

LETTERS

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Fibre laser based on tellurium-doped active fibre

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Abstract. **We have studied the lasing properties of tellurium-doped germanosilicate fibre, identified its gain and excited-state absorption bands, and assessed the effect of cooling to low temperature (77 K) on the bands. The excitation spectrum of the near-IR luminescence in the fibre has been measured. Lasing at 1.55 μm has been demonstrated for the first time in this gain medium at liquid-nitrogen temperature and pump wavelengths of 1.064 and 1.085 μm. The measured Raman spectrum of the fibre provides some insight into the structure of the near-IR luminescence centre.**

Keywords: *tellurium, tellurium-doped optical fibre, lasing.*

Optical fibres most widely used in the fabrication of fibre lasers and amplifiers are those doped with rare earths. The spectral range employed by modern optical fibre communication systems is determined by the gain band of the erbium-doped fibre amplifier (1.53–1.61 μm), whereas germanosilicate telecom fibres have an acceptable level of losses (within 0.4 dB km^{-1}) in a much broader spectral range (~1.3 to ~1.5 μm). To extend the wavelength range of lasing and amplification, the possibility of using other dopants should be examined, because there are no efficient rare-earth-doped fibre lasers or amplifiers for the spectral range in question.

Significant advances in this range have been made due to bismuth-doped fibres, which offer lasing in the range 1150–1550 nm and optical amplification at wavelengths near 1320 and 1430 nm. More detailed information concerning bismuth-doped gain media can be found in Dianov [1] and references therein.

In addition to bismuth, other post-transition elements (Pb, Sb, Sn, Te and In) can be used as dopants leading to the formation of near-IR luminescence centres [2–5]. In particular, Dianov et al. [6] have already reported that, when pumped around 1 μm, tellurium-doped germanosilicate fibre has a broad (~400 nm) luminescence band centred near 1.5 μm. This paper addresses low-temperature luminescence, optical amplification, excited-state absorption and lasing in this gain medium.

We used the same multimode fibre (Te : 94 SiO_2 – 6 GeO_2) as previously [6] and a single-mode fibre drawn out from the same preform. The single-mode fibre was used to measure excitation, gain, and absorption spectra and investigate lasing. The techniques used in this study were similar to those reported previously [6–8]. Raman spectra were measured with the multimode fibre. The spectra were obtained using a Jobin Yvon T64000 triple-grating monochromator with a resolution of ~1 cm^{-1}. Excitation was provided by a Spectra-Physics Stabilite 2000 argon laser at a wavelength of 514.5 nm.

Figure 1 shows the luminescence spectra of the multimode fibre at room temperature (RT) and liquid-nitrogen temperature (NT), and the inset in Fig. 1 illustrates the excited-state relaxation for the luminescence signal in the range ~1.1 to 1.7 μm. It is seen that cooling to NT markedly changes the luminescence properties of the fibre: the luminescence peak height increases by almost one order of magnitude, the peak shifts slightly (by 20–30 nm) to longer wavelengths, and its full width at half maximum (FWHM) decreases from 400 to 300 nm. The luminescence decay curves are well represented by equations of the form $A_0 + A_1\exp(-t/\tau_1) + A_2\exp(-t/\tau_2)$, with best fit parameters $A_0 < 0.01$, $A_1 \sim 0.4$, $A_2 \sim 0.6$, $\tau_1 \sim 3$ μs, $\tau_2 \sim 1$ μs at RT and $A_0 < 0.01$, $A_1 \sim 0.6$, $A_2 \sim 0.4$, $\tau_1 \sim 13$ μs, $\tau_2 \sim 4$ μs at NT.

