Tellurite Fiber Raman Amplifiers

Atsushi Mori† *and Hiroji Masuda*

Abstract

NTT Photonics Laboratories is developing optical amplifiers capable of amplifying multiple signal channels across a wide wavelength region of 100 nm or more. This is achieved through the use of a newly developed fiber Raman amplifier that employs tellurite fiber.

1. What is a fiber Raman amplifier?

The fiber Raman amplifier (FRA) differs in principle from rare-earth-doped fiber amplifiers in that it uses molecular vibration and an optical-scattering phenomenon in the fiber material that acts as an amplification medium. **Figure 1** compares the operating principles of the FRA and the erbium (Er^{3+})-doped fiber amplifier (EDFA). With the FRA, a pump light of frequency *ν* is scattered by the thermal vibration with frequency Ω of a Si-O (or Ge-O) molecule and is consequently emitted with a frequency of ν–Ω. Making use of this energy-conversion phenomenon, the pump light stimulates the occurrence of Raman scattering to perform Raman amplification. The signal that can be amplified has a wavelength that is longer than that of the pump light by only the molecular vibration frequency Ω (i.e., Stokes shift: 100 nm in the 1500-nm band (Fig. 1(a)). In contrast, an EDFA utilizes the absorption or stimulated emission between the energy levels in an Er^{3+} ion, which means that the wavelength of the amplifiable signal

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

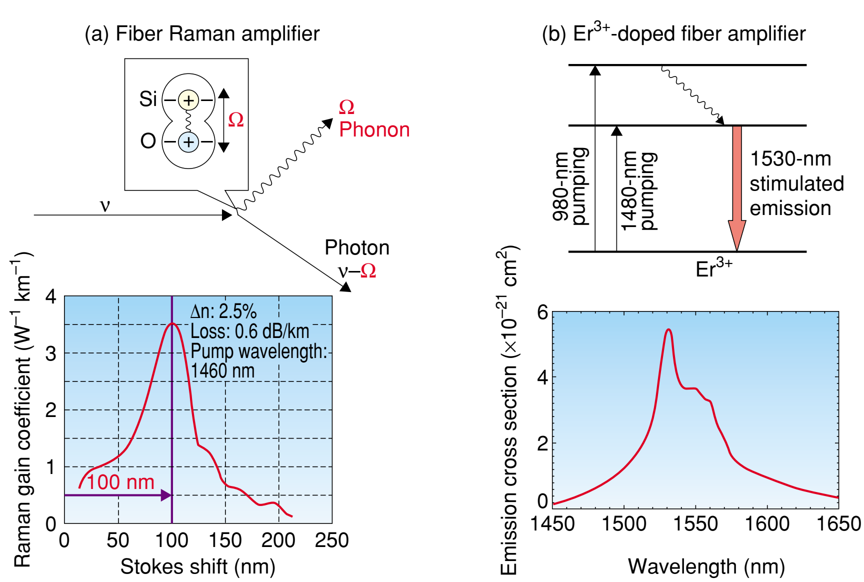

Fig. 1. Comparison of operating principles. (a) fiber Raman amplifier and (b) Er^{3+}-doped fiber amplifier. Here, Δn is the refractive index difference.

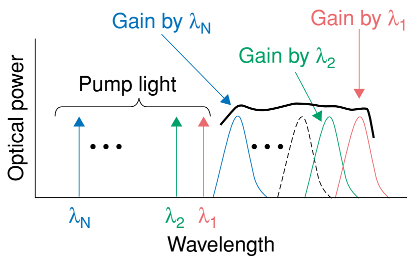

Fig. 2. Multi-wavelength pumping technique for wideband Raman amplifiers.

corresponds to the difference between those energy levels (1530 nm), as shown in Fig. 1(b). Comparing these two principles, we can see that the FRA is advantageous in that it allows the transmission fiber itself to be used as the amplification medium (distributed amplification) and enables signals of any wavelength to be amplified if we select the pump light wavelength. In particular, using a distributed FRA is a very robust approach that can improve the signal-to-noise ratio (SNR), and in combination with an EDFA, it can be used to increase the interval between inline repeaters and the transmission distance between electrical regenerators in terrestrial high-speed/large-capacity trunk systems and undersea long-haul systems [1].

In recent years, a multi-wavelength pumping technique has been used in FRAs to achieve wideband amplification (**Fig. 2**). With this technique, the optical fiber used for Raman amplification is pumped with multi-wavelength light and a wide amplification band is achieved by overlaying the Raman gain spectra thus obtained. In addition, the intensity of the pump light for each wavelength can be adjusted to flatten the resulting gain. The gain-band expansion that can be achieved by multi-wavelength pumping is determined by the magnitude of the Stokes shift. A large Stokes shift is therefore desirable for a wideband FRA using multi-wavelength pumping. The maximum amplification bandwidth of an FRA is consequently about 100 nm for silica fiber. Research continues on optical amplifiers with bandwidths in excess of 80 nm, which cannot be achieved by rare-earth-doped fiber amplifiers [2].

