Impact of Erbium-doped amplifiers on optical communication systems

By Sadakuni Shimada

It was demonstrated recently that Erbium-doped single-mode fibers (EDF) can be used as a novel traveling-wave type optical amplifier in optical communication systems. The fiber amplifiers are applicable as high power post amplifiers at the sending port, as low noise preamplifiers at the receiving port, and as intermediate optical repeater amplifiers. It is conceivable that a new revolution of optical communication systems will be brought about by employing these fiber amplifiers in new communication systems.

This article outlines the recent studies on optical amplifiers and compares the features of fiber amplifiers with those of other optical amplifiers. The impact of this new amplifier technology is then discussed and the future possibility of communication systems with optical amplifiers is assessed. Systems applications are described using the effectiveness of these fiber amplifiers—long repeater spacing, undersea systems, soliton transmission, and subscriber loop systems. A compact fiber amplifier for general use is also mentioned.

EDF amplifiers are expected to significantly influence the future of optical communication systems. Research on these applications has just begun and many issues remain to be explored. While some of the expectations noted below may not prove to be correct, they are actually very conservative. One problem in making technical predictions is that progress is extremely rapid.

Optical fiber communication

Present optical fiber communication systems are composed of regenerative repeaters, which are inserted into the line to compensate signal attenuation created by long fiber transmission distances. In a conventional repeater, the optical signal is first converted to an electrical signal by a photodiode, then the electrical signal is amplified by semiconductor electronic circuits. The amplified electrical signal is converted to an optical signal with a semiconductor laser diode, and then the optical signal is injected into the fiber. If the optical signal can be directly amplified with low noise, the repeater can be smaller and cheaper than existing repeaters. Also, branching loss may be easily compensated with an optical amplifier. This means that an extremely flexible communication network can be created because signals can be easily handled in the optical format without changing it into the electrical format. Thus, the application potential of an all-optical communication system is quite extensive and advanced communication services will become possible at a reasonable cost.

An induced emission phenomena, which was the foundation of the optical amplifier, was confirmed by a microwave amplifier demonstrated for the first time by Towns et al. in 1954. Research on optical amplifiers for communication systems has been advancing since 1980. Semiconductor
laser amplifiers (SLAs) such as the Fabry-Perot SLA or travelling-wave SLA have been studied.

Along with progress in single-mode fiber technology, fiber amplifier research has created the rare-earth doped fiber amplifier, the induced Brillouin amplifier, and the induced Raman amplifier. The latter two use the nonlinear effects of fiber material. Optical transmission experiments have been performed in many research organizations and Erbium-doped fiber (EDF) is the most promising material.

The oscillation of a rare-earth-doped glass laser was first reported in 1964. Recently, Erbium has drawn attention as doping material for the 1.5 $\mu$m wavelength region because this is the silica fiber's low loss wavelength region. Originally, it was studied as a high output laser source in the 1.5 $\mu$m region. Many communication systems researchers now pay keen attention to Erbium-doped fiber because it has become clear that the fiber amplifier exhibits different features than the SLA or Raman amplifier. This heightened interest was evident at the 1989 Conference on Optical Fiber Communication (OFC® '89), for example, where 12 papers on Erbium-doped fiber were presented.

One of the most impressive reports detailed a 212 km non-repeated transmission experiment at 1.8 Gb/s using LD pumped Er-doped fiber amplifiers in an IM/Direct-detection system. The feasibility experiment was thought to indicate a new era in transmission system technology and will have a profound effect on the R&D strategy of communication systems. This work caps a steady increase in system performance for a 50 km repeater spacing experiment in 1978, a 104 km spacing using DFB-LD and single mode fiber in 1982, and a 290 km spacing at 400Mb/s with coherent transmission in 1986.

Optical fiber ring laser and soliton amplification were also reported using Erbium-doped fiber. In sum, a new technology for optical communication appeared at OFC® '89 and study toward system applications with fiber amplifiers will be accelerated in the near future.

### Comparing optical amplifiers

There are three important optical amplifiers: Erbium-doped fiber, fiber Raman, and semiconductor lasers. Fiber type optical amplifiers are directly connected to the transmission line and the connection loss is small. Therefore, these amplifiers are easily introduced in optical fiber transmission systems. Because fiber amplifiers use light as a power source, many new applications will become possible.

On the other hand, semiconductor laser amplifiers have advantages in their smaller size and smaller power consumption, even though their temperature stability is a problem at present. SLAs can be used in combination with optical integrated circuits and optoelectronic integrated circuits.

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#### Er-doped optical amplifiers

Features and application fields of EDF amplifiers are shown in Fig. 1. They have many merits such as low noise, wide bandwidth, and high output power. Large capacity and long repeater spacing will be effective in land and undersea transmission systems. Moreover, application in CATV or distribution networks will become possible by using them as optical booster amplifiers. This function is now being inefficiently performed with electronic amplifiers in coaxial cable.

