

Erbium-Doped Fiber Amplifiers and the Next Generation of Lightwave Systems

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Erbium-doped fiber amplifiers (EDFAs) promise to revolutionize lightwave technology, lowering system costs while enhancing network performance and reliability. The high gain ($G > 40$ decibels), high output power ($P > 100$ milliwatts), and near-ideal noise performance achieved by EDFAs, which operate in the 1550-nanometer telecommunications window, have been unparalleled by any competing amplifier technology. EDFAs are inherently fiber compatible, insensitive to polarization effects, and immune to crosstalk among wavelength-multiplexed channels. These remarkable attributes, and the ease with which they can be realized, have propelled EDFAs from their discovery in the research laboratory to commercial availability in less than three years. EDFAs may be used as power amplifiers to boost transmitter power, optical repeaters to amplify weak signals, and optical preamplifiers to increase receiver sensitivity. The success of EDFA system experiments and the decision to use EDFAs as repeaters in the next generation of transoceanic submarine lightwave systems demonstrate the practical benefits of EDFAs and their potential in future lightwave systems.

Introduction

Optical fibers that transport signals for the telecommunications industry can carry an enormous amount of information between widely separated terminals. Although optical fibers are used precisely because of their low transmission losses, regeneration is still necessary to compensate for transmission and splitting losses. In current systems, this requires the use of complicated optoelectronic regenerators, in which a photodetector converts the attenuated optical signal into an electrical signal. High-speed electronic circuitry then reshapes and amplifies the electrical signals. Finally, a laser transmits the regenerated optical signal. The erbium-doped fiber amplifier (EDFA), on the other hand, directly amplifies optical signals and promises to revolutionize optical communications.

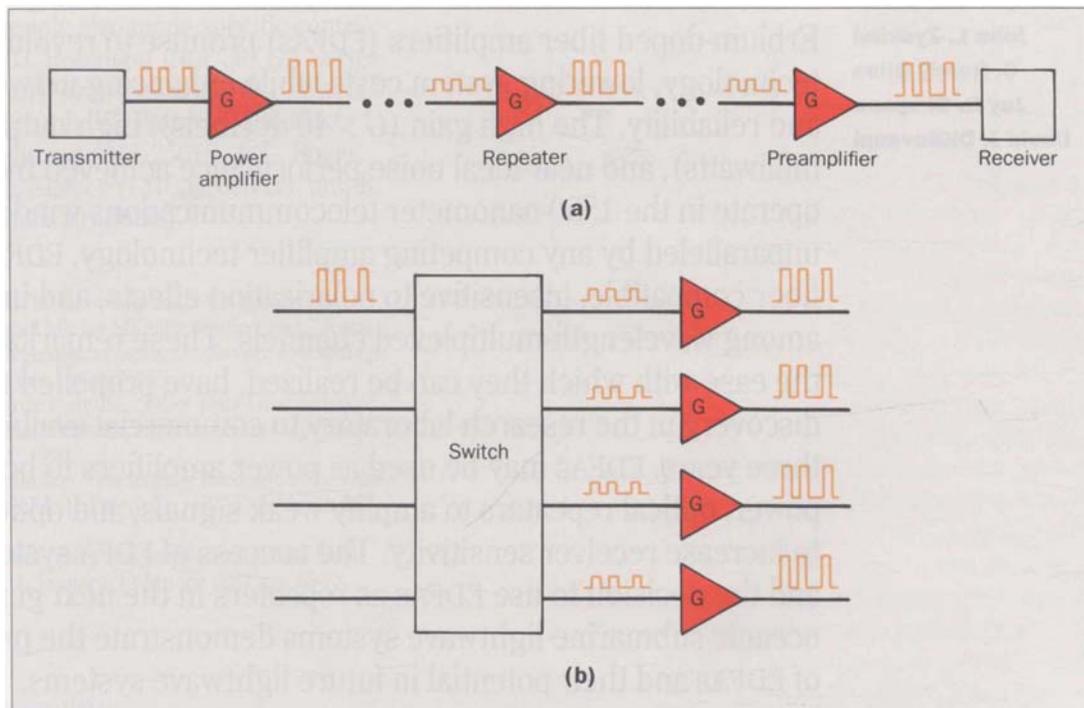
The EDFA was first reported in 1987.^{1,2} Advances since then have been so rapid that the EDFA is soon expected to replace optoelectronic repeaters in many existing applications (see Figure 1), such as:

- Power amplifiers, which boost transmitter power and increase span length in transmission systems, or which compensate for splitting losses in networking systems
- Preamplifiers, which enhance receiver sensitivity
- Repeater, which boost the signal periodically in long distance systems.