2. Advantages of tellurite FRA

When a silica fiber is used as the amplification medium, the seamless wavelength region that can be amplified is limited in principle to a bandwidth of 100 nm in the 1500-nm band. At NTT Photonics Laboratories, we have successfully extended this amplification bandwidth to 170 nm by using tellurite fiber (with tellurium dioxide as its main component) as the amplification medium (**Fig. 3**). This is possible because the vibration frequency Ω' caused by the thermal vibration of a Te-O molecule is larger than the thermal vibration Ω of a Si-O (or Ge-O) molecule. Figure 3 shows the stimulated Raman scattering spectrum for a tellurite FRA. We compared this spectrum with that of Raman scattering in a dispersion compensation fiber (DCF), of which the silica fiber shown in Fig. 1(a) is one type. This silica fiber, which has a Stokes shift of 100 nm in the 1500-nm band, has a spectrum with a unimodal shape. In contrast, the tellurite fiber has a Stokes shift 1.7 times as large (=170 nm) and a bimodal spectrum. Moreover, tellurite glass has a nonlinear susceptibility about one order of magnitude greater than that of silica glass, so its Raman gain coefficient (scattering intensity) is about 16 times larger. These features show that tellurite fiber is more promising than silica fiber for making an ultra-wideband FRA with a shorter fiber length and fewer pump wavelengths.

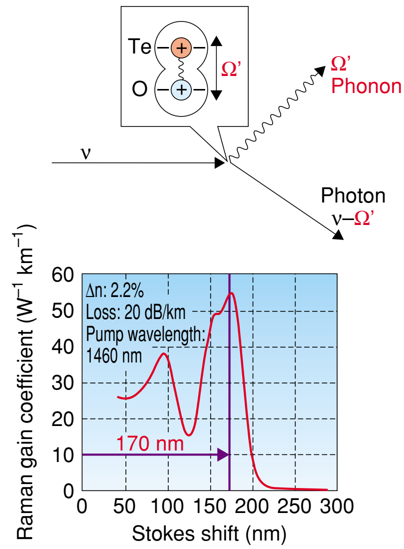

Fig. 3. Stimulated Raman scattering of tellurite FRA.

Figure 4(a) shows the configuration of a tellurite FRA using the multi-wavelength pumping technique. This amplifier pumps a 250-m tellurite fiber module using laser diodes (LDs) operating at four different wavelengths. The fiber length here is about one-tenth that of commonly used silica DCF (about 3 km). We confirmed that this amplifier achieves wideband amplification across the 160-nm wavelength region of 1490–1650 nm with a gain of greater than 10 dB

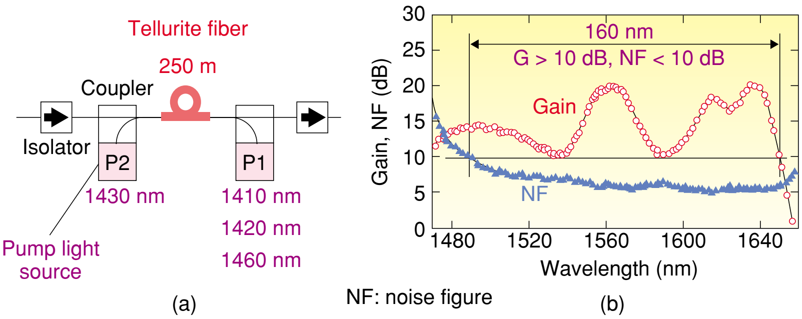

Fig. 4. Multi-wavelength pumping tellurite FRA. (a) configuration and (b) gain characteristics.

and a noise figure of less than 10 dB. The gain excursion (ΔG) is rather large with a maximum value of 10 dB and the gain flatness (ΔG/G, where G is the lowest gain) is about 100% [3], [4].

3. Issues in WDM transmission applications

As described above, the tellurite FRA has a number of attractive features. It provides a gain of greater than 10 dB across 160 nm and can cover the low-loss region of transmission fiber across the S, C, and L bands (See Fig. 2 of the overview article on page 36). However, when we use a tellurite FRA as an inline repeater in an actual wavelength division multiplexing (WDM) system, we must deal with the following problems.

(1) 20 dB gain: The repeater span in a 1500-nm-band optical transmission system is generally 80 km, and the span loss of about 20 dB including the required margin must be compensated for by gain.

