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Continuous-wave bismuth fibre laser tunable from 1.65 to 1.8 μm

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Abstract. **A single-mode fibre based on bismuth-doped germanosilicate glass with a high germanium concentration is considered as an active medium of a laser continuously tunable within the range 1.65 – 1.8 μm. The laser scheme included a broadband ring cavity, and the laser wavelength was controlled by an external plane diffraction grating in the Littrow configuration. For a pump power of 300 mW at a wavelength of 1.564 μm, the maximum output laser power was 15 mW in the zero diffraction order and 6 mW at the fibre output.**

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

1. Introduction

At present, intense laser radiation in the spectral range 1.65 – 1.8 μm attracts increasing interest due to various practical applications. In particular, the use of 1.65-μm radiation in laser surgery makes it possible to increase the penetration depth with retaining high incision quality and low light scattering, which is extremely important for surgery because it decreases collateral damages [1]. The use of a wavelength of 1.675 ± 0.02 μm in coherent tomography and multiphoton microscopy of biological tissues improves the signal-to-noise ratio (due to lower scattering and absorption by water molecules in this spectral region) and, hence, allows the information from a larger depth to be obtained [2, 3]. The spectral region near 1.7 μm is attractive for lidar probing of the Earth atmosphere [4] since it falls into the atmosphere transparency window and radiation in this range is eye safe.

Unfortunately, this spectral region lies out of the optical gain spectra of active rare-earth elements used in laser fibre optics, such as Nd, Yb, Er, and Ho (Tm-doped fibre lasers are inefficient in this region), which makes rather topical the search for and study of new laser media with optical gain in this spectral region.

It is known that fibre waveguides based of bismuth-doped silica glass allowed development of a family of new fibre lasers and broadband luminescent sources, as well as of optical amplifiers for the near-IR spectral region [5, 6]. This became possible due to a strong dependence of the spectral-luminescent properties of bismuth active centres (BACs) on the glass matrix and dopants (for example, P, Al) [7, 8].

It was previously shown that fibres with high Ge concentrations (for example, 50 mol % SiO_2/50 mol % GeO_2) can amplify in the region of 1.7 μm, with the efficiency high enough for designing lasers [9 – 11], superluminescent sources [12], and optical amplifiers [13] in the wavelength range 1.6 – 1.8 μm. As a rule, the active fibre length in this case is 50 – 100 m, which is explained by a relatively low concentration of bismuth active centres associated with germanium atoms (Ge – BAC). Pumping was performed by a 150-mW single-mode laser diode with a wavelength of 1.55 – 1.57-μm (for optical fibre amplifiers [13]) or by an erbium – ytterbium fibre laser with an output power of ~10 W (for bismuth fibre lasers [11]). As a result, amplification in the Ge – BAC band led to lasing with a maximum output power exceeding 1 W for discrete wavelengths within the range 1.625 – 1.775 μm (~150 nm wide) controlled by pairs of fibre Bragg gratings [10].

In the present work, we consider the possibility of using a bismuth fibre with a high germanium concentration to develop a laser continuously tunable within the Ge – BAC gain band 1.65 – 1.8 μm without changing optical elements of the scheme. Note that previously we have demonstrated the possibility of continuous broadband tuning within the spectral range 1.36 – 1.51 μm for the gain band of BACs associated with silicon atoms (Si – BAC) [14].

2. Scheme of a tunable bismuth fibre laser

The optical scheme of the developed laser is shown in Fig. 1. We used a ring cavity formed by broadband spectral elements. A double-clad erbium – ytterbium fibre laser (λ_p =

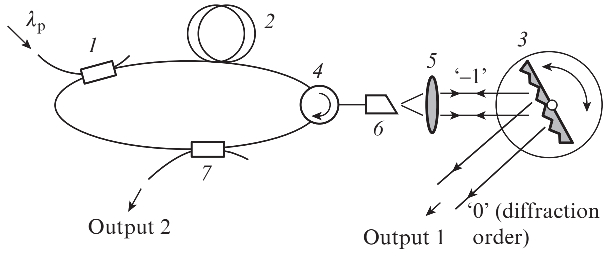

Figure 1. Scheme of the tunable bismuth fibre laser: (*1*) multiplexer; (*2*) bismuth fibre; (*3*) diffraction grating on a rotation stage; (*4*) fibre circulator; (*5*) microobjective; (*6*) angle-polished fibre connector (APC); (*7*) 30/70 fibre coupler.

