Tellurite-based fibers and their applications to optical communication networks

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This paper reviews tellurite-based fibers and their applications to optical communication networks. First, an investigation of tellurite-based glass and the fabrication of conventional step-index fibers and photonic crystal fibers (PCF) are described. By purifying the raw materials and employing a novel PCF fabrication process, low background losses were achieved for an Er^{3+} -doped, an undoped tellurite-based fiber and a tellurite-based PCF. Second, the optical properties of Er^{3+} -doped tellurite-based glass and fiber, and the gain characteristics of erbium doped tellurite fiber amplifiers (EDTFAs) were studied. A seamless, low noise and gain flattened C + L band EDTFA was realized, and an S + C + L band amplifier was constructed by combining an EDTFA and a thulium-doped fluoride fiber amplifier (TDFFA) in parallel. Third, it is confirmed that the Raman scattering characteristic of tellurite-based fiber has such a large gain coefficient and Stokes shift that it is possible to achieve a wideband tellurite-based fiber Raman amplifier. To overcome several problems, a distributed/discrete hybrid tellurite- and silica-based fiber Raman amplifier (FRA) was constructed as an S + C + L band WDM repeater with a gain bandwidth of 127-nm. Fourth, Brillouin amplification and the simulated performance of slow light generation in a tellurite-based fiber were investigated. The fiber exhibits the largest time delay per unit power of 19.9 ns/mW. Finally, a carrier-envelope offset (CEO)-locked frequency comb with low fiber coupling pulse energy (230 pJ) was demonstrated by using a tellurite-based PCF. This method has the potential to lock the CEO with a lower pulse energy and thus provide a low-noise and high-accuracy optical frequency comb at telecommunication wavelengths. These tellurite-based fibers with low background loss thus offer attractive functions for applications in the optical communication field.

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1. Introduction

The tremendous success of the deployment of silica-based fiber and waveguides in the photonic network has motivated an investigation of highly functional photonic devices for more flexible and robust transmission systems. Silica is advantageous as an optical medium because of its good transparency and high reliability, but its functionality, which is based on refractive index change and the stimulated emission of doped rare earth, is limited. The small number of raw materials that can be used for conventional fabrication processes such as vapor-phase axial deposition (VAD) or modified chemical vapor deposition (MOCVD) leads to less material diversity. A large number of fiber materials have been proposed with a view to realizing novel functionalities that are unobtainable with conventional high-silica optical fiber. Phosphate, fluorophosphate, fluoride, bismuth, tellurite, and chalcogenide glasses have been reported as host materials for rare earth doped fiber amplifiers.^{1)–7)} Bismuth, tellurite and chalcogenide glasses have been reported for use in fabricating highly nonlinear fibers.^{8)–10)} The former requires a high doping concentration and a wide operating wavelength range for Er^{3+} ions or low phonon energy for Pr^{3+} and Tm^{3+} ions as glass characteristics. The latter also needs high linear and nonlinear refractive indices. The advantage of tellurite-based fiber for photonic device applications originates not only in these two characteristics, but also in its low fiber attenuation.

Since the mid 1990s, the growth in Internet use and increases in data traffic in optical fiber communication networks have triggered the demand for increased wavelength-division multiplexing (WDM) transmission capacity. However, the available channels in WDM transmission systems are limited by the gain bandwidth of optical amplifiers. Wide-band optical fiber amplifiers have therefore been recognized as indispensable devices for future optical networks. In 1997, an Er^{3+} -doped tellurite-based fiber amplifier (EDTFA) was proposed for amplification in the C (1530–1565 nm)-band and L (1565–1625 nm)-band gain bandwidths without a parallel configuration.¹¹⁾ The key characteristics of Er^{3+} -doped tellurite-based glass lie in its large stimulated emission cross-section at around 1600 nm, and the shift in the ESA spectrum to a longer wavelength that results from the crystalline field effect on Er^{3+} ions induced by the surrounding tellurite-based ions.¹²⁾

With a view to practical EDTFA use, a great effort has been made to reduce tellurite-based fiber attenuation by purifying the raw materials.¹³⁾ A low loss of 20 dB/km was finally achieved and this reduction opens up the possibility for many nonlinear applications including Raman amplifiers, Brillouin amplifiers and slow light.^{9),14)} Silica-based fibers have been widely employed in these applications as a matter of course. However, to obtain an effective gain or time delay requires a fiber length of several or several tens of kilometers because of the low Raman and Brillouin gain coefficients of silica-based fiber. This would increase the size of the fiber module packages and the cost of the devices. We need to reduce the fiber length for practical use, and

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fiber with a high nonlinear refractive index has good potential for such applications. An important advantage of tellurite-based fiber is that its background loss is less than one-tenth those of bismuth-oxide based fiber¹⁵⁾ and As₂Se₃ chalcogenide fiber.¹⁶⁾ This lower background loss means a larger effective length defined as $L_{\text{eff}} = (1 - \exp(-\alpha L))/\alpha$ and also a larger gain $G = 10 \log[\exp(g_{\text{R,B}} L_{\text{eff}} PK/A_{\text{eff}} - \alpha L)]$,¹⁷⁾ which is an important parameter for amplifiers, and slow light generation (where, α , L , $g_{\text{R,B}}$, P , K and A_{eff} are the absorption coefficient, the fiber length, the Raman and the Brillouin gain coefficients, the pump power, the polarization factor¹⁸⁾ and the effective mode area, respectively).