(2) Gain flatness: When an FRA is used as a linear repeater in a multiple-repeater WDM transmission system, gain excursion accumulates. As a result, the maximum transmission distance and transmission quality are determined by the channel with the lowest optical SNR, so gain flatness is very important.

(3) Dispersion compensation: Although it is common to insert a DCF in an amplifier to compensate for dispersion in the transmission fiber, it remains unclear whether DCF can be successfully inserted in a tellurite FRA.

(4) Noise figure degradation on the short-wavelength side: The noise figure of a tellurite FRA deteriorates in the short wavelength region of the S band, as shown in **Fig. 4(b)**.

(5) Signal power transfer caused by stimulated Raman scattering between optical signals in transmission fiber: When WDM signals extending over a 100-nm-or-wider band are input into a transmission fiber, S-band signal power is converted into L-band signal power due to stimulated Raman scattering. This phenomenon causes attenuation of the S-band signal power.

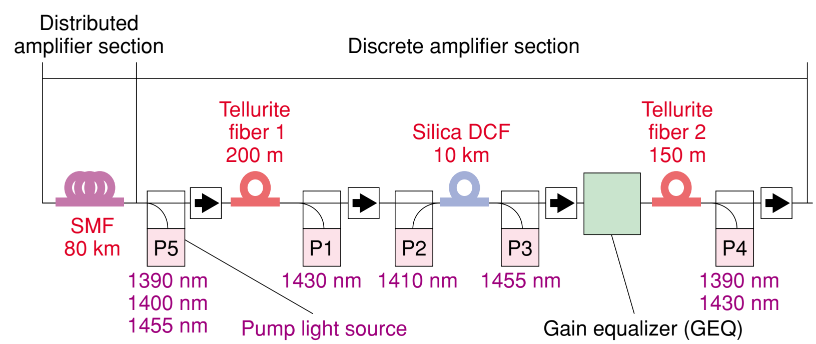

Fig. 5. Configuration of hybrid tellurite/silica FRA with distributed silica Raman amplification.

Below, we describe how we overcame these problems. For the first three problems, we examined the differences between the gain spectra of tellurite and silica FRAs and configured a discrete hybrid (tellurite and silica) FRA that can achieve both dispersion compensation and gain flattening for linear repeaters [5]. For the other two problems, we configured a distributed/discrete hybrid FRA that adds a distributed FRA with a high SNR centered on the S band to the discrete hybrid FRA (**Fig. 5**).

This optical amplifier has a two-stage configuration with the distributed FRA section as the first stage and the discrete FRA section as the second stage. The discrete FRA section itself consists of three stages connected in series with tellurite fiber for the first and

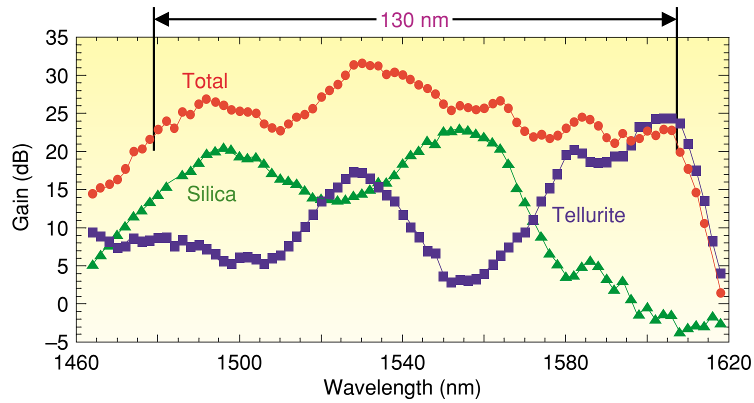

Fig. 6. Gain characteristics of hybrid tellurite/silica FRA.

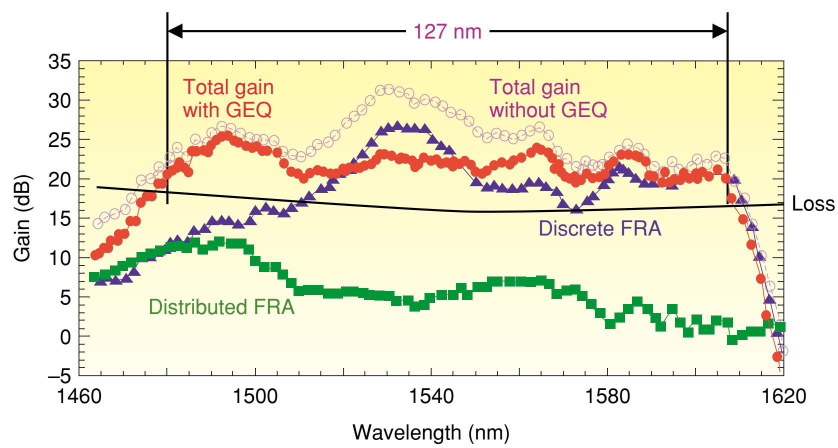

Fig. 7. Gain characteristics of hybrid tellurite/silica FRA with distributed silica Raman amplification.

