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Bismuth-doped fibre amplifier for the range 1300 – 1340 nm

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Abstract. **We demonstrate the first bismuth-doped fibre amplifier operating in the second transmission window of silica-based fibres. At a pump power of 460 mW and pump wavelength of 1230 nm, its gain reaches 24.5 dB at 1320 nm, with a gain bandwidth of 37 nm, saturation power near 10 mW, and noise figure of 5 dB.**

***Keywords**: fibre laser, fibre amplifier, bismuth-doped fibre.*

The spectral range utilised by modern optical fibre communication systems is determined primarily by the gain bandwidth of erbium-doped fibre amplifiers and covers wavelengths from 1.53 to 1.61 μm. At the same time, the low-loss window of the silica-based optical fibres in current use is considerably broader, and information can be transmitted in the wavelength range 1.3 – 1.7 μm, where the optical loss is less than 0.3 dB km^{-1}. The growing need in society for advanced information-transmission technologies requires the development of next-generation fibre communication systems, with data rates of 50 – 100 Tbit s^{-1} per fibre. One way to solve this problem is to utilise the entire range 1.3 to 1.7 μm [1], which requires the development of novel components, and first of all of optical amplifiers for this range. The wavelength range around 1.3 μm, where standard single-mode fibres have near-zero dispersion, is of special interest. Before the advent of erbium-doped fibre amplifiers, this range attracted the most interest for communications.

In earlier work, rare-earth-doped fibres were proposed as optical amplifiers for the 1.3 μm range: neodymium-doped in 1988 [2, 3] and praseodymium-doped in 1991 [4]. Such amplifiers have substantially lower gain in comparison with erbium fibre amplifiers and, moreover, they are fabricated from fluoride or chalcogenide glasses, which are considerably more difficult to prepare and handle. In 1994, the first Raman fibre amplifiers operating at 1.3 μm were proposed and demonstrated [5, 6]. Such amplifiers are capable of amplifying optical radiation at any wavelength in the transmission window of optical fibres, but a relatively high pump power (~ 1 W) is needed to reach a gain of 20 – 30 dB. In addition, to obtain a sufficiently large gain bandwidth, a Raman amplifier should be pumped by several sources at different wavelengths.

Because of this, the recent discovery of IR luminescence in bismuth-doped glasses [7] has given impetus to studies of optical amplification in the spectral range in question [8 – 11]. In 2005, the first bismuth-doped optical fibres were fabricated and shown to lase near 1170 nm [12]. Later, the gain/lasing band was shifted to the range 1300 – 1500 nm through the use of bismuth-doped fibres of various compositions [13 – 18] (see also the review by Bufetov and Dianov [19]). Here, we report the characteristics of a bismuth-doped phosphogermanosilicate fibre amplifier operating in the short-wavelength part of this spectral region.

The fibre for the amplifier was fabricated by the MCVD process. The core – cladding index difference was 8.5×10^{-3}, the numerical aperture NA = 0.16, and the mode field diameter 6.4 μm. The second order mode cutoff wavelength was near 1.2 μm. The bismuth content of the fibre core was less than 0.02 at. % (the detection limit of Bi with our equipment). The background loss was difficult to accurately determine because the absorption lines of bismuth active centres in the glass overlapped.

The experimental configuration is shown in Fig. 1. The pump light and signal were coupled into a 200-m-long section of the active fibre by a wavelength-division multiplexer (WDM). The pump source was a Raman fibre laser

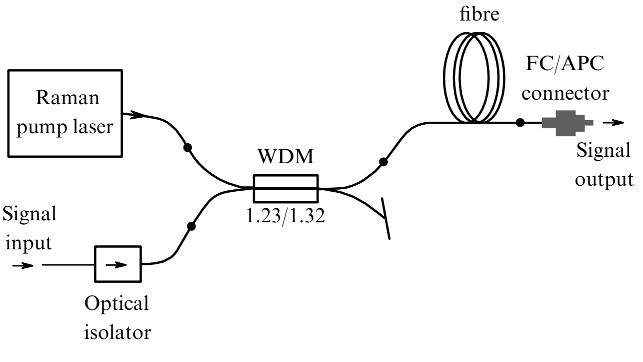

Figure 1. Schematic of the bismuth-doped fibre amplifier. The dots represent splices.

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operating at 1230 nm and providing up to 500 mW of output power in the cw regime. The input signal was provided by a broadband superluminescent fibre source with a maximum near 1.31 μm or a Raman laser emitting near 1318 nm. The broadband source was used to measure the gain spectrum, and the Raman laser, to assess the effect of input signal power on the amplifier gain.

Figure 2 shows the gain spectrum of the bismuth-doped fibre amplifier at a pump power of 460 mW and pump wavelength $\lambda_\mathrm{p} = 1230$ nm and its noise figure (NF) evaluated from the measured amplified spontaneous emission and output signal (like in Ref. [20]). The noise figure characterises the noise in the amplifier and is defined as the signal-to-noise ratio at the amplifier input divided by that at the output. The minimum noise figure of the amplifier under consideration was ~ 5 dB.