EDFAs operate at the telecommunications wavelength of 1550 nanometers (nm) with high gain, high output power, and low noise. High-power semiconductor laser diodes are practical sources to provide the light to power EDFAs. The EDFA is fiber compatible and can be spliced to transmission fibers with less than one decibel (dB) of insertion loss. The gain of EDFAs is unaffected by signal polarization. Because saturation occurs in EDFAs on such a slow time scale, EDFAs should not produce crosstalk in high-bit-rate, multichannel wavelength division multiplexed applications or pulse distortion in high-bit-rate systems.

In this paper, we present the charac-

Figure 1. Applications of optical amplifiers in (a) point-to-point transmission systems and (b) networking systems.



Panel 1. Abbreviations, Acronyms, and Terms

- ASE — amplified spontaneous emission
- CATV — cable television
- EDFA — erbium-doped fiber amplifier
- MCVD — modified chemical vapor deposition
- OVD — outside vapor deposition
- VAD — vapor-axial deposition
- WDM — wavelength division multiplexer

teristics of EDFAs that make them practical for today's fiber-optic communications systems and discuss how they will improve system capacity and simplicity, while lowering the cost.

Basic Properties of EDFAs

An EDFA consists of a short length of optical fiber whose core has been doped with less than 0.1 percent erbium, an optically active rare earth element. Reference 3 presents an excellent overview of EDFAs. As the inset of Figure 2 shows, erbium ions are pumped up to an upper energy level by the absorption of light from the pump source at, for example, 1480 nm. The transition to the ground state emits a photon and may be either sponta-

neous (the natural decay of the excited ion in the absence of any interactions) or stimulated (in the presence of photons possessing the transition energy, stimulated emission produces additional photons identical to the stimulating photons at a rate proportional to their flux). Signal photons in the EDFA stimulate depopulation of the excited state, which amplifies the signal. The long lifetime of the excited state, approximately 10 milliseconds (ms), assures that, instead of emitting noise by spontaneous emission, most erbium ions will wait to amplify signals by stimulated emission.

Figure 2 compares the optical behavior of erbium to conventional optical fiber used for transmission. The absorption in conventional fiber is very low, in a wavelength range centered at about 1550 nm, where the optical absorption is about 0.2 decibel per kilometer (dB/km); that is, about 5 percent of the propagating light is absorbed in one kilometer. By contrast, an erbium concentration of 100 parts per million in the core causes absorption of 2 dB per meter at 1530 nm. Absorption of pump light excites the erbium ions, which store the energy until, ideally, a signal photon stimulates its conversion into another signal photon. As Figure 2 shows, the erbium fiber can be pumped at several wavelengths; the absorp-

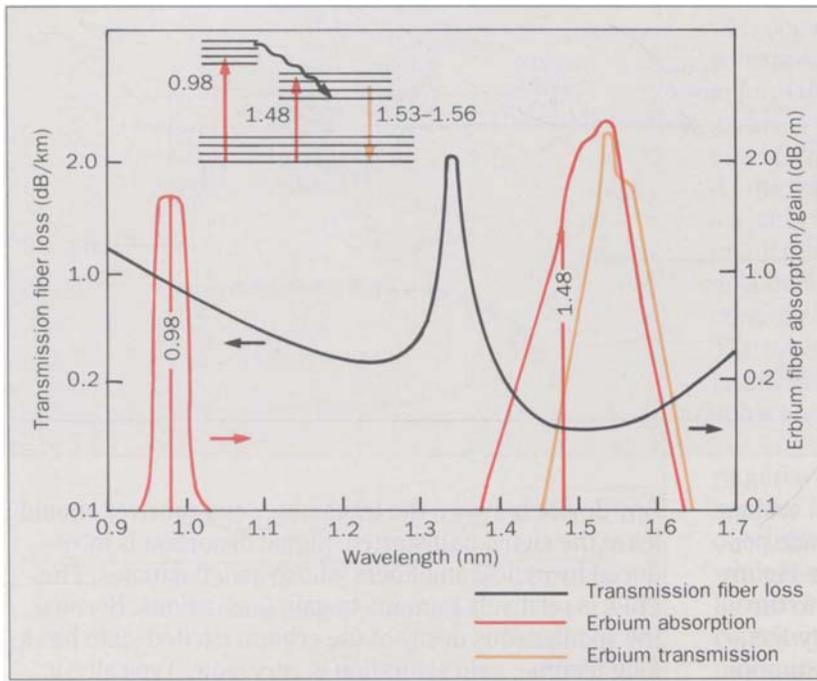


Figure 2. The optical loss of transmission fiber compared to loss and gain spectra of erbium-doped silica glasses. The inset shows energy levels of erbium ions. The straight arrows indicate pump absorption and signal emission transitions, and the wavy arrow indicates nonradiative decay to the first excited state.

tion bands at 980 and 1480 nm are the most efficient.