When applying tellurite-based fiber to nonlinear devices that employ a parametric process in a telecommunication window, the zero-dispersion wavelength of the fiber should be controlled near the 1.5- μm band.¹⁹⁾ However, the tellurite-based fiber employed for Raman amplification has a large chromatic dispersion of around -166 ps/nm/km at 1550 nm, which causes no signal degradation as a result of four-wave mixing owing to the phase mismatch of the signals.²⁰⁾

With photonic crystal fiber (PCF) we can realize fiber with a high nonlinear coefficient γ . However, PCFs with a small-core large-NA structure cause significant anomalous waveguide dispersion, and so a zero-dispersion wavelength in the 1.5- μm band has not been obtained using silica-based PCFs with a high γ of more than 100 W⁻¹km⁻¹ due to their intrinsic material dispersion properties.²¹⁾ In contrast, most nonlinear compound glasses with a large material nonlinearity (n_2) exhibit a highly normal dispersion of around -100 ps/nm/km at 1550 nm, which means it is possible to achieve a zero-dispersion wavelength near 1550 nm. By employing the significant anomalous waveguide dispersion obtained with a glass and air hole structure, it was possible to fabricate a tellurite-based PCF with a zero-dispersion wavelength of around 1.55 μm .²²⁾ The PCF also exhibited a high γ of 675 W⁻¹km⁻¹ and a minimum loss of 180 dB/km. This PCF with a high γ and a large L_{eff} offers the possibility of realizing high performance functional devices operating in the 1.5- μm band. The PCF was employed to generate an octave bandwidth supercontinuum (SC) and a carrier-envelope offset (CEO)-locked frequency comb including a telecommunication window.²³⁾ The inventors of the CEO-locked frequency comb technique, which controls optical field waveforms directly through precise control of the carrier-envelope phase, were awarded a Nobel prize in 2005, and the comb is employed as an optical frequency ruler in the hundreds of terahertz range.^{24)–26)}

This paper reviews research on tellurite-based glasses and fibers, and their applications. This paper is organized as follows. Section 2 describes research on tellurite-based glass and the fabrication of conventional step-index fibers and PCF. Section 3 describes the optical properties of Er³⁺-doped tellurite-based glass and fiber, and the gain characteristics of EDFAs. Section 4 presents the stimulated Raman scattering and Raman gain characteristics of tellurite-based fibers. Section 5 investigates the Brillouin gain performance and the potential performance with a view to using tellurite-based fiber for slow light generation. Section 6 demonstrates octave bandwidth SC generation and its application to a CEO-locked frequency comb using tellurite-based PCF. The paper concludes with a summary of these results.

2. Tellurite-based glasses and fiber fabrication

2.1 Tellurite-based glasses

Tellurite-based glasses are composed of 60–90 mol% TeO₂ and many kinds of secondary components such as alkali earths

and alkali oxides. The glasses exhibit the following characteristics. (i) They have a sufficiently wide transmission region (0.35–5 μm) for the 1.5- μm telecommunication window, (ii) they have good thermal stability ($T_x - T_g > 100^\circ\text{C}$) and corrosion resistance (10^{-5} – 10^{-6} g·cm⁻²·d⁻¹), (iii) they have a relatively low phonon energy among oxide glass formers ($h\omega = 650$ – 800 cm⁻¹), and (iv) they have a high refractive index and a high nonlinear refractive index ($n_D = 1.8$ – 2.3 , $n_2 = 10^{-19}$ – 10^{-18} m²/W). Wang et al have made a detailed comparison of the properties of tellurite, silica, fluoride and chalcogenide glasses.²⁷⁾ They investigated the binary systems TeO₂–BaO, TeO₂–ZnO and TeO₂–WO₃, which have a wide glass forming region, and added alkali oxides to them to obtain a UV edge, durability in H₂O and rare earth solubility. As the result, they achieved a wide compositional range with the TeO₂–ZnO–R₂O system, where R is Li, Na, K, Rb, Cs or Ag, to satisfy the three specific needs. Furthermore, the TeO₂–ZnO–R₂O system was investigated for low-loss fiber fabrication and the TeO₂–Bi₂O₃–ZnO–Li₂O (TBZL) or Na₂O (TBZN) system was found to have greatly improved thermal stability. This led to the fabrication of tellurite-based fibers whose core and cladding glass compositions are controlled to change the Bi₂O₃ content for the TBZL or TBZN system.

