Wideband Rare-earth-doped Fiber Amplification Technologies—Gain Bandwidth Expansion in the C and L bands

Tadashi Sakamoto†, Atsushi Mori, Hiroji Masuda, and Hirotaka Ono

Abstract

We are expanding the gain bandwidth of Er^{3+}-doped fiber amplifiers (EDFAs) by using tellurite fiber instead of silica fiber. This article describes EDFAs that cover a wide wavelength region (1535–1605 nm) in the C and L bands and EDFAs with a 50-nm amplification range (1560–1610 nm) in the L band. We also present transmission experiment results for a remotely pumped hybrid inline-repeater system that uses a tellurite-based EDFA in conjunction with distributed Raman amplification.

1. Importance of expanding the amplification bandwidth of EDFAs

Medium- and long-haul optical transmission mainly uses signals with wavelengths in the vicinity of 1550 nm because optical fiber has its minimum loss in this region. The erbium-doped fiber amplifier (EDFA), which uses Er^{3+} as the active ion, has been widely used for 1550-nm signal amplification. The EDFA features high-gain and low-noise amplification in either the 1530–1560-nm wavelength region within the C band (1530–1565 nm) or the 1570–1600-nm wavelength region within the L band (1565–1625 nm). The signal wavelengths available for practical optical-communication systems have been limited by the EDFA amplification-wavelength regions (only 30 nm wide at most). Therefore, if we can expand the EDFA amplification bandwidth, we should be able to increase the transmission capacity by increasing the number of wavelength division multiplexing (WDM) channels, which will spur the development of large-scale high-performance photonic networks.

One effective way of expanding the amplifier bandwidth is to find an appropriate optical fiber material that best exploits the amplification capability of Er^{3+} ions; we chose a tellurite glass for this purpose as a replacement for conventional silica glass fiber. In this article, we introduce two important types of amplifiers that we have made in this way: a (C+L)-band Er^{3+}-doped tellurite fiber amplifier (EDTFA) and a wideband L-band EDTFA. We also present the results of a transmission experiment that applies an EDTFA along with a distributed Raman amplifier to a remotely pumped hybrid inline-repeater system.

† NTT Photonics Laboratories
Atsugi-shi, 243-0198 Japan
E-mail: tsaka@aecl.ntt.co.jp

2. Bandwidth expansion using tellurite fiber

Extending the EDFA bandwidth requires a large Er^{3+} stimulated emission rate across a wide range of wavelengths. The wavelength dependence of the stimulated emission rate differs according to the type of glass material into which the Er^{3+} ions are doped because the stimulated emission rate of Er^{3+} is affected to some extent by the electric field (ligand field) generated by the atoms of the glass. It is important to find a glass material that can extract the latent capacity of Er^{3+} for wideband amplification. Our measurements of the basic characteristics of various types of glass material doped with Er^{3+} showed that tellurite glass is an effective material for expanding the bandwidth [1], [2].

Figure 1 shows the stimulated emission rate (solid lines) and excited state absorption (ESA) (broken lines) for tellurite glass and silica glass doped with Er^{3+}. Tellurite glass has a higher stimulated emission

