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Bismuth-doped fibre laser continuously tunable within the range from 1.36 to 1.51 μm

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***Abstract*. A single-mode bismuth-doped fibre laser continuously tunable within the wavelength range from 1366 to 1507 nm with the help of an external diffraction grating has been developed. Such a wide wavelength tuning range is achieved by inserting a long-period fibre grating in the laser cavity. The grating smoothes the gain spectrum and thus ensures stable lasing at the edges of the above-mentioned spectral range. The output laser power varies from 25 mW at the tuning range edges to 50 mW in the centre upon pumping at 1.34 μm with a power of 300 mW.**

Keywords: *tunable laser, bismuth-doped fibre laser, lasing.*

1. Introduction

Extensive study of bismuth-doped silica fibre waveguides as promising laser media has made it possible even today to fabricate fibres that efficiently amplify optical signals in four near-IR ranges, which almost completely cover the wavelength range of 1.1 – 1.78 μm [1, 2]. This became possible owing to the fact that the laser transition wavelength in the bismuth active centre (BAC) strongly depends on its local environment in the silica glass network. In particular, BACs in silica glass with aluminium amplify optical radiation within the wavelength range of 1.1 – 1.22 μm, while doping of optical fibres with phosphorus instead of aluminium shifts the gain band to the range of 1.27 – 1.37 μm. In pure silica glass or in glass with a low concentration of germanium dioxide, BACs amplify radiation with wavelengths from 1.34 to 1.52 μm, while the bismuth gain band in highly germanium-doped silica glass lies in the range of 1.65 – 1.78 μm. At present, amplification and lasing have been demonstrated in the entire mentioned spectral range (1.1 – 1.78 μm) with, in particular, an output power exceeding 1 W [1, 3].

Bismuth-doped fibres of different compositions are pumped at different wavelengths and, due to relatively low BAC concentrations achieved to date, the pump radiation is coupled into the fibre core in all bismuth-doped fibre lasers and amplifiers. Depending on the fibre type and required total gain at a given wavelength, the length of Bi-doped active fibres varies from 3 to 300 m.

Previously [4], using a bismuth-doped active fibre with a low germanium dioxide concentration, we achieved lasing with an output power exceeding 1 W for a discrete set of wavelengths determined by pairs of fibre Bragg gratings and lying within the range of 1389 – 1538 nm (width ~150 nm), which is a record for fibre lasers in this spectral region.

In the present work, we developed and studied a single-mode fibre laser based on a bismuth-doped germanosilicate fibre, which allows continuous broadband wavelength tuning without changing optical elements of the scheme. The developed laser scheme with the used elements allowed us to achieve an output power exceeding 25 mW within the wavelength range of 1.36 – 1.51 μm under pumping at wavelength λ_p = 1.34 μm with a power of 300 mW.

The currently available single-mode radiation sources with a sufficiently large (~100 nm) wavelength tuning range in the considered spectral region are based on semiconductor structures, which limits the maximum output power of these sources by several milliwatts. At the same time, high-power tunable lasers are needed to solve the problems of spectroscopy, metrology, data transfer in optical communication lines, medicine, etc.

2. Scheme of a tunable bismuth-doped fibre laser

We used bismuth-doped (less than 0.01 wt %) germanosilicate (~5 mol % of GeO_2) optical fibre produced by the MCVD method [5, 6]. The fibre had a step index profile and a cutoff wavelength of 1.1 μm. The used scheme of the tunable Bi-doped fibre laser is shown in Fig. 1. As a pump source, we used a single-mode fibre Raman laser with output wavelength λ_p = 1340 nm designed as a single-cascade converter based on a phosphosilicate fibre pumped by an ytterbium fibre laser with a power of 2 W at a wavelength of

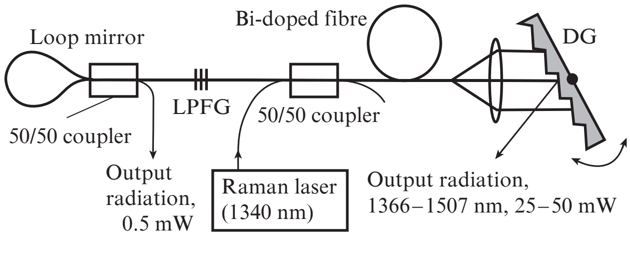

Figure 1. Scheme of the continuously tunable bismuth-doped fibre laser: (DG) diffraction grating; (LPFG) long-period fibre grating.