Compared to conventional technologies, optical amplifiers exhibit:

- high output peak power in the transmitter;
- improved receiver sensitivity;
- elimination or reduction of electronic circuit;

The signal bandwidth of these optical amplifiers is extremely wide—extending to 1 THz—because the carrier is light. This creates new possibilities for system design, since conventional electronic amplifiers are now limited to a 10 GHz bandwidth.

![FIGURE 1. Features and applications of Erbium-doped fiber amplifier.](image)
potential use for highspeed wide-band optical signal processing; and
simultaneous signal amplification for wavelength (or frequency) division multiplexed signals.

The first two features will be effective in the expansion of repeater spacing, while the others will help expand the application fields and provide simpler communication equipment. Examples of optical amplifier applications in new communication systems are shown in Fig. 2.

When an optical amplifier is inserted in a transmission line, the amplifier operates as an all-optical repeater, generally called a 1R (reshaping) repeater. The noise and jitter in a 1R repeater system accumulate with the number of the repeaters. Furthermore, there is the accumulation of waveform distortion with transmission through long fibers. To reduce such distortion, repeaters with 2R (reshaping and regenerating) or 3R (re-timing added to 2R) functions are needed in each terminal or between 1R repeaters. Such a system is sometimes called a hybrid transmission system.

The repeater spacing in an all-optical transmission system is very long compared to a conventional coaxial cable system. One significant advantage is that, because of the smaller number of repeaters, degradation does not become large even if the 1R optical repeater system is applied. Therefore, simple optical amplifier repeaters can be used to create practical hybrid transmission systems that were formerly impossible. One important research topic is to clarify the noise, jitter, and waveform distortion characteristics in 1R multi-repeated and all-optical 3R\(^{17,18}\) repeatered lines.

**Transmission experiments**

The configuration of the long repeater spacing transmission experiment given by Ref. 19 is shown in Fig. 3. The transmitter and the receiver were intensity modulation devices using the direct detection scheme developed for a F-1.6 G system with a line bit-rate of 1.8 Gb/s. The optical source, the photodetector and the fiber are a DFB-LD, an InGaAs-APD, and a dispersion-shifted single-mode fiber, respectively. Using an LD pumped Er-doped single-mode fiber amplifier, 250 km non-repeater transmission was achieved. The gain of the post amplifier and the receiver sensitivity were 10 dB and 6 dB, respectively.

The best conventional transmission system now in use has repeater spacings of 40 km at 1.3µm and up to 80–120 km at 1.55 µm. The great improvement in optical output power and receiver sensitivity made it possible to double the repeater spacing by using the newly developed optical amplifier. This spacing is comparable to that obtained in a 2.5 Gb/s-287 km transmission experiment using coherent technology.\(^{20}\) However, the coherent transmission system still has the problems of stabilization of light source frequency and the polarization compensation at the receiver. The direct detection system with the optical amplifier—featuring a simple struc-

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**FIGURE 2. Examples of optical amplifier application in new communications systems.**

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ture and configuration, excellent ca­
pabilities, and inherent stability—
paves the way toward early practical
realization of significantly enhanced
optical transmission systems.

**Systems applications**

**Long-haul transmission systems**

The increase in repeater spacing by
using EDF optical amplifiers will re­
duce transmission equipment costs,
improve line reliability, and simplify
maintenance and operation functions,
because most major telephone offices
would be connected without any out­
side repeaters. Moreover, ultra-high
speed transmission systems—for ex­
ample, at 10 Gb/s—that exceed the
present F-1.6 G system, are possible if
the optical amplifier is used as a 1R
repeater or wideband amplifier. A
161 km non-repeatered transmission
and a 216 km transmission with a lin­
ar repeater (1R repeater) were
achieved at 10 Gb/s using EDF ampli­
fiers.\(^{21}\) A combination EDF optical
amplifier and PIN-PD may replace
the avalanche photodiodes.

**Undersea transmission systems**

Transocean connections become
theoretically possible with a simple
configuration when optical amplifiers
are applied. The trend of longer spans
is shown in Fig. 4 where the accumu­
lated noise and dispersion penalty are
considered as restriction conditions.\(^{21-23}\)
The main assumptions are shown in
the figure, but distortions—which are
caused by a non-flatness of the optical
amplifier frequency response and by
gain saturation—need to be taken
into account for practical system de­
design.

The system in Fig. 4 is designed
with IM/direct-detection scheme. The
great improvement in optical output
power and receiver sensitivity made it
possible to double the non-repeatered
spacing by using the EDF amplifiers.
It was also demonstrated that a sim­
In the future, this may be designed with the coherent modulation/demodulation scheme. In IM modulation, external modulation may be practical to obtain a chirpless modulation waveform. The expected 1R repeater spacing is around 100 km when the amplifier gain is 20 dB. However, the repeater configuration will be drastically simplified. This new configuration has several merits:

- Bit-rate free transmission system is possible because the repeater does not include retiming and regenerating circuits.
- Many repeaters can be installed to one repeater housing because the repeater is quite small. Thus, multi-core fiber cable is easy to install.
- Small power consumption. Undersea cables become lighter and smaller or the remote power supply equipment can be scaled down.
- Significant cost reduction is expected due to simple repeater configuration, lightweight cable, long repeater spacing, and transmission capacity increase.