Figure 2 shows the excitation spectra of the near-IR luminescence, which have a maximum around 1.05 μm. At a pump wavelength $\lambda_p = 1064$ nm, we examined the optical bleaching of the fibre. At liquid-nitrogen temperature (77 K), partial

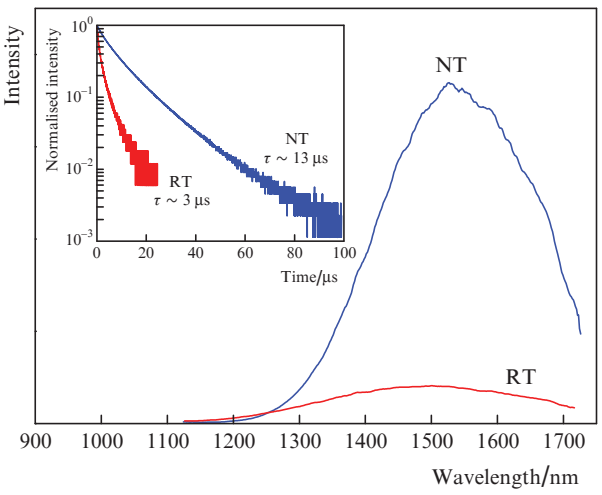

Figure 1. Luminescence spectra of the tellurium-doped germanosilicate fibre at room temperature (RT) and liquid-nitrogen temperature (NT). Excitation was provided by a laser diode ($\lambda_p = 974$ nm). Inset: corresponding luminescence decay curves.

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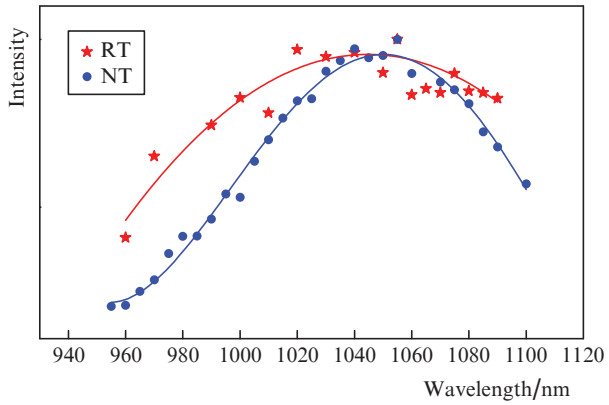

Figure 2. Excitation spectra of the 1.5-μm luminescence of the tellurium-doped germanosilicate fibre at room temperature (RT) and liquid-nitrogen temperature (NT). The lines are drawn as a guide to the eye.

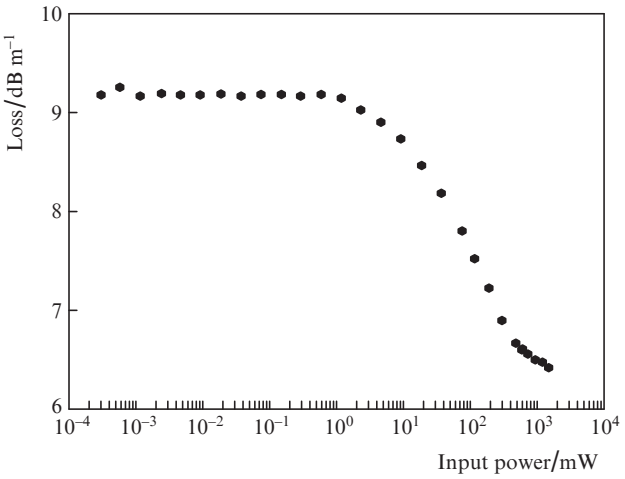

Figure 3. Optical loss at the pump wavelength ($\lambda_p = 1064$ nm) as a function of launched pump power for the tellurium-doped germanosilicate fibre at liquid-nitrogen temperature. Pumping by an ytterbium fibre laser.