Figure 3a shows the construction of a typical EDFA module. The erbium-doped fiber is compatible with conventional fiber and may be fusion spliced to other components. The pump light combines with the incoming signal using a wavelength division multiplexer (WDM). Pump light propagating along the erbium-doped fiber (EDF) is depleted as erbium ions are raised to an excited state (see Figure 3b). As the signal propagates in the EDF, it stimulates emission of light from the excited ions, thereby amplifying the signal power.

Gain, Saturation, and Noise. Gain, output power, and amplifier noise are the most important characteristics of EDFAs for use in optical communications systems. Figure 4a shows the gain, i.e., the ratio of the output signal power to input power, at 1530 and 1550 nm for a high-performance EDFA.⁴ The modest pump power needed to achieve high gain is the key to the practicality of the EDFA; such power is within the capabilities of a compact semiconductor diode laser powered by several hundred milliamperes of drive current.

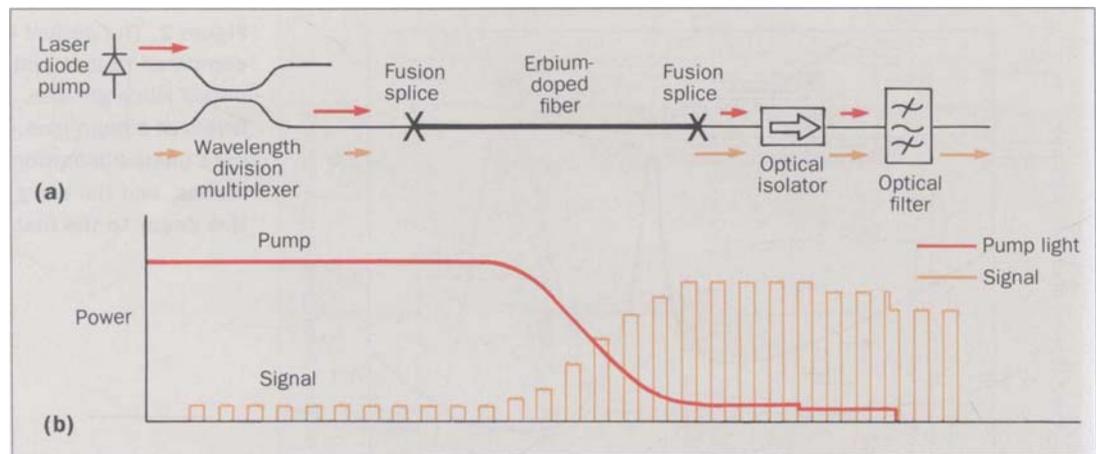
Saturation occurs when large signal powers in the EDFA decrease the gain, thereby limiting the signal output power from the amplifier. This gain saturation results when the signal power grows large and causes

stimulated emission at such a high rate that the inversion is decreased, that is, the number of excited erbium ions decreases substantially (see Figure 4b). For a three-level laser system, the output saturation power (the output signal power at which the gain is compressed by 3 dB relative to the small signal gain) is proportional to the pump power (see Figure 4c). The output signal power is limited only by the available pump power.^{5,6} Heavily saturated amplifiers can convert pump photons to signal photons with efficiencies exceeding 90 percent.⁷

An optical amplifier necessarily degrades the signal by adding noise from the amplified spontaneous emission (ASE), which arises from amplified light produced by the spontaneous emission from erbium ions. In an ideal high-gain optical amplifier, the noise figure (the signal-to-noise ratio at the input divided by that at the output) is 3 dB.⁸ Noise figures approaching this quantum limit have been demonstrated in EDFAs.^{9,10} In saturated amplifiers, where the inversion is low, the noise figure may worsen.

Theoretical Models and Optimal Design. Theoretical models based on the three-level-lasing system of Figure 2 (see for example References 11, 12, and 13) are quite successful in explaining the observed properties of EDFAs. The three-level model has been used to analyze

Figure 3. (a) Schematic representation of EDFA module with co-propagating pump. (b) Propagation of pump and signal powers through the EDFA module.



the optimal design for EDFAs.¹⁴ In the three-level erbium system, ions remaining in the ground state degrade performance because they absorb signal power (see Figure 2). The rate at which erbium ions are promoted to the excited state is proportional to the pump intensity (i.e., the pump power per unit area). To maximize the pumping rate experienced by each erbium ion while minimizing pump power requirements, both the pump power and the erbium atoms must be confined to the smallest cross-sectional area possible. Models show that this is most effectively accomplished by increasing the difference between the refractive indices of the fiber core and the cladding and by decreasing the size of the erbium-doped core. An EDFA with an index difference of 0.04 (more than ten times larger than that of a standard single mode fiber) and a core diameter of 2 μm (more than four times smaller) has a very small optical mode; the gain curve shown in Figure 4a demonstrates the low pump requirements of this efficient EDFA.

