ASE) noise background and provides a measure of the amplifier gain bandwidth. The EDFA gain spectrum differs somehow from one glass composition to another. The inclusion of aluminum as a glass network modifier (as well as efficient index-raising co-dopant for high N.A. fibers) results in the broadening and smoothing of the gain spectrum, which is desirable for multi-channel signal amplification. Other types of glass hosts for Er\textsuperscript{3+}, such as fluorozirconates (ZBLAN), offer alternate possibilities for the EDFA gain characteristics.

The gain curves in Figure 2 show that below some pump power threshold, i.e., near \( P = 2 \, \text{mW} \), the Er-fiber is absorbant, which is characteristic of a three-level system. Above this value, the gain rises quickly to reach a level that is weakly dependent of pump power. In this last regime, near-complete medium inversion is achieved, providing maximum gain in a given length of fiber.

The dashed line tangent to one of the gain curves in Figure 2 gives a measure of the amplifier efficiency: the slope of this tangent, expressed in dB/mW, is usually referred to as the EDFA gain coefficient. The EDFA corresponding to Figure 2 has gain coefficients of 5.8 dB/mW for 1.47 \( \mu \text{m} \) pump and 6.1 dB/mW for 970 pump.\textsuperscript{10} Such high gain coefficient values, for which 30 dB gains can be achieved with less than 10 mW pump power, are the result of an optimization in fiber design. This optimization consists in reducing the pump mode size, which can be done by increasing the fiber numerical aperture (or the core/cladding refractive index difference), and also in confining the Er-doped region near the center of the fiber core. The first results in a decreased pump threshold (as the pump intensity is increased), while the second makes possible a uniform pumping of the Er\textsuperscript{3+} ions in the region of the core where the pump intensity is maximum.

These two approaches, proposed initially by workers at British Telecom Research Laboratories, led to very rapid progress in EDFA gain performance with both pump wavelengths. Recently, a 10.2 dB/mW gain coefficient with 980 nm pump was reported by workers from Nippon Telegraph and Telephone Laboratories.\textsuperscript{11} Further improvements in fiber design and appropriate choice of glass co-dopants should lead to improvements, perhaps by a factor of two, of these numbers.

Another important parameter of the EDFA is the saturation output power, i.e., the output power for which the EDFA gain decreases by 3 dB due to a saturation effect. Figure 3 shows typical plots of the EDFA gain as a function of the output signal power\textsuperscript{12} for different values of input pump powers and fiber lengths. For each pump power, the fiber length is optimized to a value \( L_{\text{opt}} \) for which the unsaturated gain \( G \) is maximized (beyond the length \( L_{\text{opt}} \), the fiber reabsorbing). The figure shows the typical roll-off of the gain as the signal is increased. In this example, a maximum saturation output power, corresponding to a 3 dB gain decrease of 11.3 dBm or 13.5 mW, is obtained for 53 mW input pump. An important property of the EDFA is that such saturation output power can actually be increased by increasing the pump power, as the values indicated in the figure show.

From a system standpoint, the -3 dB saturation power of the EDFA represents an important reference number, as it tells how much output power the amplifier can attain before its gain characteristic begin to degrade. By contrast, the mere output power is not really an EDFA characteristic, as it can in principle be increased as high as the level of input pump power, at the expense of signal gain. As LD-pumps with output powers in excess of 200 mW at both 980 nm and 1480 nm have now been demonstrated, the saturation output power of the EDFA could potentially be increased to at least 50 mW. Through the combination of high gains and high output saturation powers, the EDFA can be used to boost short pulse signals generated by gain-switched laser diodes. Pulses of 9 ps duration with 12 W peak power, generated by a DFB laser diode followed with two LD-pumped EDFAs, were recently reported,\textsuperscript{13} opening new perspectives to the study of nonlinear optics using LD signal sources.

Finally, the noise characteristics of the EDFA eventually limit the system performance, as some amount of signal-to-noise ratio (SNR) degradation occurs in the amplification process. Such degradation is best represented by the noise figure parameter or the ratio of input to output SNRs. Under maximum gain conditions, the main contribution to the amplifier noise is due to the beating between the signal and the ASE. The best or lowest noise figure achievable is 3 dB, which is referred to as the quantum limit. For the 980 nm pumping, noise figures as low as 3.2 dB were measured,\textsuperscript{14} while a best value of 4.1 dB was

![Figure 2. High-efficiency Er-fiber amplifier with 1.48 \( \mu \text{m} \) pump](image)

![Figure 3. Gain vs. output signal power](image)
obtained for the 1.48 µm pump. The 1 dB penalty above the quantum limit observed for the 1.48 µm pump is explained by the incomplete inversion that occurs with this pump band, as opposed to the 980 nm band for which Er behaves as an ideal three-level laser system. With such low noise figures, a record sensitivity of 215 photons/bit at 1.8 Gb/s could be demonstrated with a 1.49 µm-pumped EDFA used as a preamplifier.

In summary, the EDFA characteristics include: low insertion loss (<0.5 dB), high gains (30-45 dB) with polarization insensitivity, high saturation output powers (>10 dBm), slow gain dynamics (100 µs-1ms) giving negligible crosstalk at frequencies greater than 100 kHz, and quantum-limited noise figures.

**EDFA system perspectives and applications**

Because of their multiple advantages, EDFAs are likely to have a major impact in future optical communications and even open the vistas of new generations of lightwave communication systems. Thus far, the span of conventional lightwave systems has been extended by use of regenerative repeaters that electronically perform the functions of reshaping, retiming, and regeneration (3R). The timing circuits of the repeater are made to function at a specified bit rate. For example, the undersea lightwave systems crossing the Atlantic or the Pacific oceans, such as TAT-8 and TPC-3, deployed since 1988 by AT&T, are based on this principle. The increase in traffic demand between continents (20 to 30% per year) requires that, in the near future, the technology of long-haul digital communications evolve to multigigabit rates capability.