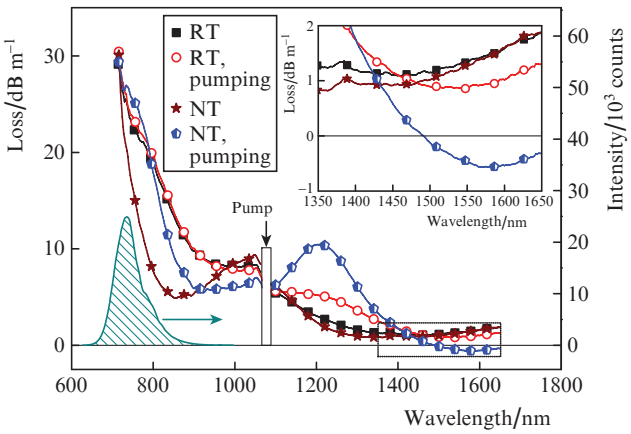

Figure 4. Room-temperature (RT) and 77-K (NT) optical loss spectra of the tellurium-doped germanosilicate fibre under pumping ($\lambda_p = 1085$ nm) and without it, and low-temperature upconversion luminescence spectrum (hatched area). Inset: outlined region on expanded scales.

Thus, we are led to conclude that the lack of bleaching at room temperature is due to partial overlap of the IR luminescence excitation band with the excited-state absorption band. At 77 K, the overlap is substantially smaller, owing to both the shift of the absorption band to longer wavelengths and the narrowing of the two bands. As a result, pump efficiency is higher at lower temperatures. This allowed us to achieve lasing with the simple configuration schematised in Fig. 5.

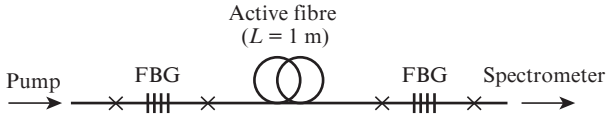

Figure 5. Schematic of the tellurium-doped germanosilicate fibre laser: (FBG) high-reflectivity fibre Bragg grating, (×) fibre fusion splice.

bleaching took place (Fig. 3). In contrast, at room temperature the optical loss was observed to increase.

The next step was to study optical amplification and excited-state absorption. To this end, optical loss spectra were measured at liquid-nitrogen and room temperatures under pumping and without it (Fig. 4). It is seen that, in the range 700–1050 nm, the room-temperature loss spectrum is not influenced by pumping. In the range 1100–1450 nm, the spectrum has an excited-state absorption shoulder. Between 1450 and 1650 nm, an on/off gain is observed.

The 77-K loss spectrum differs primarily in shape from the RT spectrum. Without pumping, the absorption band around 1 μm becomes narrower and stronger. The same refers to the corresponding excitation band (Fig. 2; an increase in peak intensity at NT is evidenced by the increase in signal-to-noise ratio). Pumping results in a net gain with a 3 dB bandwidth of ~125 nm and a maximum near 1.57 μm. The largest gain coefficient is ~0.6 dB m^{-1}. The excited-state absorption band shifts to longer wavelengths and has a well-defined maximum near 1.2 μm. Its FWHM is ~200 nm. Bleaching is observed in the range 900–1050 nm, and there is a shoulder due to another excited-state absorption band in the range 750–850 nm.

Figure 6 shows output emission spectra of the tellurium-doped germanosilicate fibre laser. Lasing was obtained under pumping at 1064 and 1085 nm. In both cases, the lasing threshold was ~300 mW.

In addition, we observed pump upconversion in the form of red luminescence (with a peak emission wavelength of ~735 nm), whose spectrum is presented on the left of Fig. 4. The red emission of the fibre was seen by the naked eye.

As reported previously [3, 9], absorption and luminescence bands of tellurium-containing materials may originate from tellurium dimers, neutral (Te_2) or charged (Te_2^-). The vibrational energies of the dimers are known and may contribute to Raman spectra. To verify this assumption, we examined the Raman spectrum of the tellurium-doped germanosilicate fibre (Fig. 7). Also shown for comparison in Fig. 7 is the Raman spectrum of an undoped fibre produced by the same procedure as the doped fibre but without solution doping. No IR luminescence was detected in the undoped fibre. The shape of its Raman spectrum is typical of germanosilicate fibres. The Raman spectrum of the tellurium-doped germanosilicate fibre (Fig. 7b) contains two characteristic sharp peaks at 198 and 244 cm^{-1}. We failed to find out the