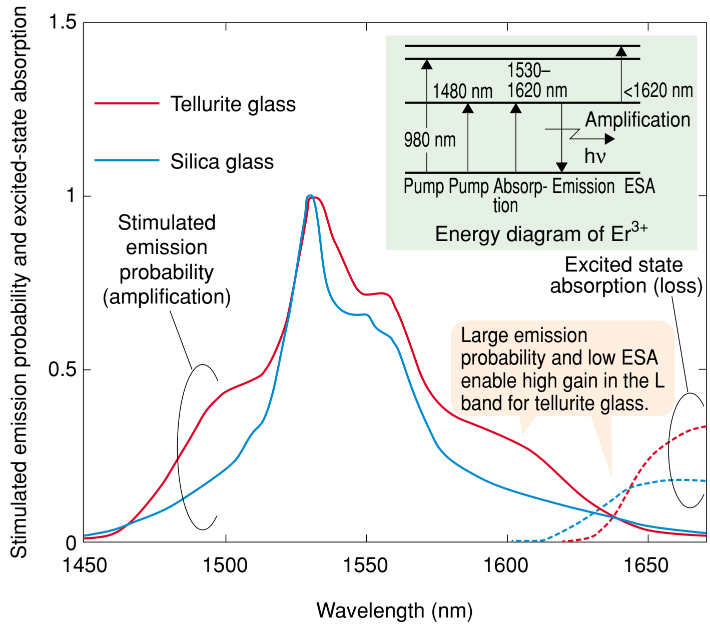
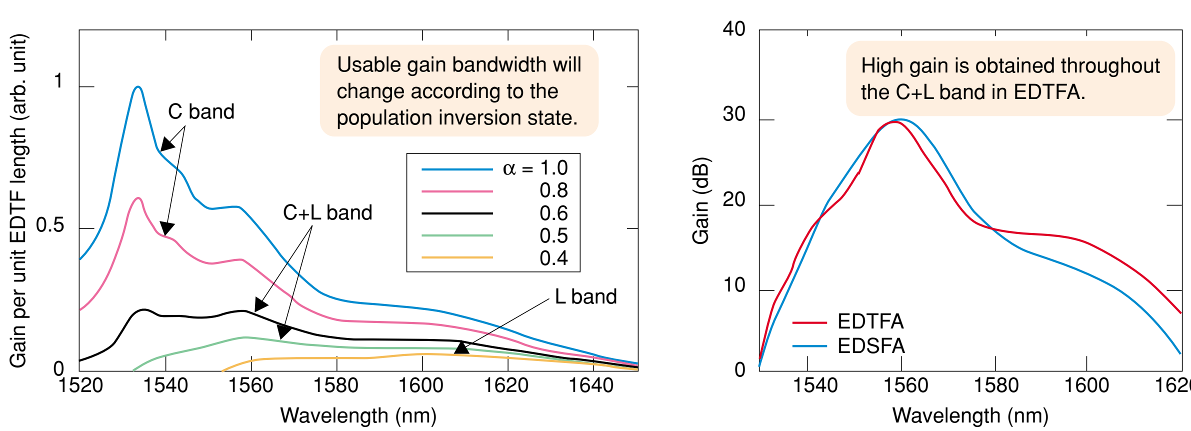


Fig. 1. Optical properties of Er^{3+} ions in tellurite glass.

rate especially in the 1580–1630 nm wavelength region, which is advantageous for obtaining high gain in the L band. ESA, which corresponds to signal loss, arises at wavelengths longer than 1610 nm with silica glass but longer than 1620 nm with tellurite glass, so tellurite glass is also advantageous in terms of ESA, especially when we expand the amplification bandwidth of the EDFA to wavelengths above 1610 nm in the L band. The basic characteristics described above show that tellurite glass is a promising optical fiber material for wideband amplification with an EDFA.

3. EDTFA providing (C+L)-band amplification

It is known that the EDFA gain dependence on wavelength changes if the population inversion state is altered by pumping. **Figure 2(a)** shows an example in the case of an EDTFA. The population inversion factor α is defined as the Er^{3+} density in the excited state divided by the total density of doped Er^{3+}. When