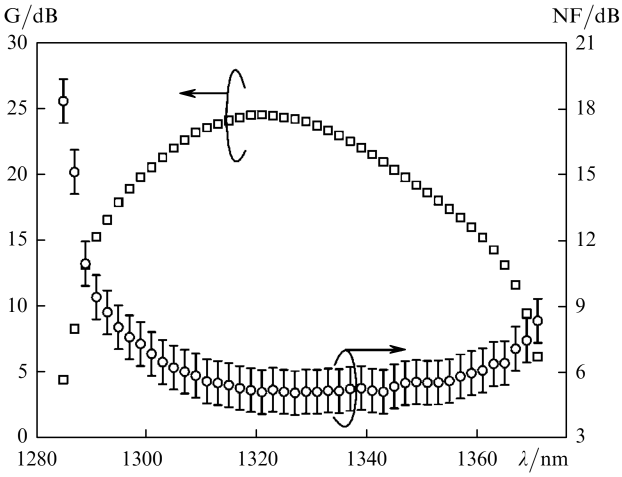

Figure 2. Gain spectrum and noise figure of the bismuth-doped fibre amplifier at $P_\mathrm{p} = 460$ mW and $\lambda_\mathrm{p} = 1230$ nm.

Positive gains were obtained at wavelengths in the range $\lambda_\mathrm{s} = 1283 - 1372$ nm. The maximum gain was 24.5 dB at $\lambda_\mathrm{max} = 1321$ nm, and the 3 dB gain bandwidth was $\Delta\lambda_{0.5} = 37$ nm. As shown earlier [15], the optical gain around 1320 nm is due to bismuth active centres related to the presence of phosphorus in the fibre core.

Figure 3 shows the gain as a function of pump power near the peak gain wavelength. The maximum gain efficiency, g_max, equal to the slope of the dashed line passing through the origin, is ~ 0.09 dB mW^{-1}.

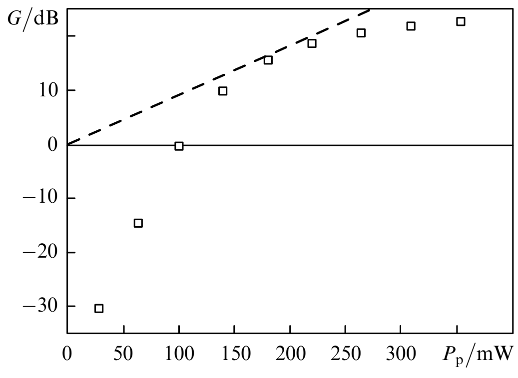

Figure 3. Gain at $\lambda_\mathrm{s} = 1318$ nm as a function of pump power ($\lambda_\mathrm{p} = 1230$ nm).

Figure 4 plots the gain against signal power ($\lambda_\mathrm{s} = 1318$ nm) at pump powers of 350 and 460 mW. The saturation power of the amplifier, P_sat, is 8.9 mW (9.5 dBm) at $P_\mathrm{p} = 350$ mW and 11.2 mW (10.5 dBm) at $P_\mathrm{p} = 460$ mW.

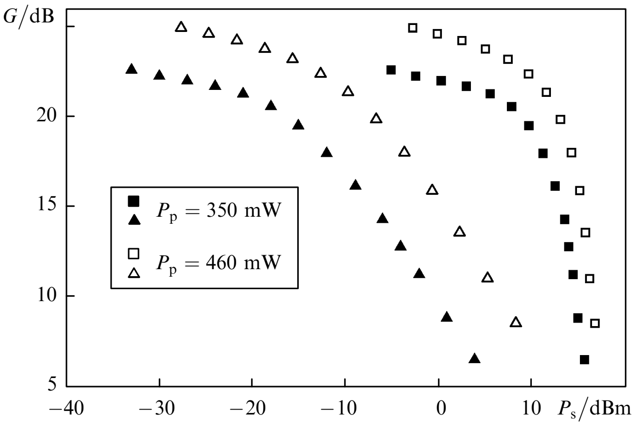

Figure 4. Gain as a function of output (squares) and input (triangles) signal power at $\lambda_\mathrm{s} = 1318$ nm.

From the above data, the pump-to-signal power conversion efficiency of the amplifier was determined to be 9 % at a gain near 10 dB. This comparatively low efficiency seems to be associated with the high background loss and possibly with excited-state absorption, leading to an unbleachable loss of ~ 30 dB km^{-1}.

Thus, we have demonstrated the first bismuth-doped fibre amplifier operating in the range 1300 – 1340 nm. At a pump power of 460 mW and $\lambda_\mathrm{p} = 1230$ nm, its maximum gain is 24.5 dB at 1320 nm and its NF is 5 dB. The active medium of the amplifier is recently proposed bismuth-doped phosphogermanosilicate fibre. Further work is needed to enhance the performance of the amplifier by optimising the fibre composition, fabrication technology and length and the pump system.

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