The erbium concentration and the choice of additives in the EDFA core are also important. For example, adding aluminum to the core broadens and flattens the amplifier spectrum. The higher the concentration of erbium used, the more amplification the EDFA provides per unit length, and the shorter it can be. If the erbium concentration is too high (greater than 10^{19} cm^{-3} for aluminum co-doped cores or 10^{18} cm^{-3} for those with only germanium co-doping), the ions clump together and energy transfer between the ions degrades performance.¹⁵

Gain Dynamics, Crosstalk, and Polarization Sensitivity.

Data from a lightwave transmitter is sent by modulating the optical power emitted from a semiconductor laser.

Any device between the transmitter and receiver should leave the signal undistorted. Signal distortion is introduced by optical amplifiers whose gain fluctuates. The EDFA is relatively immune to gain fluctuations. Because the spontaneous decay of the erbium excited state has a long lifetime, gain saturation is very slow. Typically, it takes 0.1 to 1 ms for gain compression to occur after a saturating signal is launched into the EDFA. Because these times are very long compared to both the pulse period in gigabit digital systems and the signal modulation in analog systems, EDFAs add minimal signal distortion or crosstalk.

The gain of an optical amplifier should be unaffected by the polarization of the input signal. Otherwise, signals might fade or noise might worsen as signal polarization in the transmission fiber varies randomly with time. The polarization-independent gain of the EDFA is the result of the circular symmetry of the fiber and the random orientation of erbium ions in glass.

EDFA Component Technology

In describing EDFA component technology, we will examine erbium-doped fiber fabrication, splices, pump lasers, passive components, and the EDFA module.

Erbium-Doped Fiber Fabrication. Optical fibers with erbium-doped cores can be fabricated by modified chemical vapor deposition (MCVD), outside vapor deposition (OVD), and vapor-axial deposition (VAD). We will discuss only the MCVD process used for fiber manufacture by AT&T¹⁶ and other manufacturers.

In the MCVD process, a silica tube with a 25-millimeter outer diameter is mounted on a glassworking