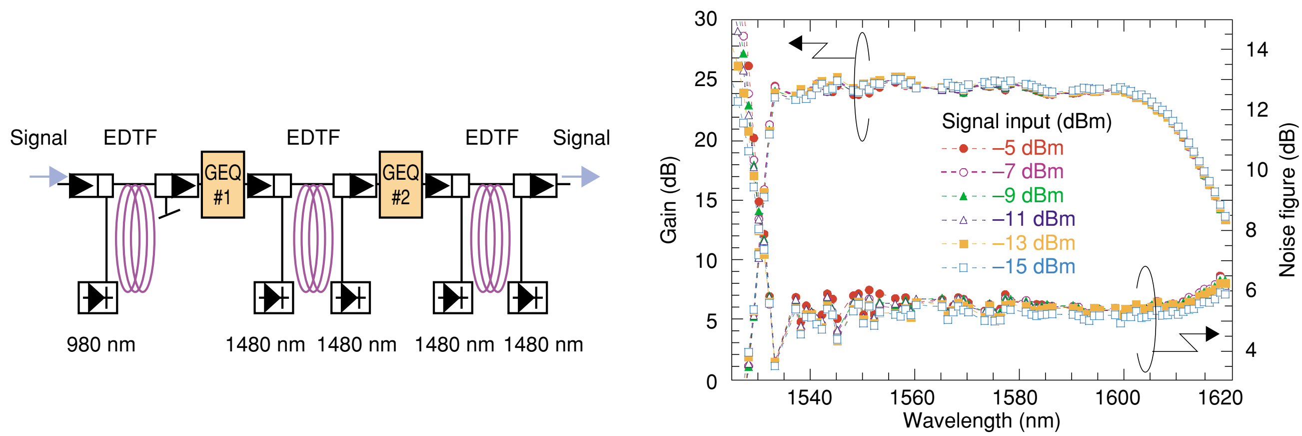


(a) Gain bandwidth for various population inversion states

(b) Comparison between EDTFA and EDSFA for (C+L)-band amplification

EDTF: erbium-doped tellurite fiber

Fig. 2. (C+L)-band amplification in EDTFA.



(a) Amplifier configuration (b) Gain characteristics

Fig. 3. Gain-equalized (C+L)-band EDTFA.

α is in the range 0.8 to 1, we can obtain an EDTFA with a large gain in the C band. For α = 0.4, we get an EDTFA with gain in the L band. (This requires a long Er^{3+}-doped fiber because the gain per unit length is small.) For α = 0.5–0.6, we obtain an EDTFA with C+L amplification with gain across both these bands.

Figure 2(b) shows the amplification characteristics of Er^{3+}-doped tellurite and silica fiber amplifiers (EDTFA and EDSFA, respectively) calculated from the basic optical properties, including emission probability and ESA shown in Fig. 1, when the population inversion factor and peak gain near 1560 nm were set to 0.5 and 30 dB, respectively. The EDTFA gain is relatively flat above 15 dB in the 1580–1610-nm wavelength range, while the gain of the EDSFA continues to fall as the wavelength increases in this range. Referring again to Fig. 1, this difference arises from the stimulated emission rate for Er^{3+}-doped tellurite glass being higher than that of Er^{3+}-doped silica glass in the 1580–1630-nm range. These results demonstrate that tellurite glass is an effective material for amplifying the broad C+L band.

By applying gain equalization to this (C+L)-band EDTFA, we developed an amplifier that can be applied to WDM transmission systems [3]. As shown in **Fig. 3(a)**, this amplifier had a 3-stage configuration. Because of the extremely large deviation in gain that occurred during wideband amplification in the C+L band (Fig. 2(b)), a gain equalizer (GEQ) with a large loss was needed to flatten the gain. If the amplifier had been configured in two stages, the large GEQ loss would have caused the noise figure of the amplifier to increase. In contrast, a 3-stage configuration distributed the GEQ loss, which kept the noise figure low. The erbium-doped tellurite fiber (EDTF) in the first stage was forward pumped with a 980-nm laser diode (LD) and those in the second and third stages were bidirectionally pumped with 1480-nm LDs (total pump power: 674 mW, consisting of 116 mW from the 980-nm LD and 151+158+151+98 mW from the four 1480-nm LDs).

Figure 3(b) shows experimental results for the amplification characteristics when the total power of a WDM signal input to the amplifier was varied between –15 and –5 dBm. Good characteristics consisting of a flat gain of 24.3 dB, gain deviation of 1.5 dB, noise figure of less than 6 dB, and output power of 19.5 dBm were obtained over a wide wavelength range (70.8 nm) from 1532.7 to 1603.5 nm. Here, the wavelength dependence of the gain was the same even when we varied the signal input power, which shows that we can easily control the gain spectrum.