2.2 Step-index tellurite-based fibers

Tellurite-based fiber was fabricated using the elongation and jacketing-drawing method shown in **Fig. 1**. The preforms and jacketing tube were prepared by suction-casting and rotational casting methods, respectively.^{28,29)} All the operations in the melting and casting processes used for fabricating the preform and jacketing tube were carried out in a clean dry gas atmosphere. High-purity TeO₂ was prepared as a raw starting material from Te metal whose purity exceeded 6N.¹³⁾ Almost all the commercially obtained TeO₂ raw material contained more or less yellow or gray TeO₃, or black TeO. By controlling the drying condition when forming TeO₂ by wet-chemical synthesis so that its valency did not change, high purity TeO₂ raw material was realized that was pure white. The other raw materials were commercially available and more than 99.9% pure. All the raw materials were weighed and mixed, and melted in gold crucibles at 800°C. The preform was first elongated together with a cylindrical jacketing tube into a composite preform to reduce the core diameter. The composite preform was drawn into a fiber with a taper jacketing tube to obtain a fixed core diameter and a UV-curable acrylate coating.

Figure 2 compares the transmission losses of tellurite-based EDFs fabricated using commercial TeO₂ raw material (fiber 1) and the developed high-purity TeO₂ (fiber 2). Optical absorptions of around 800, 980 and 1400 nm correspond to the ⁴I_{9/2}–⁴I_{15/2}, ⁴I_{11/2}–⁴I_{15/2} and ⁴I_{13/2}–⁴I_{15/2} ground state absorption in Er³⁺. The background loss of fiber 1 was 900 dB/km at 1230 nm. By contrast, fiber 2 exhibited a low background loss of 27 dB/km at 1230 nm. This result indicates that the background loss of tellurite-based fibers strongly depends on the purity of the TeO₂ raw material.

Figure 3 compares the loss spectra of tellurite-based fiber modules without Er³⁺ ion doping fabricated using the same raw materials as those used for fiber 2 in **Fig. 2** (module 1) and raw materials dehydrated by using vacuum degassing (module 2). The modules are composed of 250-m long tellurite-based fibers and two V-groove connection parts with high NA silica fibers. The loss increases beyond 1400 nm and around 1550 nm of module 1 are caused by fundamental and overtone OH ion absorption, respectively. Conversely, module 2 exhibited consid-

Fig. 1. Tellurite-based fiber fabrication process (a) suction casting method, (b) rotational casting method, (c) fiber fabrication process.

Fig. 2. Transmission losses of tellurite-based EDFs fabricated using commercial TeO_2 raw material (fiber 1) and the high-purity TeO_2 we developed (fiber 2).

erably less OH ion absorption and achieved a low background loss of 20 dB/km at 1560 nm. Since nonlinear applications such as Raman fiber amplifiers require tellurite-based fiber with a length of 200–300 m, the Raman gain characteristics depend

Fig. 3. Loss spectra of tellurite-based fiber modules without Er^{3+} ion doping fabricated using same raw materials as those used for fiber 2 (module 1) and dehydrated raw materials (module 2).

Fig. 4. Tellurite-based PCF fabrication process.

directly on this loss reduction in the 1.5 μm wavelength region.⁹⁾

2.3 Tellurite-based photonic crystal fiber²²⁾

The TeO_2 -based glass used to fabricate the PCF exhibits a high linear coefficient of 2.04 at 1550 nm and a nonlinear refractive index of $5.9 \times 10^{-19} \text{ m}^2/\text{W}$. To realize the glass and air hole structure of the PCF the new fabrication method shown in Fig. 4 was developed. With this process, a cross-shaped glass rod is prepared by casting melted glass into a cross-shaped mold. The fiber fabrication process is the same as that mentioned in 2.2. The fabricated tellurite PCF was more than 1.2 km long with core sizes in the 2.6–2.9 μm range.

In order to design a core glass and cladding air hole structure so that the PCF has a zero-dispersion wavelength around 1550 nm, a semi-vectorial mode calculation was performed using the finite difference method to determine the optical properties of the structure. Figure 5 shows zero-dispersion wavelength as function of core size and the defined structure model (inset). The core

size for the zero-dispersion wavelength at 1550 nm was predicted to be $2.45 \mu\text{m}$. **Figure 6** shows SEM images of the PCF. The core size, outer hole diameter and outer fiber diameter were 2.6, 25 and $110 \mu\text{m}$, respectively. The predicted effective mode area A_{eff} for a core size of $2.6 \mu\text{m}$ was $3.54 \mu\text{m}^2$. Therefore the γ value is calculated to be $675 \text{ W}^{-1}\text{km}^{-1}$.

