Ultra-wideband Amplification Technologies for Optical Fiber Amplifiers

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Abstract

To make a large-scale optical communication system that exhibits high performance, we must expand the range of operating wavelengths of optical fiber amplifiers. In this report, we describe S-band amplification with a Tm^{3+}-doped fluoride fiber amplifier and an Er^{3+}-doped fiber amplifier and broadband fiber Raman amplification with a tellurite fiber.

1. Importance of broadband optical fiber amplifiers

Optical fiber amplifiers play an important role in telecommunication networks because they compensate for the insertion loss of the optical fiber used for transmission lines and for the loss due to the optical components used at optical nodes. Their amplification band determines the operating wavelength region of the network.

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2. Wideband amplification techniques in NTT Labs.

There are two types of optical fiber amplifier: i) rare-earth-doped fiber amplifiers, such as the erbium-doped fiber amplifier (EDFA) and ii) the fiber Raman amplifier (FRA), which uses stimulated Raman scattering. Figure 1 shows their amplification bandwidths

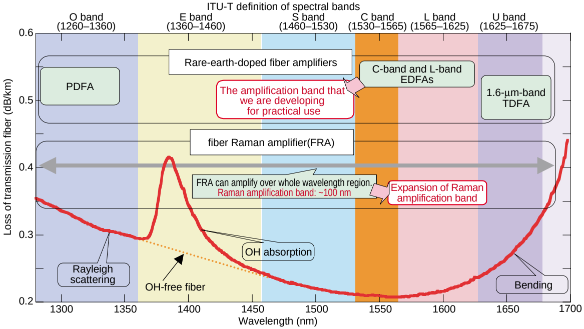

Fig. 1. Amplification bandwidth of each type of amplifier and loss spectrum of transmission fiber.

and the transmission fiber loss.

NTT Photonics Laboratories have been expanding the amplification bands of both types. An S-band rare-earth fiber amplifier is being developed as a successor to the C-band EDFA (amplification bandwidth: 1530–1565 nm) and L-band EDFA (1565–1625 nm). And a broadband FRA is being developed using fiber made of tellurite glass, which has excellent Raman amplification band characteristics.

3. Principle and characteristics of S-band rare-earth fiber amplifiers

S-band amplification can be achieved with two types of rare-earth fiber amplifier: the thulium-doped fiber amplifier (TDFA) and the S-band EDFA, as shown in Fig. 2.

3.1 TDFA

The TDFA uses Tm^{3+}-doped fiber (TDF) as the amplification medium. As shown in the energy level diagram of Tm^{3+} in Fig. 2, S-band amplification utilizes stimulated emission between the $^3H_4$ and $^3F_4$ energy levels. Fluoride glass is used to obtain efficient S-band amplification. (S-band amplification using Tm^{3+}-doped silica fiber has been reported, but the stimulation efficiency was low.) The fluorescence lifetime of the upper level ($^3H_4$) is short compared with that of the lower level ($^3F_4$), so a population inversion between the $^3H_4$ and $^3F_4$ levels is created by the two-step excitation process in which i) Tm^{3+} ions are excited from the ground level ($^3H_6$) to the lower level ($^3F_4$) and ii) the accumulated Tm^{3+} population in the lower level ($^3F_4$) is excited to the upper level ($^3H_4$) [3]-[4]. If the population inversion is high, a TDF gain peak appears at about 1460 nm in the gain spectrum. By choosing a population inversion rate of about 40%, we can get an amplification bandwidth with a peak in the S-band. For this reason, a TDFA that operates in the S-band is called a gain-shifted TDFA. At present, this population inversion is achieved by adding a high dose of Tm^{3+} (6000 ppm) to a fluoride fiber and increasing the number of Tm^{3+}

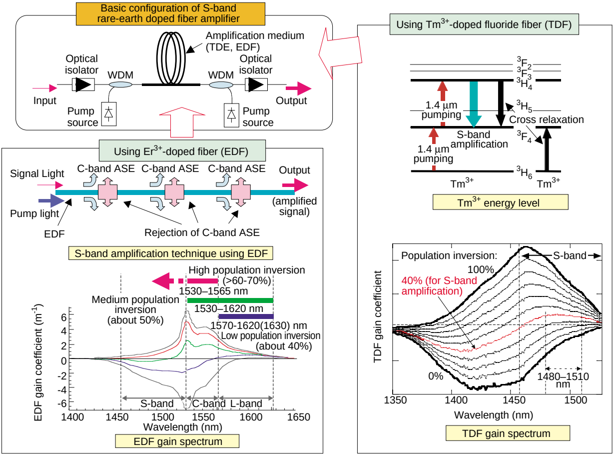

Fig. 2. S-band rare-earth doped fiber amplifiers.

ions in the lower level ($^3F_4$) by utilizing cross relaxation among Tm^{3+} ions.

Figure 3(a) shows the gain spectrum of the S-band TDFA [5] obtained with the above technique and 1.4-µm semiconductor laser pumping for both excitation processes. It shows that practical high-gain and low-noise amplification was achieved in the S-band. Furthermore, excellent flat gain characteristics were obtained in the 1480–1510-nm band by using a gain equalizer.

3.2 S-band EDFA

As shown in Fig. 2, an S-band EDFA can be made by utilizing the S-band amplification bandwidth that appears together with the C-band when the excitation of the Er^{3+}-doped fiber (EDF) is increased to achieve greater population inversion (at least 60 to 70%) and by suppressing the amplified spontaneous emission (ASE) in the C-band that occurs to maintain the high population inversion [6]-[7]. Figure 3(b) shows the gain spectrum of the S-band EDFA [7]. The gain and noise figure were measured by scanning the gain bandwidth with a low-power probe signal (input probe power: –30 dBm) while inputting five WDM channels (wavelengths: 1493.7, 1499.2, 1504.8, 1511.9, and 1517.6 nm, input signal power: –12 dBm/ch). We obtained an S-band EDFA with a high gain of over 21 dB (gain excursion was less than 1.9 dB) and a low noise figure of less than 6.7 dB in the 1491–1518-nm wavelength region by inserting an ASE elimination filter in the EDF.