4. Wideband L-band EDTFA

Figure 4 shows the amplification characteristics of the L-band EDTFA and L-band EDSFA with maximum gain of 28 dB and relatively flat gain [4]. The amplifier performed bidirectional pumping using a 1480-nm LD. The EDTFA had a wider “3-dB-down gain bandwidth” than the EDSFA: 50 nm (from 1560 to 1610 nm) compared with 38 nm (from 1568 to 1606 nm). The noise figure was less than 6.5 dB and the output power was 18 dBm. The power conversion efficiency (= output signal power ÷ pump power) was nearly the same (about 50%) for both the EDTFA and EDSFA.

The noise figure rose at longer wavelengths, start-

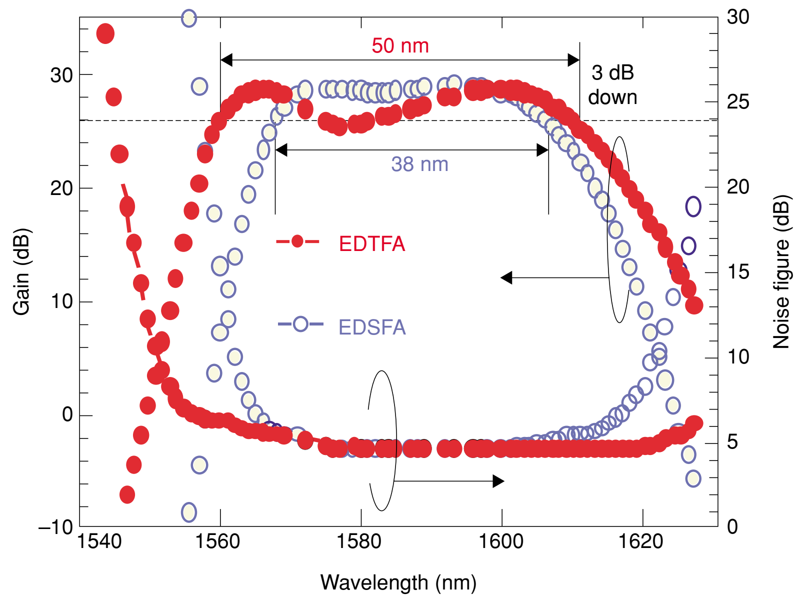


Fig. 4. Gain characteristics of L-band EDTFA.

ing from 1610 nm for the EDSFA and from 1620 nm for the EDTFA due to ESA effects. Furthermore, for the EDTFA, the gain remained above 10 dB even at wavelengths above 1620 nm. These results indicate that the EDTFA is preferable to the EDSFA when using wavelengths longer than 1610 nm. In fact, efforts are being made to shift this EDTFA gain into a longer-wavelength region from 1583 to 1617 nm. It has been reported that if WDM transmission were to be performed in this band through a dispersion-shifted fiber, the four-wave mixing* effect would be less of a problem than with transmission in the EDSFA amplification band of 1570–1600 nm in the L band [5]. This would increase the tolerance in L-band WDM transmission even when the zero-dispersion wavelength of the dispersion-shifted fiber fluctuates.

5. Application of EDTFA to R-EDFA/DRA hybrid repeater system

We conducted a transmission experiment where we used the EDTFA along with a distributed Raman amplifier to make a remotely pumped hybrid inline-repeater system (R-EDFA/DRA hybrid repeater system) [6]. We inserted an erbium-doped tellurite fiber at a (remote) point along the transmission path in a system that uses a DRA and operated the fiber as an EDFA using residual light from the pump light used for the DRA. Even though this scheme does not involve a power supply along the transmission path, it can improve the optical signal-to-noise ratio (OSNR) (or alternatively increase the tolerable loss per span) compared with the use of the DRA alone. When an EDSFA is used as a remotely pumped EDFA (R-EDFA), the signal band is about 30 nm wide for the C or L band, but when an EDTFA is used as an R-EDFA, the signal band is about 80 nm wide (about 2.7 times as wide).