Ultimately, the transmission capability of such systems will be limited by the speed of electronics. In this respect, the advantages of optical amplifiers over electronic repeaters are twofold. First, they offer higher gain and greater bandwidth, both being insensitive to bit rates. Second, simultaneous amplification of multiple optical channels is possible, allowing a fuller use of the optical bandwidth available in optical fibers without significant increase in system complexity. In fact, the possibility of replacing electronics regenerators by optical amplifiers in transcontinental links of 7500-9000 km spans appears to move to reality as AT&T and KDD recently announced a joint venture to lay a high-capacity undersea cable across the Pacific. This cable would use LD-pumped EDFAs spaced every 20-30 miles, allowing a traffic capacity of 600,000 simultaneous telephone conversations, compared to 40,000 conversations with the electronic repeater technology developed so far.

Much attention is given to EDFAs in the research domain. At the IOOC '89 conference, EDFA-based system experiments at 10-11 Gbit/s with record transmission lengths (100-200 km) were reported by NTT and Bellcore. The first transmission experiment of data-encoded solitons (2.8 Gbit/s) was also achieved by NTT, using exclusively laser diodes for the signal transmitter and the EDFA pumps. By the end of the same year, KDD reported at ECOC the error-free transmission of 1.2 Gbit/s data over 904 km, using 12 cascaded LD-pumped EDFAs. At OFC '90, NTT could present results of a 2.5 Gbit/s FSK signal transmission over 2,223 km, which required 25 EDFA modules at 80 km spacings. In such a very short period, fiber amplifiers brought about tremendous progress in the bit-rate/length product capability of lightwave systems.

Another breakthrough was achieved at this time in the field of optical solitons. Solitons are short (10-50 ps) optical pulses that can propagate in a length of optical fiber without change in pulse envelope, due to compensating effects of fiber dispersion and nonlinear self-phase modulation. Because of this property, multichannel transmission of 100 Gbit/s aggregated rate is potentially possible over multi-thousand kilometer lengths. At ECOC '89, L.F. Mollenauer and colleagues from AT&T Bell Laboratories reported a soliton transmission experiment over 6000 km, using distributed Raman amplification in a recirculating fiber loop. At CLEO '90, the same group presented results obtained with low-gain EDFAs with a transmission distance of 200 MHz-rate solitons of 10,000 km. The setup for this experiment is shown in Figure 4. The inset shows the effect of the soliton effective pulse width broadening and corresponding standard deviation, due to jitter in soliton arrival times. At present, the transmission distance was brought by the same investigators to 13,000 km with 2.5 GHz repetition rate signals.

Such outstanding results illustrate the great potential offered by the combination of the Er-fiber amplifier technology with the advantageous propagation properties of optical solitons. A question that still remains is whether signal modulation formats other than ON-OFF keyed solitons (e.g., non return-to-zero format or FSK) could eventually be
implemented in future ultra-long distance communications.

Other significant progress took place in the field of optical frequency-division multiplexed (FDM) distribution networks. In 1989, NTT reported a 16-channel FDM network, with 622 Mb/s per channel—the first to use an EDFA preamplifier to increase the number of network subscribers. At OFC '90, Bellcore showed, also through an EDFA-based network experiment, the simultaneous distribution to 4096 potential terminals of 100 subcarrier-multiplexed FM-TV channels and six 622 Mb/s channels, the latter having enough bandwidth for 24 HDTV signals. BTRL also reported that year a 10-channel WDM broadcast network using a single EDFA as a power amplifier; each channel would transmit 2.2 Gbit/s.

In 1989, NTT reported a 16-channel FDM network, with 622 Mb/s per channel—the first to use an EDFA preamplifier to increase the number of network subscribers. These important developments may have considerable impact on local area networks (LANs) and digital broadband ISDN services. Other potential applications of EDFAs, used to compensate for splitting loss in complex network architectures, include optical interconnects for supercomputers, currently being investigated at the University of Colorado.

Actually, the use of low Er³+ concentrations in doped fibers (10-100 ppb averaged over the fiber core) makes it possible to distribute the gain over the transmission fiber itself, thereby minimizing the power excursion of the signal. Such an approach makes possible virtually lossless signal transmission from one fiber network node to the next. Figure 5 shows an OTDR measurement of a 22 km-long fiber amplifier pumped at 1.48 µm (after J.R. Simpson et al., 1990).

The concept of distributed amplification, experimentally demonstrated by AT&T and BTRL in 1990, could have many applications in novel types of lossless network architectures, as well as soliton transmission systems.

There are many other possible applications for EDFAs, too numerous to be described in detail here. For instance, femtosecond pulse compression can now be achieved through soliton narrowing, taking advantage of the high peak power (30W) that can be achieved through the EDFA from gain-switched laser diodes, opening new perspectives to the spectroscopy of ultrafast phenomena and to the exploitation of nonlinear effects in single-mode fibers. Other potential applications of EDFAs include lossless fiber network switches, nonlinear Sagnac loop switches, lossless star couplers, and recirculating fiber delay lines for timeslot interchange and optical memories.

Over a very short period of time, the Erbium-doped fiber amplifier has made significant progress indeed, from its initial status of "exotic device" to that of a key component that has made many breakthroughs possible. It has already changed the course of optical communications and fiber optic research.

References
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