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1.564 μm) was used as a pump source. The pump radiation was coupled into the ring cavity through a multiplexer (*1*), which was fabricated by thin-film technology and had a rather flat spectral characteristic in the range 1.63–1.8 μm. The maximum pump power (300 mW) was restricted by the radiation resistance of the multiplexer.

As an active laser medium, we used an MCVD germanosilicate fibre (50 mol % SiO_2/50 mol % GeO_2) doped with bismuth with a concentration below 0.01 wt % [10]. The fibre had a step index profile (numerical aperture NA $\approx$ 0.45) and the cutoff wavelength $\lambda_c \approx 1.2$ μm. The absorption in the Si–BACs and Ge–BACs bands in this fibre was $\sim$1 dB m^{-1} (Fig. 2), which is two-threefold lower than the value given in [10, 11] and indicates a lower concentration of these centres. Because of this, the length of the bismuth active fibre was increased to 55 m, which ensured almost complete absorption of pump radiation.

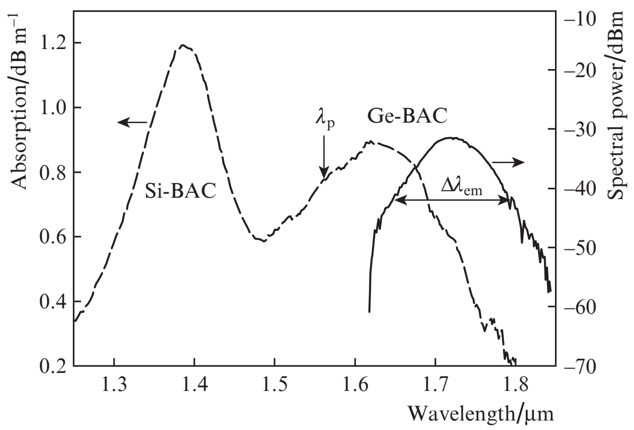

Figure 2. Absorption (dashed curve) and luminescence (solid curve) spectra of the bismuth active fibre (λ_p is the pump wavelength, $\Delta\lambda_{em}$ is the wavelength tuning range).

Analogously to [14], laser wavelength selection was performed using a 600 line mm^{-1} external diffraction grating [(*3*) in Fig. 1]. The laser radiation was coupled out from the ring cavity using a circulator (*4*), formed into a parallel beam $\sim$5 mm in diameter (NA = 0.2) by a microobjective (*5*) with compensated for spherical and chromatic aberrations, and sent to the dffraction grating. To eliminate Fresnel reflection, the output fibre end face [APC connector (*6*)] was angled at 7°. The first-order diffracted beam returned to the laser cavity (Littrow configuration), while radiation in the zero diffraction order was a parallel output laser beam. The laser wavelength was tuned by rotating the diffraction grating mounted on a motorised rotation stage. The laser wavelength linearly depended on the rotation angle in the entire tuning range with a coefficient of 49.4 nm deg^{-1}. The used rotation stage (Standa 8MR190-2) allowed wavelength tuning with a minimum step of $\sim$60 pm.

In the scheme presented in Fig. 1, 70 % of laser radiation was coupled out from the ring cavity through a broadband coupler (*7*). All elements of the scheme, except for the active fibre, were made based on a standard SMF-28e fibre. It should be noted that the used bismuth fibre is characterised by a relatively high numerical aperture, which leads to high ($\sim$3 dB) losses for coupling with low-aperture (including standard) fibres. These losses can be decreased by using intermediate matching fibres [15] or by forming a tapered fibre [16]. The simplest and simultaneously efficient method of decreasing the splice losses for germanosilicate fibres with considerably different mode fields is to increase the fusion time, which, due to germanium diffusion into the fibre cladding, leads to a local increase in the core diameter of the large-aperture fibre and to formation of the required tapered fibre [17, 18]. An increase in the fusion time allowed us to decrease the splice losses for the active fibre with an SMF-28e fibre from 3 to 0.5 dB. Taking into account the parameters of the optical elements used in the scheme and the splice quality, the total losses in the ring cavity (without losses in the active fibre) were about 10–12 dB.