Figure 7 shows the propagation loss spectrum of the PCF. The minimum loss of the PCF was 180 dB/m at 1400 nm. The loss increases beyond 1400 nm and around 1550 nm are caused by fundamental and overtone OH ion absorption, respectively. Therefore, the loss increases to 400 dB/km around 1550 nm. It is speculated that the difference between the losses of the PCF and the tellurite-based fiber for a FRA is attributable to surface roughness and OH ions on the fiber surface. Therefore the appli-

cation of a polishing and etching process to the glass rod surface is expected to result in an improvement in the optical loss.³⁰⁾ The minimum loss was less than one tenth the value obtained for compound glass-based PCFs.^{31)–33)}

The material dispersion of the tellurite glass was derived by second order differentiating the measurement curve of the refractive index dispersion with respect to wavelength. This material dispersion is shown in **Fig. 8**. The dispersion at 1550 nm was around -100 ps/nm/km and the zero-dispersion wavelength was 2290 nm. **Figure 8** also shows the chromatic dispersion curve of the tellurite PCF with a core size of $2.6 \mu\text{m}$. The dispersion curve was measured using a Fourier-transformed cross correlation.³⁴⁾ The zero-dispersion wavelength was successfully shifted towards the $1.5\text{-}\mu\text{m}$ band. The exact zero-dispersion wavelength was 1573 nm, which agrees well with the simulated wavelength of 1575 nm for a core size of $2.6 \mu\text{m}$.

3. Er^{3+} -doped tellurite-based fiber amplifiers

Since EDFAs operate as three-level laser systems, the gain coefficient, G , can be written as $G \propto \sigma_e(\lambda)N_2 - \sigma_a(\lambda)N_1$, and therefore depends on the population inversion rate. Here N_1 and N_2 are the population densities of the upper and lower energy levels, respectively. $\sigma_e(\lambda)$ and $\sigma_a(\lambda)$ are the stimulated emission and absorption cross-sections for wavelength λ , respectively. The population inversion rate can be controlled by controlling the pump power or EDF length used for EDFAs. By contrast, the stimulated emission and the absorption cross-sections depend on the Stark splitting of Er^{3+} ions induced by the crystalline field of the host.

Fig. 5. Calculated zero-dispersion wavelength as a function of core size a and the defined model structure (inset).

Fig. 6. SEM images of PCF.

Fig. 7. Propagation loss spectrum of PCF.

Fig. 8. Chromatic dispersion curve of tellurite PCF and tellurite glass material.

Fig. 9. $^4I_{13/2}$ – $^4I_{15/2}$ stimulated emission and $^4I_{13/2}$ – $^4I_{9/2}$ excited state absorption (ESA) cross-sections of Er^{3+} in tellurite and silica-based glasses.

Fig. 10. Calculated spectra of different population inversion rates for EDTFAs.

Fig. 11. Diagram of three-stage C + L band EDTFA.

Figure 9 shows the $^4I_{13/2}$ – $^4I_{15/2}$ stimulated emission and $^4I_{13/2}$ – $^4I_{9/2}$ ESA cross-sections of Er^{3+} in tellurite and silica-based glasses. The stimulated emission spectrum of Er^{3+} in tellurite-based glass is larger than that in silica-based glass over the entire 1450–1600 nm wavelength range and, in particular, the cross-section at around 1600 nm is double that in silica-based glass. Furthermore, the longer operation wavelength limit, which is defined as the point at which the ESA and the stimulated emission cross-section are equal, is shifted to a longer wavelength. These two advantages lead to a wider amplification band and a longer wavelength region.

Figure 10 shows calculated spectra of different population inversion rates for EDTFA. The inversion rates are 75%, 55% and 40%, which give us gain-flattened C, C + L and L-bands, respectively. EDTFAs are advantageous in the 55% and 40% operation bands, which include the L-band wavelength region. When controlling the inversion rate with a 55%, EDTFA a C and L-band operation bandwidth of around 80 nm was achieved in the 1530–1610 nm region. With regard to C and L-band operation, an EDTFA is superior to an EDSFA in terms of gain excursion. However, even an EDTFA needs a gain equalization of 20–30 dB to achieve a flattened gain beyond 20 dB in the C and L band wavelength range. Therefore, to realize both a low noise figure and a high output power, the EDTFA employs a three-stage configuration and uses 980-nm band pumping for the first stage amplifier.³⁵⁾ Figure 11 is a diagram of the EDTFA. The second and third stages were bidirectionally pumped with 1480-nm LDs. Gain equalizers (GEQs) were inserted between the first and second stages, and between the second and third stages to achieve a flattened gain and large output power simultaneously. Figure 12 shows the gain and noise figure spectra for various input signal powers. A 70.8-nm gain bandwidth (from 1532.7 to

Fig. 12. Gain and noise figure spectra of EDTFA for various input signal powers.

1603.5 nm) was obtained, with a gain excursion of less than 1.5 dB, an average gain of 24.3 dB and a noise figure of less than 6 dB for input signal powers of –15 to –5 dBm.