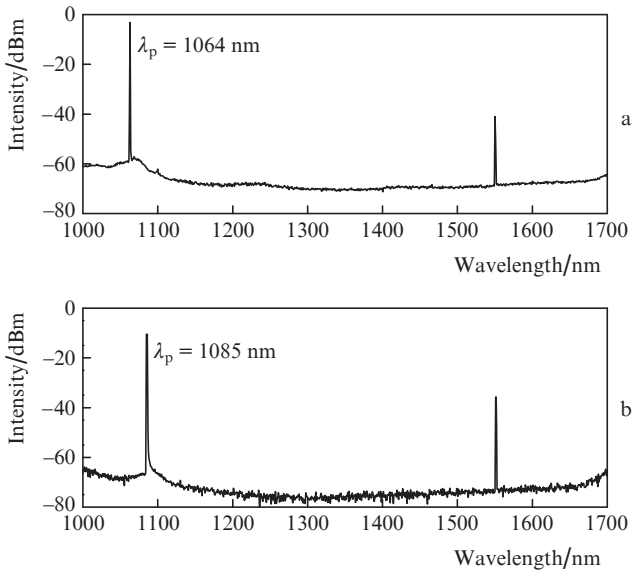

Figure 6. Output emission spectra of the tellurium-doped germanosilicate fibre laser at pump wavelengths λ_p = 1064 and 1085 nm.

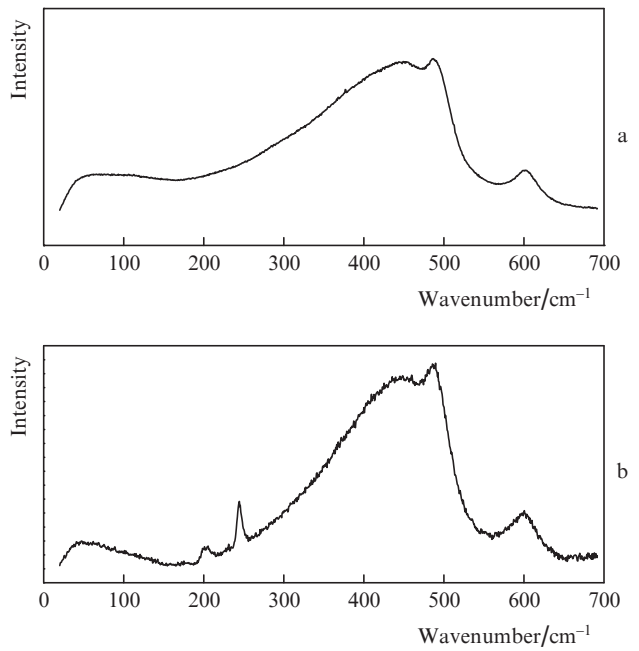

Figure 7. Raman spectra of (a) undoped and (b) tellurium-doped germanosilicate fibres under excitation by an argon laser (λ_p = 514.5 nm).

origin of the former peak, whereas the latter can be attributed to the neutral Te dimer with a high degree of certainty [9, 10].

Clearly, at the present stage there is no sufficient evidence that the Raman lines and IR luminescence in question originate from the same centre. Note, however, that the tellurium dimer has levels with energy differences in the visible and near-IR spectral regions [10] and a vibrational frequency near 244 cm^{-1} [9, 10]. This suggests that interstitial tellurium dimers in the fibre glass network are likely to act as luminescence centres.

Thus, we have measured the excitation spectrum of the IR luminescence of a tellurium-doped germanosilicate fibre and examined the influence of low temperature and pumping on the optical loss spectrum of the fibre. At 77 K, we obtained a net gain with a 3 dB bandwidth of ~125 nm, a maximum near 1.57 μm, and the largest gain coefficient of ~0.6 dB m^{-1}. This allowed us to demonstrate the first lasing at 1.55 μm in this type of gain medium under pumping at λ_p = 1.064 or 1.085 μm, using a cavity with high-reflectivity mirrors. The observed Raman band at 244 cm^{-1} suggests that one possible luminescence centre in the fibre is the tellurium dimer, Te_2.

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