At present, the S-band TDFA has advantages in efficiency (power conversion efficiency is about 40% for TDFA compared with about 10% for S-band EDFA) and amplification characteristics below 1590 nm. On the other hand, the S-band EDFA can be made using basically the same optical components as for conventional C- and L-band EDFAs. We intend to continue improving the characteristics of both amplifiers for practical use.

4. Broadband Raman amplification using tellurite fiber

Compared with a rare-earth-doped fiber amplifier, an FRA has two advantages:

- It can use the optical fiber that is transmitting the data signals as a Raman amplification medium (distributed amplification).
- It can amplify a signal at an arbitrary wavelength by using a pump light with a wavelength shorter than the signal (approx. 100 to 170 nm shorter for the 1.5 µm wavelength region).

Distributed amplification is particularly effective for reducing the signal deterioration caused by the nonlinearity of the transmission fiber, which was a problem in high-speed communication systems such as 40-Gbit/s transmission systems, and similar applications where a high signal-to-noise ratio is required. At present, the FRA is being studied not only for distributed amplification, but also for discrete amplification such as that provided by a rare-earth-doped fiber amplifier. The goals are to expand the amplification band and increase the operating efficiency. An FRA using tellurite fiber has a higher operating efficiency and superior bandwidth characteristics to a conventional FRA using silica fiber.

The FRA amplifies light signals via stimulated

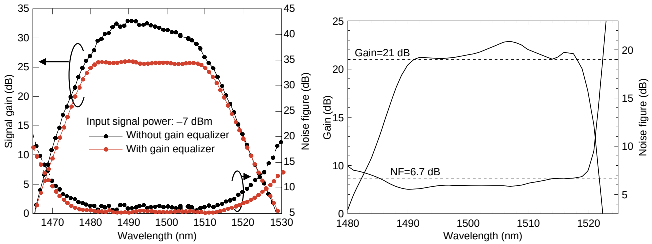

Fig. 3. (a) Amplification characteristics of TDFA,
(b) Amplification characteristics of S-band EDFA.

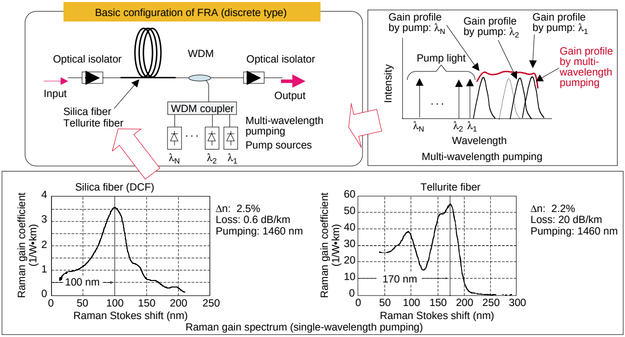

Fig. 4. Configuration of broadband FRA.

Raman scattering, which is a nonlinear optical effect, when intense excitation light is passed through an optical fiber. The resulting gain spectrum (Raman gain spectrum) depends strongly on the composition of the glass used in the fiber. As shown in Fig. 4, with dispersion-compensated fiber, which is a type of silica fiber, the Raman shift in the 1.5-µm band is about 100 nm and the full width at half maximum is about 30 nm. In contrast, the tellurite fiber spectrum has twin peaks, but the gain coefficient is 16 times that of silica fiber and the Raman shift is 170 nm (1.7 times that of silica fiber) [8].

Furthermore, the FRA employs a multi-wavelength pump technique [9] for broadband amplification. This utilizes the Raman gain spectrum superimposition that occurs when pump lights of various wavelengths are combined and passed through an optical fiber. Thus, broadband operation is achieved. In addition, by adjusting the pump intensity at each wavelength, we can obtain flat gain characteristics. The limit to the gain bandwidth expansion that can be achieved using multi-wavelength pumping is determined by the Raman shift. Whereas the maximum bandwidth of an FRA using a silica fiber is about 100 nm, a tellurite fiber can inherently achieve broadband amplification because of its larger Raman shift. It has now been confirmed that an FRA using a tellurite fiber can achieve amplification over a wide bandwidth up to 160 nm (see Fig. 5) [8]. However, in terms of efficiency, the tellurite fiber still has slightly high loss, so we cannot make optimum use of its high efficiency. For this reason, determined efforts are being made to reduce the loss of this fiber to establish tellurite fiber Raman amplification technology that permits highly efficient broadband operation.

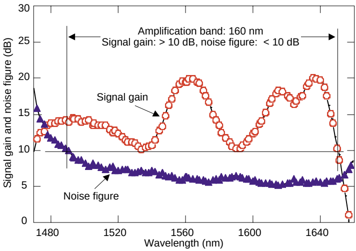

Fig. 5. Amplification characteristics of tellurite FRA.

5. Application of broadband amplification technology

By efficiently combining the already developed S-band rare-earth-doped fiber amplification, broadband tellurite fiber Raman amplification, C- and L-band rare-earth fiber amplification, 1300-nm bandwidth Pr-doped fiber amplification (another type of rare-earth-doped fiber amplification), the 1650-nm-band TDFA, and silica fiber Raman fiber amplification, we expect to achieve amplification over a wide waveband extending from 1300 to 1650 nm. We hope that all of these optical fiber technologies can be put to effective use to help make a large-scale, highly functional photonic network.

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