Furthermore, when a long EDF is employed and the inversion rate controlled at a low value of 40%, the EDTFA exhibits wide L-band operation. The L-band EDTFA is advantageous in the extended L-band wavelength region beyond 1610 nm where an EDSFA cannot obtain sufficient gain. Practical gain flattened L-band and extended L-band EDTFAs have been developed.^{36),37)}

By combining an EDTFA and a thulium doped fluoride fiber amplifier (TDFFA) in parallel, a coarse WDM amplifier was constructed for 8-channel WDM signals with 20-nm wavelength intervals thus allowing the effective use of the low loss wavelength range of installed transmission fibers around 200 nm with

a loss of less than 0.25 dB/km. This amplifier achieved a total gain bandwidth of 148 nm with an average gain of 22.5 dB, a noise figure of less than 8 dB and a gain excursion of 2 dB.³⁸⁾ The amplifier can be used to upgrade a dense WDM amplifier with a high output power by employing higher pump powers for future ultra-high capacity WDM transmissions.

4. Tellurite-based fiber Raman amplifiers

With an FRA, a pump light of frequency ν is scattered by optical phonons (vibrational mode) with a frequency ν_R of the molecules that compose the core glasses and is consequently emitted with a frequency of $\nu - \nu_R$. By making use of this energy-conversion phenomenon, the signals can be amplified with a wavelength that is longer than that of the pump light simply with the molecular vibration frequency ν_R . Furthermore, a multi-wavelength pumping technique has been used in FRAs to achieve wideband amplification as shown in Fig. 13. 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.

The Raman gain spectrum of silica-based fiber consists of Si-O and Ge-O vibrations of 440 cm^{-1} . Because the gain coefficient for Ge-O is eight times larger than that for Si-O, a core glass with large amounts of GeO_2 is advantageous for achieving a large gain coefficient.³⁹⁾ The Raman gain spectrum for tellurite-based fiber is the result of the 665 and 440 cm^{-1} stretching vibrations of TeO_4 trigonal bipyramids, and of the 740 cm^{-1} stretching vibration of TeO_3 trigonal pyramids.⁴⁰⁾ When TeO_2 is predominant in the glass composition it exhibits TeO_4 trigonal bipyramids. As the network modifier grows, the structure changes into TeO_3 trigonal pyramids. Furthermore, by modifying the glass components or adding components such as P_2O_5 , and WO_3 to tellurite-based glasses, the Raman spectra could be modified to some extent.⁴¹⁾

Figure 14 compares the gain coefficient spectra of tellurite-based and silica-based fiber, and Table 1 summarizes their stimulated Raman scattering characteristics. Tellurite-based fiber with a refractive index difference (Δn) of 2.2% and a scattering loss of 20 dB/km at $1.56\text{ }\mu\text{m}$, and a silica-based fiber (commercially available dispersion-compensation fiber) with a scattering loss of 0.6 dB/km at $1.56\text{ }\mu\text{m}$ were used. To measure the Raman gain spectra, each fiber was pumped with 1460-nm LDs in a backward pumping scheme. It is clear that the maximum gain coefficient for the tellurite-based fiber was $55\text{ W}^{-1}\text{km}^{-1}$, which was 16 times larger than the value of $3.5\text{ W}^{-1}\text{km}^{-1}$ for the silica-based fiber. The Stokes shift of the main gain peak for the tellurite-based fiber was 170 nm, which was 1.7 times larger than that for the silica-based fiber. The most significant difference between these spectra was their spectral shape. The tellurite-based fiber had a twin-peaked spectrum, while the silica-based fiber had a spectrum with a single peak. These features make it possible to extend the seamless amplification bandwidth to 170 nm by using a short length of tellurite-based fiber as the amplification medium, whereas the amplification bandwidth is limited in principle to 100 nm when using a long silica-based fiber.

The tellurite-based FRA can provide a gain bandwidth of 170 nm and cover the low loss region of transmission fiber across the S (1460–1530 nm), C and L bands. However, when a tellurite-based FRA is used as an inline repeater in an actual WDM system, the following problems must be dealt with: (1) a flat gain of over 20 dB, (2) dispersion compensation, (3) noise figure degradation in the S band, and (4) the signal power transfer from the

Fig. 13. Multi-wavelength pumping technique for wideband Raman amplification.

Fig. 14. Raman gain coefficient spectra (a) tellurite-based fiber, (b) silica-based fiber.

Table 1. Stimulated Raman Scattering Characteristics of Tellurite- and Silica-based Fiber

	Max. gain coefficient	Stokes shift	Remarks
Tellurite	$55\text{ W}^{-1}\text{km}^{-1}$	$\sim 170\text{ nm}$	Twin peaks
Silica	$3.5\text{ W}^{-1}\text{km}^{-1}$	$\sim 100\text{ nm}$	Single peak

S to L band caused by stimulated Raman scattering between optical signals in transmission fiber. As regards the first two problems, the differences between the gain spectra of tellurite- and silica-based FRAs were examined and a discrete hybrid tellurite and silica FRA were configured that can achieve both dispersion compensation and gain flattening for linear repeaters.

Fig. 15. Configuration of hybrid tellurite/silica FRA with distributed silica Raman amplification.