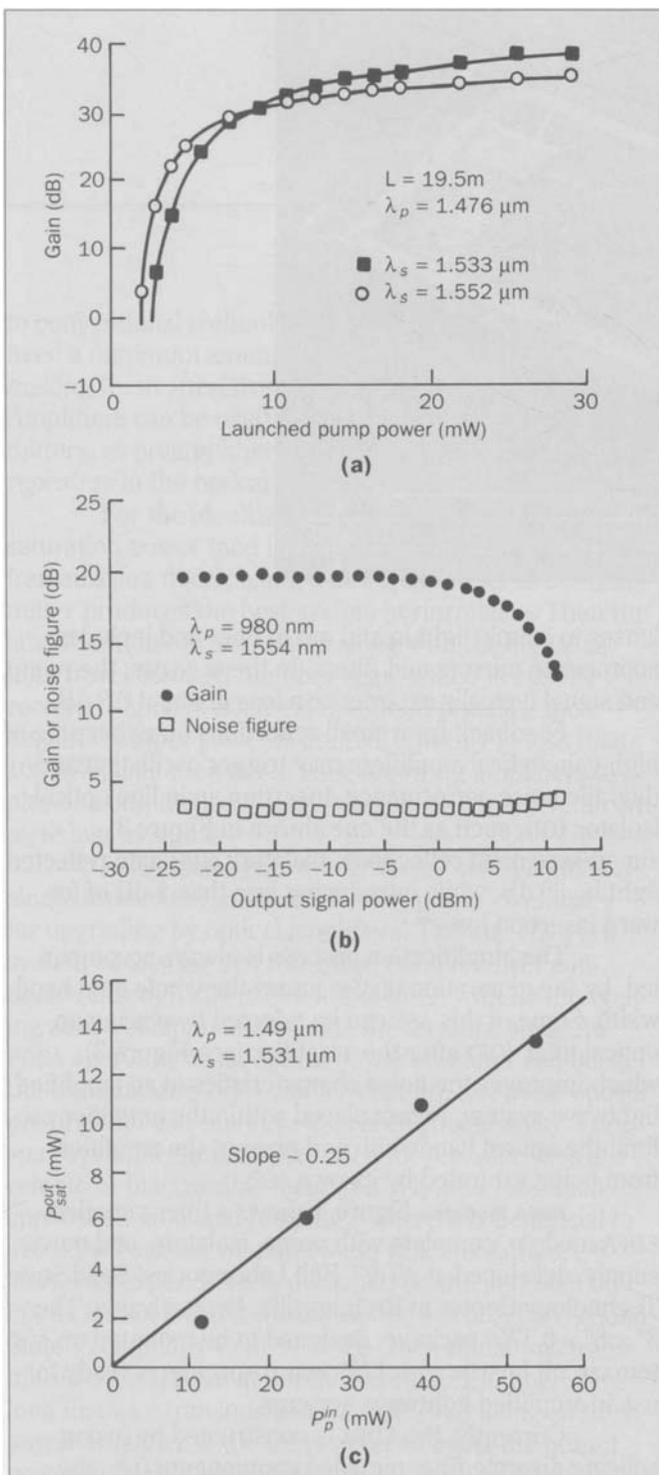


Figure 4. (a) Gain versus pump power for a high-gain EDFA. (b) Gain and noise figure versus output signal power for a low-gain EDFA. (c) Output saturation power as a function of input pump power for an alumino-silicate EDFA.

lathe and locally heated to about 1900°C (degrees Celsius) by an oxy-hydrogen torch that travels along the length of the tube. Chemical reagents consisting mainly of silicon tetrachloride (SiCl_4) and oxygen gas (O_2),

with dopants such as germanium tetrachloride (GeCl_4), flow through the tube and react at the traveling hot zone to form doped silicon dioxide (SiO_2) particles. These particles are deposited downstream on the wall of the tube, forming a porous layer several millimeters thick. As the traversing torch passes over this deposit, the silica particles sinter into clear, pore-free glass that is tens of micrometers thick. Repeated passes of the torch build up a thickness of deposited glass whose composition is controlled by the composition of the reagent gas stream. The tube is then heated to 2300°C, at which point it collapses to a solid rod under its own surface tension and is subsequently drawn into fiber.

Incorporation of erbium into the MCVD process requires changes to accommodate the low vapor pressure source. These changes to MCVD entail heating an ampule of erbium trichloride (ErCl_3) to 1000°C to generate vapor while the core layers are being deposited.¹⁷ The silica soot formed is thus doped with erbium. Alternatively, vapor containing erbium can be created using an aerosol technique, in which a cloud of ultrasonically generated liquid droplets are injected into the tube.¹⁸ The liquid is appropriately doped with soluble erbium compound.

A third technique, called solution-doping,¹⁹ entails depositing the core soot at a lower temperature to forestall sintering. The tube is removed from the lathe and filled with an aqueous solution containing, for example, ErCl_3 . After the tube is drained, dried, and collapsed, the ErCl_3 trapped in the soot pores becomes incorporated in the core glass during sintering.

A fourth technique also involves removing the preform from the lathe, in this case after the core layer has been sintered. The dipcoating method²⁰ is used to coat the inner wall of the preform with an erbium-doped silica sol-gel material. The tube is dehydrated, collapsed, and drawn into fiber. In both VAD and OVD, similar doping schemes use either high-temperature vapor sources or immersion in doped solutions.

Splices. Optimal amplifier performance requires core diameters and optical spot sizes much smaller than conventional fiber. For example, present EDFAs have 2.5- μm cores that produce optical modes with a diameter of 4 μm , compared to 7 to 8 μm for conventional fiber. Even for such large differences in spot sizes, splice losses of 0.1 to 1 dB between the erbium-doped fiber and conventional fiber can be obtained by heating the fibers to produce a fusion splice with a low-loss transition region.

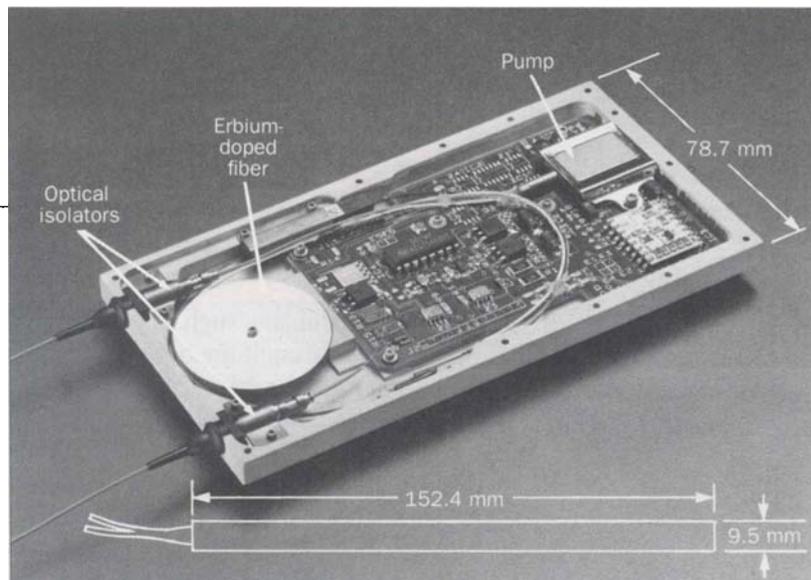


Figure 5. EDFA module designed at AT&T Bell Laboratories' Solid State Technology Center (from T. W. Cline and K. A. Yanushefski).