third stages and silica DCF for the second stage. A gain equalizer (GEQ) was placed between the second and third stages (between the DCF and second tellurite fiber). The distributed FRA section consists of 80 km of single-mode fiber (SMF) as transmission fiber, which is backwardly pumped by LDs operating at three wavelengths. The pump wavelengths and powers were determined to give this amplifier a low noise figure and high output as well as a flat gain spectrum. **Figure 6** shows the individual gain spectra of the tellurite and silica FRA and their total combined gain spectrum (without gain equalization). The gain achieved by the silica FRA compensated for the gain dips that occur in the tellurite FRA. As a result, the 130-nm gain band (1478–1608 nm) indicated in the figure exhibits a minimum gain of 20.9 dB and a maximum gain of 31.4 dB. The gain excursion is consequently 10.5 dB, but the use of a gain equalizer could flatten this gain without degrading the noise figure or the output power. We were therefore able to improve the gain flatness ΔG/G to about 50%.

Figure 7 shows the gain spectra of the discrete and distributed FRAs and the total gain spectrum with and without gain equalization. The figure also shows the loss for 80 km of SMF. The distributed Raman gain of this amplifier is about 10 dB in the short-wavelength amplification region (1480–1500 nm) while the discrete Raman gain is greater than 15 dB across a wide wavelength region of 1500–1610 nm. The total gain spectrum after equalization indicates an average gain of 22 dB across the 127-nm wavelength region of 1480–1607 nm. For the 80-km SMF loss (15.5–18 dB), a system margin of about 3 dB can be obtained in the same band.

Finally, **Fig. 8** shows the noise figure spectrum for the discrete hybrid FRA and the equivalent noise figure for the discrete/distributed hybrid FRA. The "equivalent noise figure" is computed as the net noise figure (defined as the loss between the input end of the 80-km SMF and the amplifier output) minus the SMF loss in dB units. The noise figure of the discrete FRA degrades to more than 8 dB in the short wave-

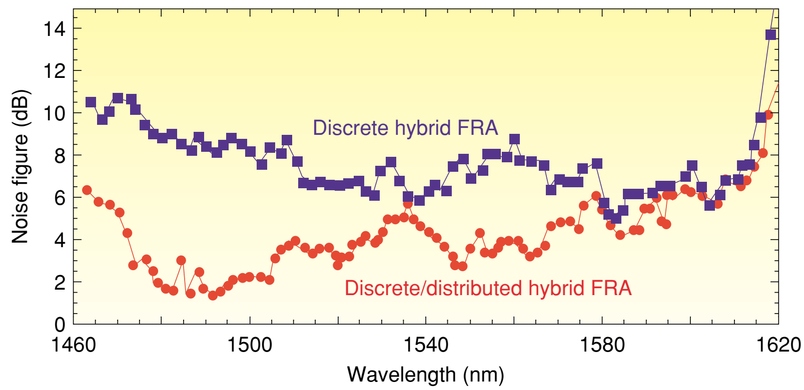

Fig. 8. Noise figure spectra of discrete hybrid FRA and discrete/distributed hybrid FRA.

length region corresponding to the S band and near 1560 nm corresponding to the gain dip of the tellurite FRAs. For the same wavelength regions, the equivalent noise figure is less than 4 dB, which is especially low, and for the entire flat region, it is less than 7 dB. In particular, the low equivalent noise figure in the short wavelength region was designed to suppress the SNR degradation caused by stimulated Raman scattering that occurs between optical signals in this region in high-speed large-capacity transmission systems.

We used this amplifier as a linear repeater in a large-capacity WDM experiment (channel rate: 10 Gbit/s; 313 channels). The results showed that this amplifier could achieve error-free operation seamlessly across a 124-nm (1485–1609 nm) gain band. This is the widest seamless amplification band yet reported [6].

4. Future developments

To make high-efficiency tellurite FRAs, we plan to research ways of reducing the loss in tellurite fiber and optimizing fiber parameters. We also aim to develop amplifiers with even wider bandwidths and flatter gains by optimizing the multi-wavelength pumping technique.

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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 the Institute of Electronics, Information and Communication Engineers (IEICE) of Japan, the Japan Society of Applied Physics, 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.