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Problems of development of tunable hybrid bismuth–erbium fibre lasers

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Abstract. **Experimental data and experience in the development of tunable fibre lasers based on active bismuth centres in silica glasses with different compositions and luminescence bands in the range 1200–1800 nm are considered. It is shown that continuous-wave narrow-band laser radiation with a milliwatt power (1–10 mW) covering this wavelength range can be obtained using hybrid fibre schemes and, probably, co-doping of matrices with bismuth and erbium. Continuously tunable bismuth fibre lasers with partially overlapping spectral ranges of 1270–1370, 1360–1540, and 1600–1800 nm are studied. Hybrid schemes of fibre lasers emitting in the spectral range from 1500 to 1600 nm, which includes the erbium luminescence band, are proposed.**

Keywords: *erbium, bismuth, single-mode fibre waveguide, fibre laser, tunable laser.*

1. Introduction

Bismuth-doped fibre lasers have been extensively studied since 2005 due to the fact that the main luminescence bands of bismuth lie within the wavelength range of 1200–1600 nm, which coincides with the wavelength range of optical fibre communications. These bands themselves are rather broad (200–300 nm), and the MCVD technology makes it possible to synthesise different silica glass matrices and shift the luminescence maxima, i. e., somewhat vary the wavelength ranges of lasing and optical amplification. The intensities of luminescence peaks also depend on the wavelength and pump power (see, for example, Table 1 in [1]). This provides additional possibilities for shifting the edges and peak positions of working wavelength ranges. Reviews [1, 2] present numerous data on lasing in the range 1150–1550 nm. The laser powers ranged from tens of milliwatts to 20 W and higher. It was found in [3, 4] that it is also possible to develop watt lasers emitting at longer wavelengths (1625–1775 nm). Apart from high-power lasers, of interest for communication engineering and fibre detectors are moderate-power (1–10 mW) lasers with continuous wide wavelength tuning. This initiated the development and study of widely tunable narrowband bismuth fibre lasers as an independent branch of laser engineering. For practical application, it is desirable to have similar or identical laser schemes with a common output fibre, and, if possible, with one spectrally selective control element.

2. Goals and objectives of the study

We will call hybrid lasers the lasers based on different-type active centres or optical schemes developed to extend the continuous wavelength tuning range using one control element and one or two output fibres. Bismuth active centres are attractive for hybridization due the broad (from ~1100 to ~1800 nm) luminescence bands in different silica glasses. Up to now, bismuth fibre lasers have been studied mainly to understand the physics of their operation and search for most efficient schemes for lasing with highest powers (1–20 W). Despite the significant advance in the development of bismuth lasers and optical amplifiers, the nature of the luminescence of bismuth active centres in silica glasses is still under study and refinement.

In our opinion, another important line of research, which follows from the studies of numerous bismuth lasers and their operation regimes, is the development of continuously tunable fibre lasers with narrow spectra and output powers of 1–10 W for information transfer, measurements, and sensor systems.

In the present work, we summarise the accumulated experience and data on bismuth-doped fibre lasers emitting in the region of the main bismuth luminescence peaks near 1300, 1400, and 1700 nm, as well as available data on erbium fibre lasers emitting near $\lambda = 1550$ nm, in order to develop a fibre scheme or a single fibre medium with Bi–Er co-doping, which will efficiently generate continuously tunable laser radiation in a broad wavelength range (1.2–1.8 μm) preferably without gaps in the tuning range and with only slightly changing output power in the process of tuning. Actual problems arising after development of continuously widely tunable lasers will be how to obtain single-frequency radiation with narrow homogeneously broadened lines and low amplitude and phase noise levels. The noise properties of single-frequency fibre lasers are of significant interest due to the possibility of using these sources in highly sensitive fibre-optic equipment and interferometric detectors, because fibre lasers do not have flicker or $1/f$ noise existing in diode lasers in which pump current is directly converted into laser radiation. An important problem of fabrication of silica glass laser fibres is the synthesis of preforms with a homogenous impurity composition for extrusion of fibres without clusterization and formation of

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additional undesired excited states in the energy spectrum of the active element, which can cause parasitic lasing and radiation pulsations.

Figure 1 shows the main laser wavelength ranges covered by Bi or Bi–Er lasers, as well as the ranges to be covered, including the region of the Er^{3+} luminescence band. For silica glasses used for fibre cores, we used the following designations: PSB (bismuth-doped phosphosilicate glass), LGSB [bismuth-doped germanosilicate glass with a low (1–5 mol%) germanium concentration], HGSB [bismuth-doped germanosilicate glass with a high (~ 50 mol%) germanium concentration], and ASG + Er (erbium-doped aluminosilicate glass with germanium or phosphorous).