The configuration of an experimental system using a single-mode fiber as the transmission path is shown in **Fig. 5(a)**. The figure shows the configuration of only one repeater (one span) in a multi-repeater transmission. This span consisted of a 180-km transmission path and an inline amplifier ((C+L)-band amplifier). An R-EDTFA was located 120 km from one end, and DRA pump light was input at both ends of the transmission path (1500 nm into the shorter segment and both 1455 and 1500 nm into the longer segment).

The configuration of the R-EDTFA module is shown in **Fig. 5(b)**. It has two stages: the first stage is a single pass with forward pumping and the second stage is a double pass. Here, 1500-nm DRA residual

* Four-wave mixing (FWM) is a phenomenon of nonlinear optics. In FWM, three signal lights of different wavelengths generate light of yet another wavelength as a result of nonlinear effects. This newly generated light greatly degrades the optical signal of the same wavelength due to cross talk. Therefore, to achieve high-quality WDM transmission, one must take care to avoid generating FWM.

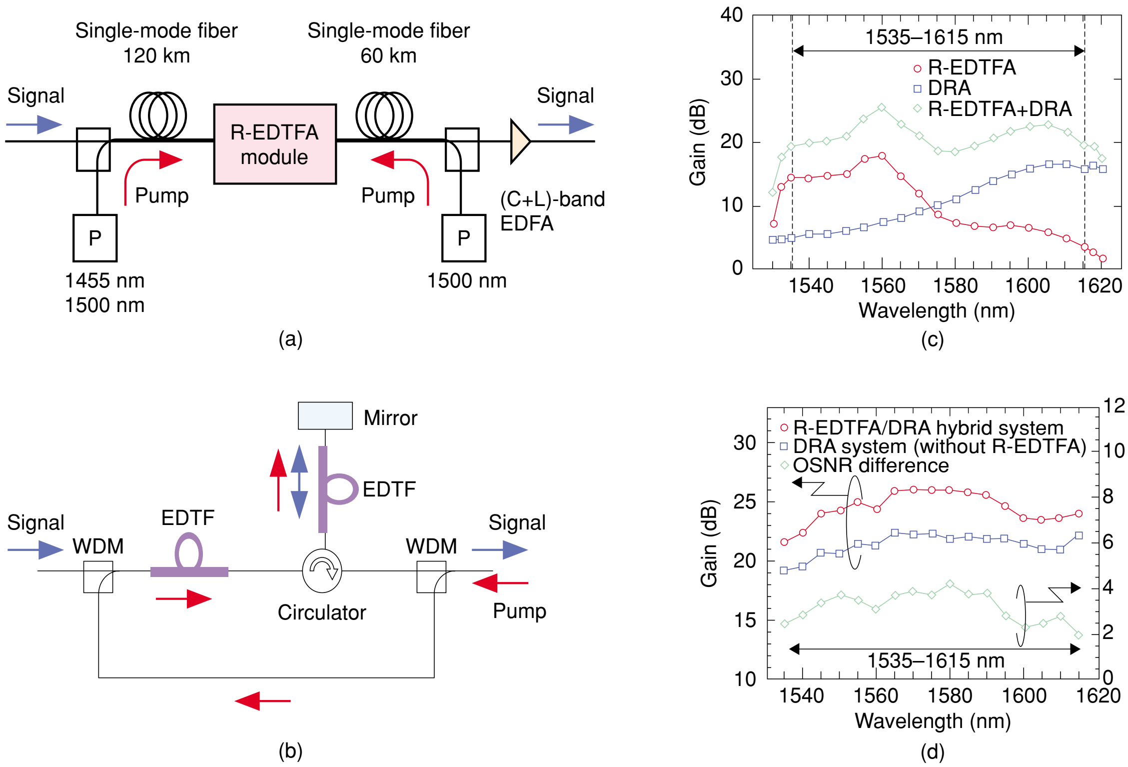


Fig. 5. Transmission experiment with R-EDTFA/DRA hybrid system.
(a) Configuration of transmission experiment (one span). (b) Configuration of R-EDTFA module.
(c) Gain characteristics of R-EDTFA/DRA hybrid amplification.
(d) Comparison of OSNR with and without R-EDTFA.