For the other two problems, a distributed/discrete hybrid FRA was configured that adds a distributed FRA with a high signal to noise ratio (SNR) centered on the S band to the discrete hybrid FRA. Here, the distributed FRA allows the transmission fiber itself to be used as the amplification medium, whereas the discrete FRA needs the amplifier fiber as the amplification medium.

Figure 15 shows the amplifier configuration.⁴²⁾ 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-based fiber for the first and third stages and silica DCF for the second stage. A GEQ was placed between the second and third stages. The distributed FRA section consists of 80 km of single-mode fiber as transmission fiber, which is backward pumped by LDs operating at three wavelengths. The pump wavelengths and powers were determined in order to give this amplifier a low noise figure and high output as well as a flat gain spectrum. **Figure 16** shows the total gain spectrum with and without gain equalization, and the equivalent noise figure. The equivalent noise figure is computed as the net noise figure (defined as the loss between the input end of the 80-km single-mode fiber (SMF) and the amplifier output) minus the SMF loss in dB units. The figure also shows the loss spectra for 80 km of SMF. The total gain spectrum after equalization indicates an average gain of 22 dB across the 127-nm wavelength region of 1480–1607 nm. For an 80-km SMF loss of 15.5–18 dB, a system margin of about 3 dB can be obtained in the same band. For the same wavelength regions, the equivalent noise figure is less than 7 dB. The low equivalent noise figure in the short wavelength region was specifically designed to suppress the SNR degradation caused by the stimulated Raman scattering that occurs between optical signals in this region in high-speed large-capacity transmission systems. This amplifier was used as a linear repeater in a large-capacity WDM experiment of 313 channels with a channel rate of 10 Gbit/s. 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.⁴³⁾

Some calculations have been performed to obtain a wideband and flat gain spectrum with only tellurite-based FRA operated

Fig. 16. Total gain spectrum with and without gain equalization, equivalent noise figure and loss spectra for 80-km of SMF.

multi-wavelength pumping. Qin et al. demonstrated a flatter gain profile with a larger effective bandwidth by increasing the number of pump wavelengths from 2 to 8 using $\text{TeO}_2\text{-BaO-SrO-Nb}_2\text{O}_5\text{-P}_2\text{O}_5\text{-WO}_3$ (TBSNPW) and TBZN tellurite fibers.⁴⁴⁾ The relative gain flatness of an S + C + L band FRA for 8 pump wavelengths is 4.51% and 11.72% for TBSNPW and TBZN fibers, respectively. However, the corresponding flatness values for 4 pump wavelengths are both around 20%. This is because an FRA requires a configuration with more than two stages to realize a gain beyond 20 dB owing to double Rayleigh scattering,⁴⁵⁾ and a configuration with the polarization multiplexing of two LDs for one pump wavelength owing to the polarization dependence of gain.⁴⁶⁾ When considering the practical number of pump LDs, we should investigate ways of obtaining a flatter gain profile and a larger effective bandwidth using around 4 pump wavelengths.

5. Stimulated Brillouin scattering (SBS) in tellurite-based fiber for amplification and slow light generation¹⁴⁾

With stimulated Brillouin scattering, a pump light of fre-

quency ν is scattered by an acoustic wave with frequency ν_B of the molecules composing the core glasses, and is consequently emitted with a frequency of $\nu - \nu_B$. As with the FRA, the signals can be amplified with a wavelength that is longer than that of the pump light solely by the acoustic vibration frequency ν_B . However, SBS can amplify the light propagation in a direction opposite to the light.

Figure 17 shows the experimental setup for Brillouin amplification. A CW single frequency laser at 1550 nm was divided into two parts by a 3 dB coupler. One part was amplified with an EDFA for use as the pump source, while the other part was frequency downshifted using an optical single-sideband (SSB) modulator by an amount approximately equal to the Brillouin frequency shift for use as the probe signal. For the Brillouin amplification experiments, a 100 m long tellurite-based fiber with background losses of 59 dB/km was used. **Figure 18** shows the dependence of the Brillouin gain spectra on the pump power. A peak gain of 29 dB was achieved with a pump power of 10 mW at 1550 nm. **Figure 19(a)** shows the value of the peak Brillouin gain as a function of the pump power. The Brillouin gain coefficients of tellurite-based fiber were calculated by substituting the gain data measured with a pump power of 6 mW and the parameters of the tellurite-based fiber presented in **Table 2** into

$$G = 10 \log[\exp(g_B L_{\text{eff}} P K / A_{\text{eff}} - \alpha L)] \quad (1)$$

which is shown in Fig. 19(b). The peak Brillouin gain coefficient value of 1.6989×10^{-10} m/W was obtained for tellurite-based fiber and this is 8.5 times larger than that of silica-based fiber. From Fig. 19(b), a Brillouin shift of 7.97 GHz and a 3-dB Brillouin shift gain linewidth ($\Delta\nu_B$) of 20.98 MHz were obtained for tellurite-based fiber by fitting the Brillouin gain coefficient spectrum with a Lorentzian spectral profile. In addition, the acoustic velocity in this tellurite-based fiber was calculated as 3042.7 m/s using the relation $\nu_A = \Delta\nu_B \lambda_p / 2n$ where, n is the refractive index, λ_p the pump wavelength, and ν_B the Brillouin shift. The parameters are shown in Table 2.