Pump Sources. Extremely efficient pumping has been demonstrated at both 980 nm²¹ and 1480 nm,⁴ with gain exceeding 20 dB produced by less than 5 milliwatts (mW) of pump power. Typically, 10 to 100 mW are needed to ensure adequate output power. The quantum-limited noise figure of 3 dB has been achieved at 980 nm. But at 1480 nm the noise figure is about 1 dB larger²² because the pump absorption and signal gain bands are the same, and emission stimulated by the pump light limits the population inversion.

Semiconductor diode lasers suitable for pumping EDFAs can emit hundreds of milliwatts at both 980 nm and 1480 nm (see e.g., References 23, 24, and 25). For 980-nm lasers, strained indium gallium arsenide (InGaAs) quantum wells are grown on gallium arsenide (GaAs); for 1480-nm pumps, the materials used, either indium gallium arsenide quantum wells or indium gallium arsenide phosphide grown on indium phosphide, are very similar to those used for standard communication lasers. The shorter wavelength 980-nm diode lasers require less injection current and less cooling, thereby reducing electrical power requirements. Currently, 1480-nm pumps are more widely used, largely because they are more readily available and there is greater confidence in their reliability. Reliability is especially important for pump lasers, which will be called on to deliver high levels of power over long periods. Power amplifier applications will require the highest pump power, and pump reliability should be a key issue in their development. If confidence in the reliability of 980-nm pump diodes continues to grow, they may become the pumps of choice, except in applications where pump transmission losses must be minimized, such as remotely pumped amplifiers or distributed EDFAs.

Passive Components. The pump and signal are combined by a wavelength division multiplexer, shown in Figure 3, which is typically either a fused fiber coupler or a miniature bulk optic device. The latter device uses

lenses to couple light in and out of fiber and includes appropriate mirrors and filters. In these WDMs, the pump and signal typically experience a loss of about 0.5 dB.

Feedback from small reflections on either side of high-gain optical amplifiers may trigger oscillation and degrade noise performance. Inserting an in-line optical isolator (OI), such as the one shown in Figure 3, suppresses most reflections. Isolators attenuate reflected light by 35 dB, while introducing less than 1 dB of forward insertion loss.^{26,27}

The amplification process is always accompanied by the generation of ASE across the whole gain bandwidth. Some of this ASE can be rejected by placing an optical filter (OF) after the amplifier (see Figure 3), which improves the noise characteristics of an amplified lightwave system. Filters placed within the amplifier can limit the optical bandwidth and prevent the amplifier from being saturated by its own ASE.

EDFA Module. Figure 5 shows a fiber-pigtailed EDFA module, complete with pump, isolators, and power supply, developed at AT&T Bell Laboratories' Solid State Technology Center in Breinigsville, Pennsylvania. The 3" × 6" × 0.375" package, designed to be mounted on system circuit boards with 1/2" board spacing, is ready for use in amplified lightwave systems.

Currently, the EDFA is constructed by fusion splicing discrete fiber-pigtailed components (i.e., the erbium-doped fiber, the WDM, the isolator, the filter, and the pump). In the future, EDFAs may use advanced technologies, such as silicon hybrid optical packaging (silicon optical bench)²⁸ or photonic integrated circuits²⁵ to combine many functions into an integrated package.

Systems

Economics and performance will determine where to place optical amplifiers in lightwave systems. System economics dictate that the installation and service of an optical amplifier must be inexpensive relative

to conventional technologies, or it will not be used. EDFAs need a minimum amount of supervision and service, making them attractive as repeaters in remote locations. Amplifiers can be used as power amplifiers in transmitters, as preamplifiers in receivers, or as analog optical repeaters in the optical link.

For the idealized case of unlimited amplifier saturation power (and ignoring nonlinear effects in the transmission fiber), using a power amplifier at the transmitter produces the best system performance. Then the amplifier noise is attenuated along with the signal as both travel through the fiber span, which keeps the received signal-to-noise ratio high. In practice, the amplifier output power is limited, typically to less than 100 mW, and often much less, requiring amplifiers to be placed along the lossy transmission path to prevent complete loss of signal.

