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Bismuth-doped fibre amplifier operating between 1600 and 1800 nm

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Abstract. **We report the first bismuth-doped fibre amplifier operating between 1600 and 1800 nm, which utilises bidirectional pumping (co-propagating and counter-propagating pump beams) by laser diodes at a wavelength of 1550 nm. The largest gain coefficient of the amplifier is 23 dB, at a wavelength of 1710 nm. It has a noise figure of 7 dB, 3-dB gain bandwidth of 40 nm and gain efficiency of 0.1 dB mW^{-1}.**

Keywords: *bismuth, fibre amplifier, laser, optical fibre.*

1. Introduction

There are currently bismuth-doped optical fibres with luminescence in the wavelength range 1000–1800 nm [1, 2]. Such fibres are regarded as promising media for effective lasing in a wide spectral region covering the range between the gain bands of ytterbium and thulium (1150–1775 nm).

The advent of optical fibres based on bismuth-doped silica glass [3, 4] was an important step forward in creating bismuth-doped fibre lasers and amplifiers. Over the decade that has passed since the demonstration of the first bismuth-doped fibre laser [5], significant advances have been made in this direction [6]: bismuth-doped fibres have been created that are capable of ensuring lasing in the wavelength range 1150–1530 nm.

Moreover, it has been shown that, based on the new type of bismuth-doped fibre, cw lasers can be produced that emit at longer wavelengths, in the range 1625–1775 nm [7]. The maximum output power of such lasers already exceeds 1 W [8]. In this paper, we report the first bismuth-doped fibre amplifier (BDFA) operating between 1600 and 1800 nm. Interest in this spectral range is aroused by the potential of using it in order to extend the information transfer region for raising the data rate of modern optical fibre communication systems. Practical importance of this direction is evidenced by recent reports on the development of optical amplifiers based on thulium-doped silica fibres for the range 1640–1720 nm (see e.g. Ref. [9]).

2. Bismuth fibre amplifier design

As the active medium of the BDFA, we used a single-mode bismuth-doped fibre segment with an outer diameter of 125 μm and core diameter near 2 μm. The fibre preform was produced by MCVD. The fibre core consisted of a bismuth-doped high-germania silica-based glass. The bismuth concentration was ~0.02 wt %. The length of the active fibre was 60 m, with an absorption of about 2 dB m^{-1} and unbleachable loss of 0.2 dB m^{-1} at a pump wavelength of 1550 nm.

Figure 1a shows a schematic of the BDFA. The amplifier utilised bidirectional pumping (co-propagating and counter-propagating pump beams). The pump sources used were commercially available laser diodes emitting at 1550 nm, with an output power no higher than 150 mW. The pump light was coupled into the core of the active fibre through a fibre-optic wavelength-division multiplexer (WDM). Two optical isolators were placed at the BDFA input and output: the input isolator served to reduce the effect of amplified spontaneous

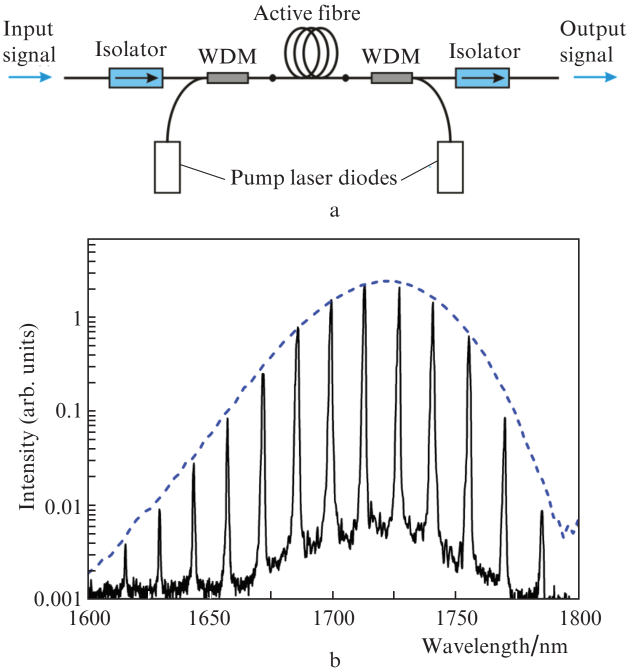

Figure 1. (a) Schematic of the bismuth-doped fibre amplifier, (b) output emission spectrum of the bismuth-doped superluminescent source (dashed line) and spectrum of the signal at the amplifier input (solid line).

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emission of the bismuth-doped fibre on the signal source, and the output isolator prevented possible laser action. The dots in Fig. 1a represent the fusion splices between the active fibre and SMF-28 single-mode fibres, where the loss level was ~1 dB.

The gain spectrum of the BDFA was measured using a signal in the form of a comb comprising 13 narrow (~1 nm) bands centred at wavelengths from 1615 to 1775 nm and spaced 15 nm apart. This shape of the signal was "cut out" from the spectrum of a bismuth-doped superluminescent light source, whose output, passing through a fibre-optic circulator, was reflected from sequentially written fibre Bragg gratings at appropriate wavelengths. The output emission spectrum of the bismuth-doped superluminescent source is shown by a dashed line in Fig. 1b. To assess the effect of the input signal power on the gain of the BDFA, we used the output of a bismuth-doped fibre laser emitting at a wavelength of 1680 nm.