Recently, Abedin investigated the stimulated Brillouin scattering (SBS) properties and the slow light generation performance in Er^{3+} -doped tellurite fiber with a loss of ~ 0.5 dB/m, and confirmed that tellurite fiber performs well as regards slow light generation via SBS.⁴⁷⁾ The SBS induced time delay per unit power and unit length was also calculated using the measured Brillouin coefficients for the undoped tellurite-based fiber with a low background loss of 20 dB/km, as defined in^{48,49)}

$$\Delta t_d / (P_p L_{\text{eff}}) = \frac{g_B K}{A_{\text{eff}} (2\pi \Delta\nu_B)} \quad (2)$$

Measured data for the Brillouin gain coefficients and the tellurite-based fiber parameters shown in Table 2 were used. The calculated results are shown in **Fig. 20(a)**. A peak value of 0.09245 ns/mW/m was obtained for this tellurite-based fiber. Another important parameter with respect to slow light generation is the time delay slope efficiency defined as

$$S_{\text{dg}} = \Delta t_d / G_B \approx \frac{1}{8.686 \pi \Delta\nu_B} \quad (3)$$

Figure 20(b) shows the time delay as a function of the Brillouin gain, which gives a time slope efficiency of 1.75 ns/dB.

Fig. 17. Experimental setup used for Brillouin amplification.

Fig. 18. Brillouin gain spectra vs pump power.

Fig. 19. (a) Value of peak Brillouin gain as a function of pump power, (b) Brillouin gain coefficients of tellurite-based fiber.

Table 2. Comparison of Nonlinear Optical Properties of silica, Bismuth Oxide, Tellurite and As₂Se₃ Chalcogenide Fibers

Parameters	Silica	Bismuth oxide ¹⁵	Tellurite	Chalcogenide ⁴⁸
Refractive index (n)	1.45	2.22	2.03	2.8
Brillouin gain coefficient (g_B , m/W)	2×10^{-11}	6.43×10^{-11}	1.6989×10^{-10}	6.08×10^{-9}
Brillouin frequency shift (ν_B , GHz)	10.86	8.825	7.97	7.968
Brillouin gain bandwidth ($\Delta\nu_B$, MHz)	25	32	20.98	45
Background loss (dB/m)	0.0005	0.8	0.0588	1
A_{eff} (μm^2)	50	3.08	6.9697	39
$\frac{g_B K}{A_{\text{eff}}(2\pi\Delta\nu_B)}$, ns/mW/m	0.00127	0.067	0.09257	0.2
Time delay slope efficiency ($S_{\text{dg}} = \frac{1}{8.686\pi\Delta\nu_B}$, ns/dB)	1.46	1.1452	1.75	0.82

Fig. 20. (a) SBS induced time delay per unit power and per unit length, (b) time delay as a function of Brillouin gain.

This value calculated using tellurite-based fiber is higher than the time delay slope efficiencies previously obtained for silica, bismuth oxide-based and As₂Se₃ chalcogenide fibers. Equation (3) shows that a smaller $\Delta\nu_B$ leads to a larger S_{dg} . As shown in Table 2, tellurite fiber exhibits the smallest $\Delta\nu_B$, so it exhibits the largest S_{dg} of these four types of fibers.

Furthermore, taking the background loss into consideration, the dependence of the SBS induced time delay per unit power on the fiber length was calculated by employing the following equation

Fig. 21. Dependence of SBS induced time delay per unit power on fiber length for four types of fibers. Inset: background losses of these fibers.

$$\frac{\Delta t_d}{P_p} = \frac{g_B K}{A_{\text{eff}}(2\pi\Delta\nu_B)} \times (1 - \exp(-\alpha L)) / \alpha. \quad (4)$$

Here, background losses for silica, bismuth-based, tellurite-based and As₂Se₃ fibers of 0.5, 800, 20 and 1000 dB/km, respectively, were selected. **Figure 21** shows the calculated results. The inset in Fig. 21 shows the background losses of these four types of fibers. Tellurite-based fiber exhibits the largest time delay per unit power of 19.9 ns/mW as a result of its low background loss and relatively higher Brillouin gain coefficient.

6. Carrier-envelope offset locking with low pulse energy²³⁾

A carrier-envelope offset (CEO)-locked frequency comb at telecommunication wavelengths with a downsized and high-repetition-rate laser system could provide an optical frequency “ruler” in a robust, power-efficient fiber-optics package that would be suitable for a variety of applications. CEO frequency detection with an f-to-2f self-referencing interferometer requires an optical bandwidth of more than an octave (a factor of 2 in frequency). To reduce the pulse energy needed for the generation of an octave-bandwidth spectrum for the downsized laser system, a method was proposed for locking the CEO by employing the

Fig. 22. Experimental setup for the CEO locking with low pulse energy: f_{CEO} , CEO frequency; f_{rep} , repetition rate; PBS, polarization beam splitter.