Long-span lightwave systems, which contain a single transmitter and receiver, are prime candidates for upgrading by optical amplifiers. The objective is a system consisting of a transmitter and receiver connected through 200 to 300 km of fiber, with no intervening active components outside the terminal sites. An EDFA operating as an optical power amplifier can boost the transmitter power, and a front-end, low-noise optical preamplifier can increase the receiver sensitivity. Long-span systems eliminate the need for repeater sites at remote or inaccessible locations. A typical long-span application is "island-hopping," where it is beneficial to avoid the expense of underwater repeaters. Figure 6 shows an experiment to demonstrate the potential of EDFAs for such applications, carried out at AT&T's Solid State Technology Center. A 2.5-Gb/s signal was transmitted over 318 km of unrepeated optical fiber. This long-distance transmission was achieved using an EDFA power amplifier at the transmitter to boost the output power to 16 dBm (decibels above 1 mW) and an EDFA preamplifier at the receiver to increase the sensitivity to -41 dBm.²⁹

EDFAs are also being considered by U. S. network operators to increase capacity economically. Network upgrades in North America must use existing fiber plant, which was originally designed for 1.3- μ m signal wavelengths. The effects of polarization dispersion and chromatic dispersion limit the bit rate of a single channel. Lightwave channels operating at 1.5 μ m can transmit data over optical links of the AT&T terrestrial network at rates up to about 2.5 Gb/s. Because EDFAs can amplify

multiple wavelengths on the same fiber, very high network capacities can be achieved by wavelength-division multiplexing several 2.5-Gb/s channels, i.e., several 2.5 Gb/s channels on one fiber, each channel operating at a different wavelength. One possible scenario would be to replace regenerators at repeater sites with optical amplifiers and to wavelength multiplex several 2.5-Gb/s data channels to achieve aggregate bit rates of 10 to 20 Gb/s.

Local area networks and distribution networks can use optical amplifiers to compensate for losses from components, including fiber-optical splitters and filters. Cable television (CATV) now uses 10- to 20-km-long fiber-optic trunk lines. With optical amplifiers, this distance could be extended beyond 30 km. EDFA power amplifiers can also be used to compensate for splitting losses, which will enable optical fiber to penetrate further into the network toward the customer. Because CATV uses analog signaling, its sensitivity to distortion and noise imposes strict requirements on optical amplifiers. The EDFA can provide CATV with the necessary flat amplifier gain spectrum, high saturated output power, low crosstalk, and low noise.

The possibility of optically amplified transoceanic lightwave systems has fascinated researchers for years. Increasing the bit rate of transoceanic lines using conventional technology necessitated the redesign of regenerators. Now, if optically amplified systems are used, only the land-based terminal equipment need be upgraded, while the undersea lightpipe design could remain unchanged. Unlike the terrestrial network, an amplified transoceanic system for which new cable must be laid is not constrained to use fiber already in place. This flexibility to choose the fiber and components for best system performance is fortunate, in view of the complexity of the optical processes that act to corrupt the data. As the signal traverses thousands of kilometers and hundreds of optical amplifiers, it is degraded by a combination of chromatic dispersion, polarization dispersion, optical nonlinearities in the transmission fiber, and amplifier noise. However, these problems can be overcome by methodical design, as seen in the 5-Gb/s, 9000-km signal transmission recently demonstrated by researchers at AT&T.³⁰ This and other experiments have stimulated development programs for undersea amplified lightwave systems. The first such system from AT&T is targeted for transatlantic service by 1995.

If we look into the future of amplified lightwave systems, soliton pulse transmission, pioneered at AT&T,