light input backward on the transmission path is introduced into the module and used as a pump light for the R-EDTFA. The individual gains and the total gain for the R-EDTFA and DRA are shown in **Fig. 5(c)**. The R-EDTFA had a high gain in the 1535–1565-nm range, while the DRA gain peaked at 1610 nm. Combining the two gains resulted in a total gain of no less than 19 dB in the 1535–1615-nm range (80-nm bandwidth). **Figure 5(d)** compares the R-EDTFA/DRA hybrid amplification output from the 180-km transmission path with DRA-only amplification in terms of OSNR for the same pump power. The addition of the R-EDTFA improved the OSNR by at least 1.9 dB in the 1535–1615-nm wavelength region. WDM signals modulated by a 43-Gbit/s carrier-suppressed return-to-zero (CS-RZ) code were transmitted over a five-repeater span (total length: 900 km (= 5 × 180-km spans)).

In conclusion, an EDFA with tellurite fiber achieves wideband amplification in the C+L and L bands, which is impossible using a silica-fiber EDFA. Therefore, we can expect to reduce the transmission cost per channel by increasing the number of WDM transmission channels by using this amplifier.

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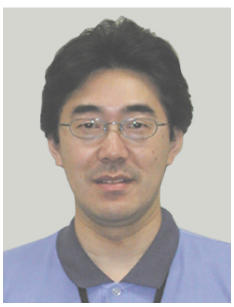
Tadashi Sakamoto

Senior Research Engineer, Photonics Integration Laboratory, NTT Photonics Laboratories.

He received the B.S. and M.S. degrees in electronic engineering from Waseda University, Tokyo in 1990 and 1992, respectively. In 1992, he joined NTT and has been working on optical fiber amplifiers and their application to the optical transmission systems. He received an IEICE Young Researchers' Award in 1995, two OECC Best Paper Awards in 1997 and 1998, and a JSAP Young Scientist Award for the Presentation of an Excellent Paper in 1998. He is a member of IEEE, the Institute of Electronics, Information and Communication Engineers (IEICE) of Japan, and the Japan Society of Applied Physics (JSAP).



Atsushi Mori

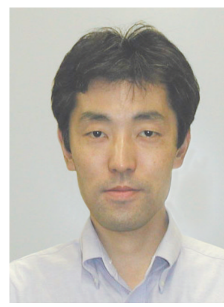
Senior Research Engineer, Photonic Integration Laboratory, NTT Photonics Laboratories.

He received the B.S. and M.S. degrees in physics from Tohoku University, Sendai, Miyagi in 1989 and 1991, respectively. He joined NTT Opto-Electronics Laboratories in 1991, where he was engaged in research on multicomponent glass fiber including oxide, fluoride and chalcogenide glass fiber for optical fiber amplifiers. Since 1995, he has mainly been engaged in research on wideband optical fiber amplifiers using Er^{3+}-doped tellurite fibers and on tellurite fiber as a fiber Raman amplifier medium. He received the 1996 JSAP Young Scientist Award for the Presentation of an Excellent Paper and the 2000 IEICE Achievement Award. He is a member of IEICE, JSAP, and the Physical Society of Japan.

Hiroji Masuda

Senior Research Engineer, High-speed Lightwave Transport Systems Research Group, Photonic Transport Network Laboratory, NTT Network Innovation Laboratories.

He received the M.Sc. degree in physics from Tokyo Institute of Technology, Tokyo in 1988. He joined NTT Laboratories, Kanagawa, Japan, in 1988. He has been engaged in research on optical amplification technologies and high-speed and large-capacity transmission systems. He is a member of IEICE and IEEE.



Hirotaka Ono

Research Engineer, Photonics Integration Laboratory, NTT Photonics Laboratories.

He received the B.S., M.S., and Ph.D. degrees in applied physics from Tohoku University, Sendai, Miyagi in 1993, 1995, and 2004, respectively. In 1995, he joined NTT and has been engaged in R&D of optical fiber amplifiers used in WDM transmission and access systems. He also worked on research into WDM transmission systems. He is a member of IEICE, IEEE, and the Optical Society of America.