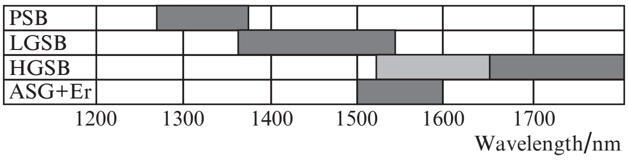

Figure 1. Continuous tuning ranges that can be covered by bismuth or hybrid Bi–Er lasers in the 1200–1800 nm range. The left column presents abbreviations of the main silica glass matrices.

Development of lasers with widely tunable wavelength can be useful for new applications in fibre engineering, for polling of multiple fibre sensors with wavelength multiplexing, in coherent DWDM, astronomy, medicine, etc. It is expected that, when solving the problems of creating tunable bismuth fibre lasers, one will develop single-mode fibres with optimal concentrations of active codopants, select and optimise all main components of fibre laser schemes (fibre multiplexers, pump wavelengths, filters, and selective elements), as well as fibre input and output couplers, in order to obtain broadband amplification of DWDM signals for communication and wavelength multiplexing systems.

At present, there exist data on optical amplification and lasing in the wavelengths range 1100–1800 nm, as well as on developed and studied schemes of bismuth fibre lasers continuously tunable in the wavelength ranges of 1366–1507 nm [5] and 1654–1794 nm [6]. First bismuth optical fibre amplifiers for the spectral range from 1600 to 1800 nm have been developed and tested [7]. Between these ranges, one observes the Er^{3+} luminescence band (near λ = 1550 nm), which can be used for 'stitching' the spectra of tunable lasers into one broad band. The edges of the bismuth luminescence bands in silicate glass fibres can noticeably shift depending on the aluminium, phosphorous, or germanium impurities, which, in combination with the choice of the pump wavelength and power, makes it possible to shift the edges of working wavelength ranges of lasers and amplifiers and to match wavelengths in laser schemes. The grey rectangle in Fig. 1 indicates the luminescence range of bismuth active centres in a fibre with a high germanium concentration, which potentially can also cover the erbium luminescence range of 1500–1600 nm. Co-doping of single-mode fibres with a high germanium concentration (HGSB) with bismuth and erbium allows one to extend the range of efficient optical amplification, including the C+L+U telecommunication bands; in particular, optical fibre amplifiers in a broad (1515–1775 nm) band with a gain of 15 dB at a pump laser diode power of 350 mW (λ = 1460 nm) were developed in [8].

At this stage, we consider the possibility of developing tunable hybrid bismuth and erbium lasers operating in separate wavelength ranges. The main attention is paid to the width of tuning subranges so that it would be possible to obtain their slight overlap and a wide total range of continuous tuning of narrowband laser radiation. Therefore, in the present work we present the refined data on obtained continuous tuning bands (Fig. 1), especially on their edges. Then, we consider the schemes of tunable bismuth lasers according to their spectral ranges.

3. Tunable bismuth lasers emitting in the 1270–1370 nm wavelength range

As was noted above, the laser transition wavelength in active bismuth centres strongly depend on their environment. In particular, amplification in a single-mode aluminosilicate glass fibre occurs in the wavelength range of 1100–1200 nm. Doping with phosphorus instead of aluminium shifts the amplification band to the range 1270–1370 nm. Because of this, to create and study a cw bismuth fibre laser emitting in the first of the ranges shown in Fig. 1, we used single-mode waveguides with a PSB matrix, the core of which was also slightly doped with germanium. The luminescence band maximum lay at $\lambda \approx$ 1300 nm (see also [1,2]).For pumping, it was possible to use radiation with a wavelength of 1240 nm.

The scheme of a tunable fibre laser emitting in the wavelength range 1270–1370 nm is shown in Fig. 2. A single-mode PSB fibre 60 m long with a bismuth concentration of ~0.01 wt% was used as an active bismuth waveguide. A broadband mirror at one cavity edge was a loop reflector or a fibre Sagnac mirror based on a 50/50 X-type coupler, while a spectrally selective and tuning mirror of the laser cavity at the other edge was a 600-line mm^{-1} holographic diffraction grating operating in the autocollimation regime. The grating operated in the minus first diffraction order, while the laser radiation was coupled out in the zero order. The pump radiation with λ = 1235 nm was coupled into the cavity through a spectrally nonselective 50/50 fibre coupler. A fibre Bragg grating (FBG) with a high reflection coefficient at the pump wavelength 1235 nm, which was placed near the output cavity edge, reflected unabsorbed pump radiation back to the active part of the fibre laser and formed a homogeneous pump intensity distribution. Despite losses on mirrors and in the pump coupler, the stored power was high enough to maintain lasing in a wide tuning range (1270–1370 nm).