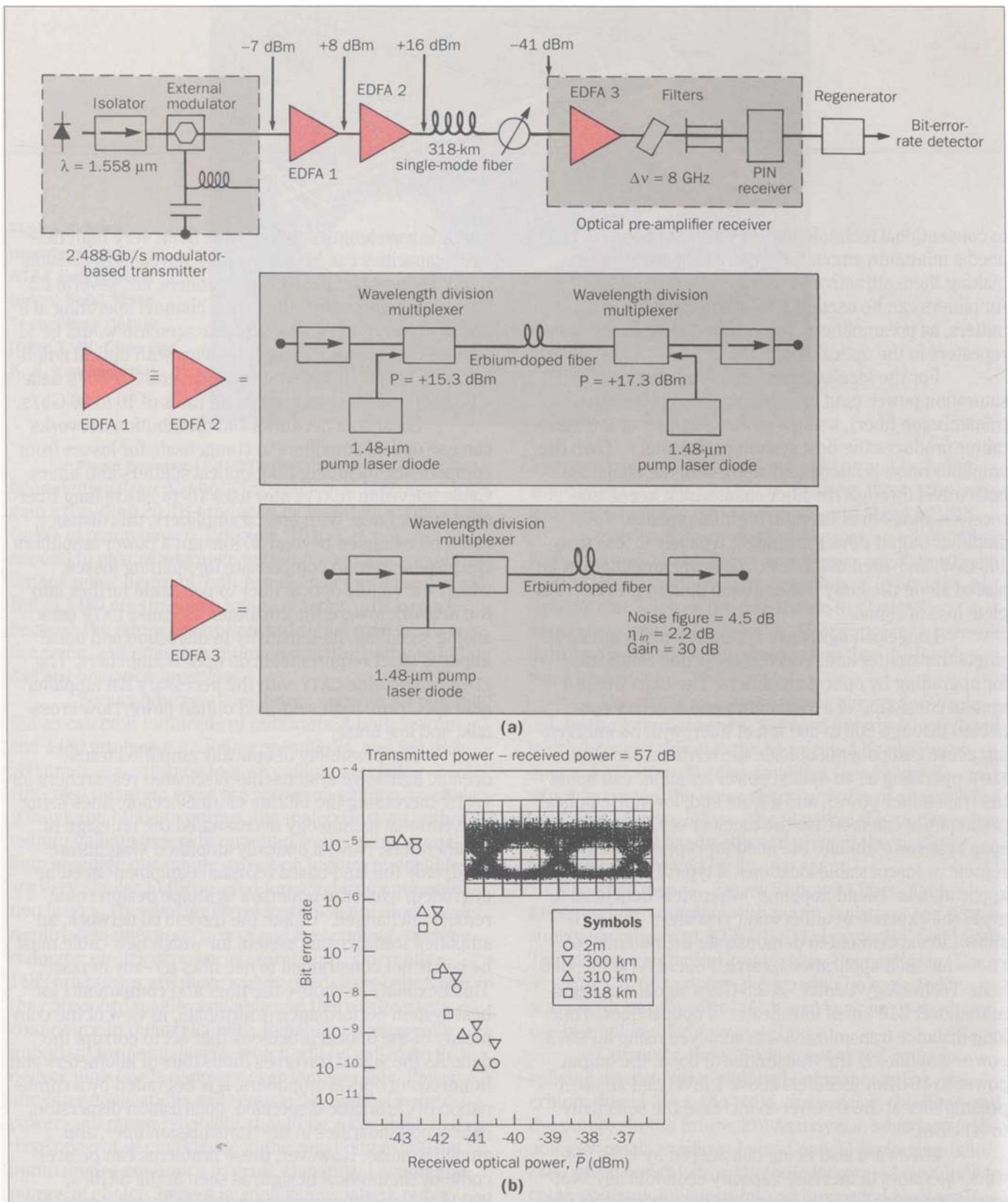


Figure 6. (a) A 2.5-Gb/s repeaterless, long-span transmission experimental set-up using EDFA preamplifier and power booster. The single-mode fiber is not dispersion-shifted. (b) Eye diagram and bit-error-rate performance of the

repeaterless, transmission experiment at 2.5 Gb/s. The transmitter power minus receiver power loss budget is 57 dB for 10^{-9} bit-error-rate transmission.

offers the promise of very low pulse distortion over long fiber spans. This low distortion results from the exact balancing of chromatic dispersion and fiber linearity while the soliton pulse traverses the optical fiber.³¹ Soliton experiments have flourished since the introduction of EDFAs, which solve two requirements for soliton pulse transmission:

- High peak power generation from the transmitter
- Maintenance of high peak power over the transmission fiber span.

Recent experiments have demonstrated soliton propagation over a distance exceeding 10,000 km³² and propagation of two wavelength-multiplexed soliton pulse trains over 9000 km.³³ Solitons will likely be used in future amplified systems as the need for higher capacity grows.

Better amplifiers have been made by distributing the gain over long lengths of transmission fiber that have low concentration of erbium in the core.³⁴ Because silica optical fiber has low intrinsic loss at 1.48 μm , this distributed gain amplifier can be pumped directly at 1.48 μm to achieve lossless transmission over long distances. These distributed amplifiers promise to have lower noise and to permit lower average signal powers to control undesirable nonlinear effects.

Conclusions

With their high gain, high output power, low noise, and other advantages, EDFAs have nearly ideal characteristics for a wide range of applications. In the next few years, they promise to revolutionize long-haul terrestrial transmission, submarine systems, and light-wave networks, as they provide tremendous improvements in system capacity and simplicity at lower cost.

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