The spectra of the input and amplified signals in the range 1500–1700 nm were measured by an HP 70950B optical spectrum analyser, and those in the range 1700–1800 nm were obtained using a grating monochromator fitted with an InGaAs photodetector. All the measurements were performed at room temperature.

3. Experimental results

Figure 2a shows the spectral dependences of the optical gain coefficient and noise figure for the BDFA. The dependences were obtained at a total pump power of 300 mW and a signal power no higher than –25 dBm in each band. The noise figure of the BDFA was evaluated from experimentally obtained signal and spontaneous luminescence spectra (see Ref. [10] for greater details). It is seen that the maximum gain of the BDFA reaches 23 dB at a wavelength of 1710 nm, with a 3-dB gain bandwidth of 40 nm. The observed asymmetry of the gain profile is due to the long-wavelength loss introduced by the multiplexer. We believe that optimising the multiplexer will ensure a marked increase in the gain bandwidth of the amplifier.

The minimum noise figure of the amplifier in the wavelength range 1670–1730 nm was about 7 dB. In this case, the amplifier operated in the small-signal regime. This is evidenced by the experimentally obtained dependence of its gain on the input signal power at a wavelength of 1680 nm in Fig. 2b. The input signal power that ensured saturation of the amplifier was about –10 dBm. Also shown in Fig. 2b is the pump-to-signal power conversion efficiency as a function of input signal power. The maximum power conversion efficiency was about 3% at an input signal power of ~5 dBm.

Figure 3 shows the 1700-nm optical gain as a function of total launched pump power for the BDFA. The counter-propagating pump power was maintained constant at a level of 150 mW, whereas the co-propagating pump power was varied. In this scheme, the BDFA had the highest gain efficiency: 0.1 dB mW^{-1}.

Thus, we have demonstrated a bismuth-doped fibre amplifier operating between 1600 and 1800 nm, which utilises bidirectional pumping (co-propagating and counter-propagating pump beams) by laser diodes at a wavelength of 1550 nm. The largest gain coefficient, 23 dB at a wavelength of 1710 nm, has been obtained at a pump power of 300 mW. The 3-dB gain bandwidth of the BDFA is 40 nm, its minimum noise figure is ~7 dB, and its gain efficiency is 0.1 dB mW^{-1}, with a maximum pump-to-signal power conversion efficiency near 3%.

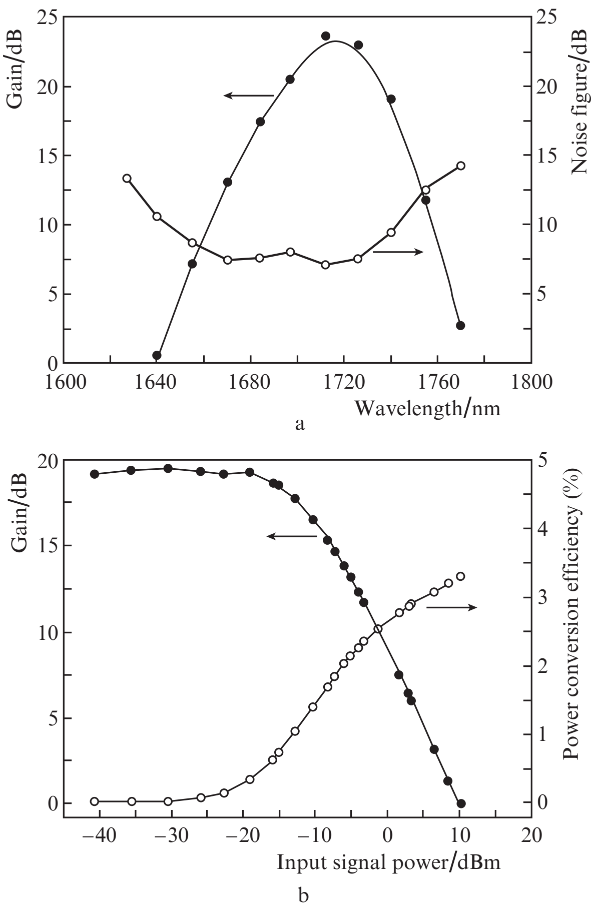

Figure 2. (a) Spectral dependences of the gain coefficient and noise figure for the bismuth fibre amplifier; (b) optical gain and pump-to-signal conversion efficiency as functions of input signal power at a wavelength of 1680 nm. All the results were obtained at an input pump power of 300 mW.

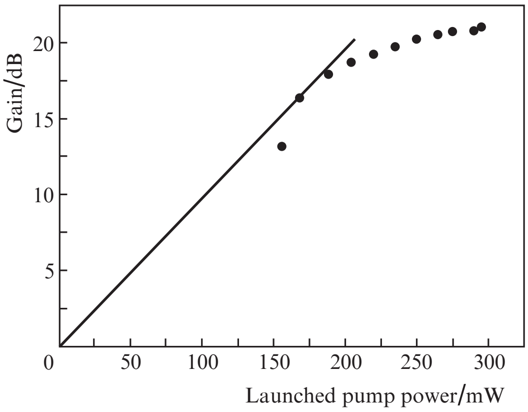

Figure 3. Optical signal gain at a wavelength of 1700 nm as a function of total launched pump power. The co-propagating pump power was varied, whereas the counter-propagating pump power was maintained constant at 150 mW.

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