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1137 nm. The output power of the Raman converter reached 600 mW, but in our experiments we used a pump power of only 300 mW due to a low optical resistance of the 50/50 fibre coupler through which pump radiation was coupled into the Bi-doped fibre laser. The pump radiation should be coupled into the cavity through the 50/50 coupler because it was necessary to use broadband optical elements to achieve a widest possible tuning range. All the elements of the scheme except for the active fibre were based on a standard SMF-28e fibre. Typical loss in the fusion splice between the bismuth-doped and SMF-28e fibres did not exceed 0.5 dB (in the case of using a standard fusion program for SMF-28e fibres).

The laser cavity was formed by a loop reflector (Sagnac mirror) and a plane diffraction grating (DG) with a line density of 600 lines mm^{-1}, which was rotated to select a needed wavelength. A parallel beam ~5 mm in diameter formed by a microobjective (NA = 0.2) with compensated spherical and chromatic aberrations (apochromat) was directed to the grating. The first-order diffracted beam returned back to the fibre, while the output Bi-doped fibre laser beam propagated in the zero diffraction order. The output beam power was 25–50 mW depending on the wavelength. Radiation from the loop mirror (see Fig. 1) had a power of ~0.5 mW and was used to measure the laser spectrum and control wavelength tuning. The active fibre length was ~65 m, which ensured almost complete absorption of pump radiation with λ_p = 1340 nm. The gain spectrum measured upon pumping at λ_p =1320 nm and the absorption spectrum of the bismuth-doped fibre are shown in Fig. 2.

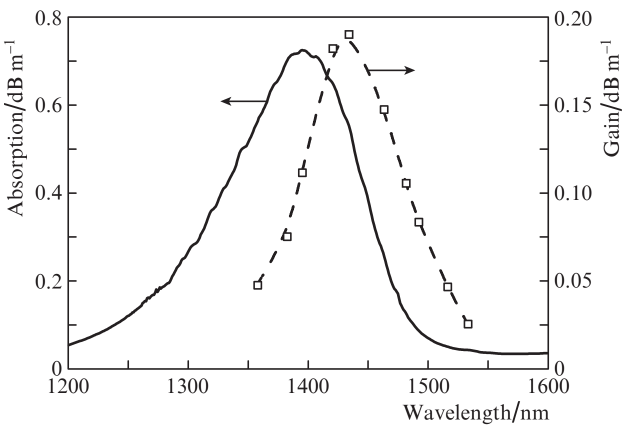

Figure 2. Absorption and gain spectra of the bismuth-doped fibre.

To flatten the gain spectrum, which is necessary for stable lasing at the gain band edges, we used a long-period fibre grating (LPFG) recorded in the SMF-28e fibre by the radiation of a frequency-doubled Ar$^+$ laser (λ = 244 nm). The LPFG transmission spectrum is shown in Fig. 3a. The grating length was 8 mm, and the grating period was 340 μm. As is seen from Fig. 3a, the optical losses introduced by the LPFG at the wavelength of its minimum transmission (~1435 nm) into the laser cavity per pass are ~6.5 dB (~80 %). The spectral width of the LPFG resonance was ~45 nm, which is approximately two times narrower than the BAC gain bandwidth (see Fig. 2).