Important avenues for future research include clarification of the ultimate limit of possible number of 1R repeaters between 3R repeaters, and the optimization of the system considering the amplifier noise characteristics and the optical filter bandwidth.

**Optical fiber soliton transmission**

The pulse power density of light is increased in ultrashort pulse and high speed transmission systems. As a result, a nonlinear effect appears in the optical fiber. Optical fiber soliton is one of the promising transmission technologies being considered. The pulse broadening that occurs through linear dispersion is compensated by the self-phase modulation (frequency chirping) caused by the nonlinear Kerr effect of the fiber. Thus, an optical fiber soliton can be generated and transmitted that preserves its optical pulse shape. In this case, the loss of optical fiber needs to be compensated, and Raman amplification or EDF optical amplification becomes necessary. Although waveform stability after long propagation distances is a major research item, there is a definite possibility of achieving Tb/s optical transmission systems.

**Subscriber loop system**

An example of using an EDF amplifier in a video distribution system such as CATV is shown in Fig. 5. In existing coaxial networks, the service area is limited to 7 km from the head end, many electrical amplifiers must be installed, and the video quality is critical to the cable length. Recently, analog optical fiber transmission systems at 1.3 µm wavelength have been introduced. In these systems, VSB-AM FDM signals of existing coaxial CATV were converted into the optical
signals. However, the transmission length is limited to 11 km.

EDF amplifiers can improve the transmission length to about 40 km by developing a 1.5 µm waveband technology. Applying EDF amplifiers not only increases the transmission length, but also offers the possibility of optical branching. FM-FDM signal format will be effective to increase the numbers of branching to 1000 or more in future all-optical CATV networks.

Because the amplifier's bandwidth is wide, common signal amplification will be also possible for wavelength-division or frequency-division multiplexed signals. Options and configurations for subscriber loop systems will be increased, network flexibility will be enhanced, and the distribution cost will be reduced with EDF amplifiers. They will contribute to development of optical CATV systems and optical LANs, as well as optical subscriber loop systems. Also, they will significantly boost the flexibility of "fiber-to-the-home."

It is often necessary to switch transmission lines when trouble such as fiber breakage occurs. An optical fiber line protection switch is easily arranged by using Erbium-doped fiber amplifiers. Their on/off switching ratio is large where amplification corresponds to the on-state and attenuation to the off-state. From environmental and economic viewpoints, optical switching by EDF amplifiers is preferable because conventional switches need signal amplification by electronic circuits after optical to electrical signal conversion.

Compact optical amplifiers

Compact optical amplifiers such as the fiber type amplifier shown in Fig. 6, and an optically integrated circuit amplifier in which rare-earth materials dope the optical waveguide, are very effective in various fields. To realize compact optical amplifiers, several important research issues must be addressed, such as how to obtain a simple and high power pumping optical source, choice of a new wavelength—for example, around 0.8 µm, where the laser diodes are easily created by proper selection of rare-earth materials—and finding a high-efficiency excitation wavelength. One candidate is 0.98 µm pump-wavelength, where gain-pump efficiency may be improved three times higher than that at 1.48 µm pump-wavelength.

EDF amplifiers are also applicable for a space division optical switching system, because they can compensate the optical loss and serve as a functional switching element, which acts as an amplification/absorption circuit if the pumping is on/off-switched. All-optical networks receive attention because switching and cross-connects, as well as fiber transmission, can be performed without converting optical into electrical signals. This is because the naturally wide bandwidth characteristics of light is fully utilized. However, there is a problem of optical loss in present switching circuits. In most systems, electronic switching is thought to be preferable after optical to electrical conversion, since electronic signal processing is better than optical processing in terms of integration and higher functionality, even if the electronic bandwidth is not so wide. If the optical amplifier becomes feasible for use, the optical loss will not be a major problem and the research point of these applications will be changed. New technology and applications are then likely to emerge.

When a ring laser is composed of an EDF amplifier, a frequency stability of 10 kHz is achieved. This narrow spectral optical source is applicable to coherent transmission systems or measurement applications. These are new fields for EDFs.

Other optical amplifiers, such as semiconductor laser amplifiers, are being studied in many organizations. A polarization independent SLA can be achieved by LD structural improvement or by an optical circuit combining two SLAs with orthogonally polarized planes. A lot of data on the practical performance of EDF and SL amplifiers must be gathered to design and select the most appropriate devices for high performance communication systems.

FIGURE 6. Example of a compact EDF amplifier. (Size: 50 × 130 × 110 mm)
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