Fig. 23. Spectrum generated in a 30-cm-long tellurite-PCF by using fiber coupling pulse energies 30, 80, and 230 pJ. Each SC spectrum in the graph has the same intensity at 1560 nm.

tellurite PCF described in section 3.

Figure 22 shows the experimental setup. A passively mode-locked Er-fiber laser amplifier system is used. The amplifier laser drives a 100-fs, 1-nJ laser pulse with a center wavelength of 1560 nm. The repetition frequency of the fiber laser system is controlled to 250 MHz. The output power from the amplifier laser is collimated in free space and then launched into the tellurite PCF with a typical efficiency of 29% by using an objective lens ($NA = 0.8$). The optical output spectrum after the tellurite PCF spans more than an octave. The CEO frequency f_{CEO} is measured with an f -to- $2f$ self-referencing interferometer. A long-pass filter transmits infrared components at 1930 nm. These components are then frequency-doubled into the QPM-LN waveguide⁵⁰ and recombined with a 965-nm beam propagating through an arm of the f -to- $2f$ self-referencing interferometer. From a signal selected with a grating, the heterodyne beat between the interference components yields a frequency difference f_{CEO} . The CEO signal is phase-locked to $f_{CEO} = 20$ MHz using a feedback circuit.

Figure 23 shows the dependence of the SC spectrum of the tellurite PCF on the fiber coupling pulse energy. It was found that an SC spanning more than an octave (950–2100 nm) at the –30-dB level can be generated with a fiber-coupling pulse energy of 80 pJ and a 30-cm long tellurite PCF. However, it was not pos-

Fig. 24. (a) Spectrum between the fundamental light in the 965-nm region and the frequency-doubled 1930-nm light when a 230-pJ pulse was launched into the tellurite PCF. (b) Self-reference beat signal of the 250-MHz laser. Resolution bandwidth is 100 kHz. Inset: Phase difference between beat signal and local oscillator.

sible to observe the beat signal with the 80-pJ fiber-coupling pulse energy, probably because of the low output power from the tellurite PCF. Therefore, the fiber coupling pulse energy was increased and a 230-pJ pulse energy launched into the PCF. **Figure 24(a)** shows the spectrum between the fundamental light and the second harmonic generated by propagation in the QPM-LN ridge waveguide. The largest beat signal was obtained in the 965-

Fig. 25. Power spectrum density of the CEO beat signal.

nm region. Figure 24(b) shows that the beat signal between the frequency-doubled light at 1930 nm and the fundamental light at 965 nm was detected. The beat signal had a signal-to-noise ratio of about 30 dB. The beat signal was locked at a 20-MHz reference frequency by controlling the 980-nm pump laser power using a feedback circuit. The inset in Fig. 24(b) shows that the difference signal between the beat signal and the local oscillator becomes smaller with the CEO lock. **Figure 25** shows the power spectrum density (PSD) of the phase noise with and without the CEO lock. Without the CEO lock, it was difficult to measure the PSD signal at less than 1 Hz because of carrier frequency fluctuation. This means that a feedback loop with the CEO lock suppresses phase noise at frequencies less than 1 Hz. We confirmed that the CEO could be locked in the system.

7. Conclusion

In summary, this paper reviewed research on tellurite-based glasses, and considered the process for fabricating fiber with a low background loss and fiber applications to optical communication networks. By purifying the raw materials and using a novel PCF fabrication process, we achieved low background losses for Er^{3+} -doped, and undoped step-index tellurite-based fibers and a tellurite-based PCF.

As regards optical communications applications, EDTFAs, fiber Raman and Brillouin amplification, slow light generation and a CEO-locked frequency comb were studied. A seamless, low noise and gain flattened C + L band EDTFA was realized and an S + C + L band amplifier with gain bandwidths was constructed by combining the EDTFA and TDFFA in parallel. Furthermore, to overcome certain problems a distributed/discrete hybrid tellurite- and silica-based FRA was constructed as an S + C + L band WDM repeater, and it provided a 127-nm bandwidth and an equivalent noise figure below 7 dB of 1480–1607 nm. These amplifiers could be employed in WDM systems with the C + L or S + C + L band covering the low attenuation of installed fibers. Next, the Brillouin gain coefficients were investigated and the potential performance of a tellurite-based fiber for slow light generation was clarified on the basis of the Brillouin gain characteristic. Tellurite-based fiber exhibits the largest time delay per unit power and is thus a promising candidate for use in the development of memories and optical delay lines that would be compatible with fiber-optic communication. Finally, a CEO-locked frequency comb with a lower fiber coupling pulse energy was demonstrated by using a tellurite-based PCF. The reported method has the potential to lock the CEO with a lower pulse energy and thus provide a low-noise and high-accuracy

optical frequency comb at telecommunication wavelengths. The results confirm that tellurite-based fibers with low background loss can provide attractive functional applications in the optical communication field.

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