The output laser spectra were measured using ANDO-6317B (long-wavelength edge 1.75 μm, spectral resolution 0.01 nm, large (exceeding 60 dB) dynamic range due to the use of double monochromatisation of radiation) and StellarNet RED-Wave-NIRx-SR (spectral range 1.5–2.0 μm, spectral resolution $\sim$10 nm, relatively small (below 30 dB) dynamic range) spectrum analysers.

3. Results

The laser spectra measured every 0.2° of the diffraction grating rotation ($\Delta\lambda \approx 10$ nm) are shown in Fig. 3a. At a pump power of 300 mW, the laser power at the fibre output near the maximum (around 1.7 μm) was $\sim$6 mW ($\sim$15 mW in the zero diffraction order). The tuning range of wavelength $\Delta\lambda_{em}$ was

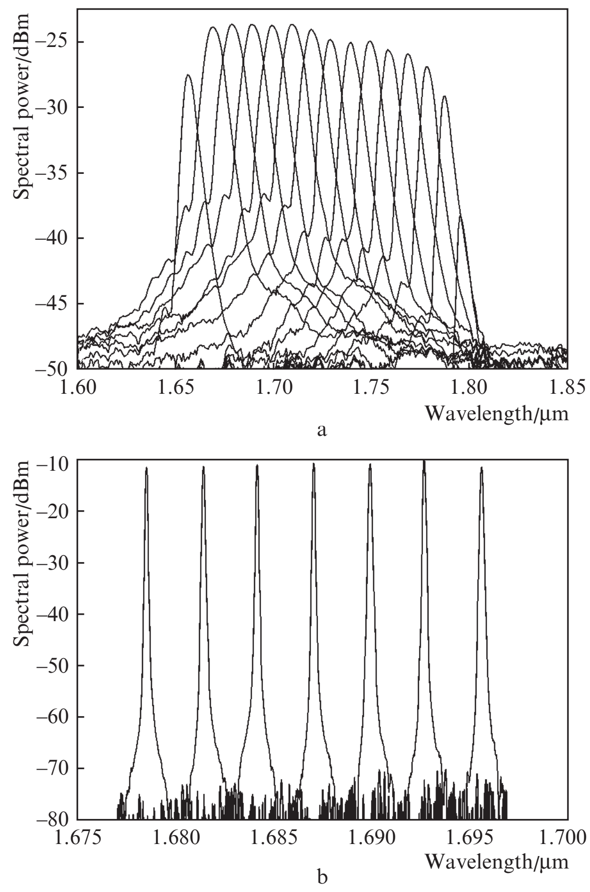

Figure 3. Laser spectra measured with a resolution of (a) 10 and (b) 0.02 nm with stepwise rotation of the diffraction grating.

~ 120 nm (1.66 – 1.78 μm) with an output power decreased by 3 dB; at the edges of the range 1.65 – 1.8 μm (150 nm), the power decreased by 15 dB.

Figure 3b shows the spectra measured by an ANDO-6317B spectrum analyser with a spectral resolution of 0.02 nm. The laser spectral linewidth (FWHM) was 0.07 nm, while the laser radiation spectral density exceeded the spontaneous emission level by more than 60 dB.

4. Conclusions

As far as we know, we have for the first time fabricated a single-mode bismuth fibre laser with an output power of ~ 15 mW in the first diffraction order smoothly tunable in the gain range of germanium-associated bismuth active centres, i. e., within the range 1.65 – 1.8 μm. Tuning was performed by rotating an external plane diffraction grating used in the Littrow configuration. In addition, the proposed ring configuration of the tunable laser has a single-mode fibre output, which, at a 300-mW pump power, provided an output power of ~ 6 mW (through a 30/70 fibre coupler). The active laser medium was a bismuth-doped fibre with a high germanium concentration and a length of ~ 55 m. The advantage of the laser is a narrow laser line (0.07 nm) with a considerable (more than 60 dB) excess of the laser power over the spontaneous emission power.

In our opinion, further optimisation of the laser scheme elements, including an increase in the radiation resistance of the broadband multiplexer used to couple in the pump radiation, will make it possible to increase the laser power and efficiency.

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