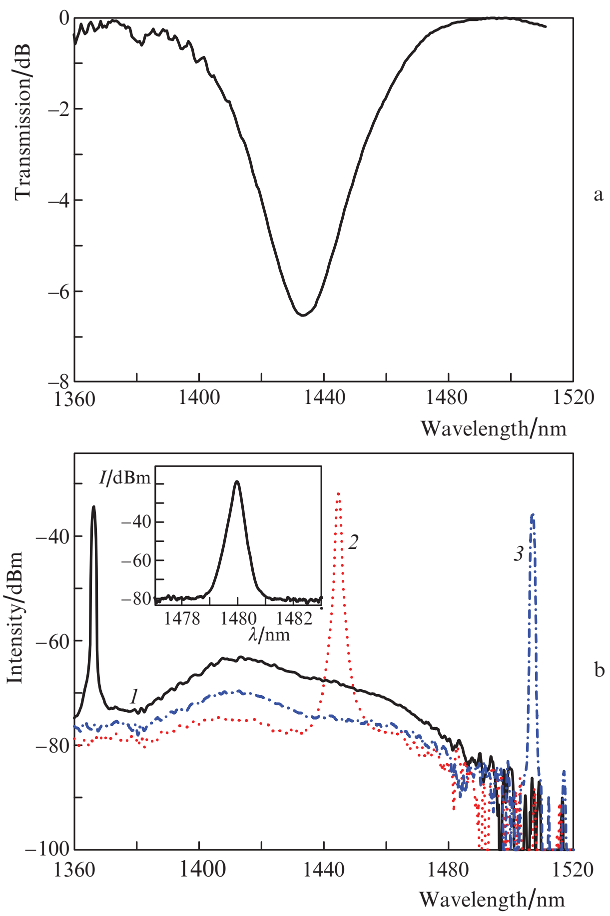

Figure 3. (a) LPFG transmission spectrum, as well as (b) bismuth-doped fibre laser spectrum at the (*1*) 1366-nm and (*3*) 1507-nm edges and (*2*) in the centre of the tuning range. The inset shows the laser spectrum measured with a high spectral resolution.

3. Results

Figure 3b shows the spectra of the studied cw bismuth-doped fibre laser at the edges of the tuning range 1366–1507 nm and a typical spectrum in the centre of this range. The aforementioned tuning range with a width of 141 nm was determined as a spectral range in which the output power decreased no more than twofold with respect to the maximum power (50 mW) near the tuning band centre. The spectra were measured on an ANDO AQ6317 spectrum analyser with a resolution of 1 nm. The spontaneous luminescence outside the Bi-doped fibre laser line turned out to be at least 30 dB lower than the spectral power density in the fundamental line at any laser wavelength. The inset in Fig. 3b shows the laser spectrum measured with a resolution of 0.05 nm. The laser linewidth was approximately 0.15 nm at a level of –3 dB.

In addition to the experiments described above, we studied the possibility of lasing in the proposed laser scheme in the longer-wavelength region (to 1530 nm), which borders the lasing range of erbium active fibres. For these experiments, the length of the bismuth-doped fibre was increased to 120 m and the 50/50 coupler was replaced by a fibre multiplexor in order to increase the pump coupling efficiency. This allowed us to shift the long-wavelength edge of the continuous tuning range of the Bi-doped fibre laser to the desired wavelength of 1530 nm, but the losses in the cavity considerably increased in the short-wavelength spectral region due to the insufficient spectral width of the multiplexor, because of which the short-wavelength edge shifted from 1366 to 1400 nm.

4. Conclusions

As far as we know, we have developed for the first time a single-mode bismuth-doped fibre laser with an output power from 25 to 50 mW and continuous wavelength tuning within a 141-nm range (from 1366 to 1507 nm) performed by rotating an external plane diffraction grating. The large tuning range was achieved by using an intracavity spectral filter based on an LPFG with the highest optical losses at a wavelength of 1440 nm.

Note that we pumped the proposed continuously tunable bismuth-doped fibre laser by a Raman laser with a power of 300 mW at a wavelength of 1.34 μm, while today there exist commercial single-mode lasers with similar output powers in this spectral region.

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