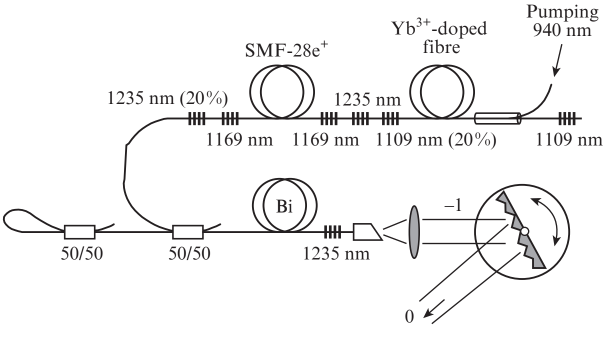

Figure 2. Scheme of a tunable fibre laser emitting in the range 1270–1370 nm (characters –1 and 0 here and in Fig. 11 are the diffraction orders).

As a pump source, we used a Raman laser consisting of a two-cascade Raman converter based on a standard single-mode SMF-28e$^+$ fibre with an output wavelength of 1235 nm, which, in turn, was pumped by an ytterbium laser with a power of 2 W at $\lambda = 1109$ nm. The ytterbium laser was pumped by a fibre-coupled diode laser at $\lambda = 940$ nm with a power of 2 W. The pump Raman laser power could reach 600 mW. 50% of the pump power, i. e., 300 mW at $\lambda = 1235$ nm, was coupled into the bismuth laser cavity through a 50/50 fibre-optic coupler. The pump power was limited from above by radiation resistance of the X-type couplers in the cavity. Since we did not need to achieve the maximum fibre laser power expected in the luminescence peak near $\lambda = 1300$ nm, then, at a lower pump power, we were able to extend the continuous wavelength tuning range and obtain lasing at the edges of the 1270–1370-nm range.

Note that we chose the simplest typical scheme of the tunable bismuth fibre laser for these experiments, so that it was possible to change only the active part and some FBGs.

Figure 3 presents the comb of the tunable narrowband bismuth laser lines in the wavelength range 1270–1370 nm. The laser power reaches ~ 50 mW in the centre of this range and decreases almost by an order of magnitude (to 5 mW) at the edges but, nevertheless, remains high enough for some applications. So strong change in the laser power makes it necessary to flatten the gain profile by using additional spectral units, namely, by including filters into the bismuth laser cavity [this will be done for the bismuth laser emitting in the next spectral range (Fig. 1)].

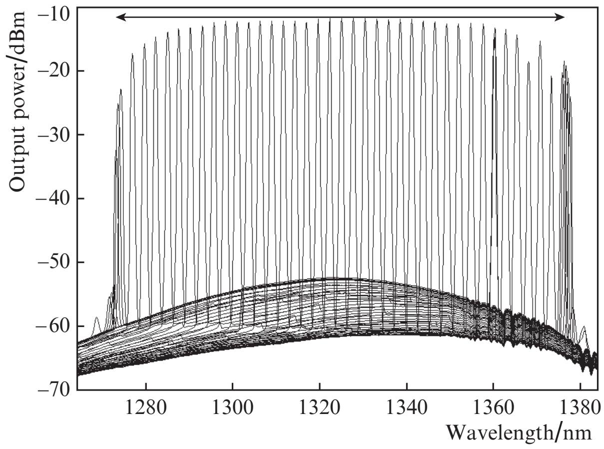

Figure 3. Continuous wavelength tuning spectra of a bismuth laser based on a PSB fibre.

We recorded laser lines near the centre wavelength 1327 nm with a higher (0.02 nm) resolution (Fig. 4). One can see that the lines are comparatively smooth and their shape is determined by the instrumental function of the spectrum analyser. It is still impossible to conclude whether they are homogeneously broadened (in this case, their shape should be Lorentzian). However, prerequisites for the formation of narrow lines with a prescribed coherence exist, because the emission at side frequencies of individual lines is suppressed by more than 40 dB. The distance between individual lines may be ~ 60 nm, which corresponds to $\Delta\nu \approx 100$ GHz.

Figure 5 shows a single line of the bismuth fibre laser peaking at $\lambda = 1327.36$ nm, which is recorded with a spectral resolution of ~ 0.01 nm. The line halfwidth is ~ 0.08 nm. The obtained data show that the developed and studied tunable bismuth laser emitting in the range of $\lambda = 1270–1370$ nm can be used in DWDM communication systems, in measuring technique, and in detectors with spectral resolution. However, for applications that require high-coherence radiation and noise level certification, it is necessary to perform additional studies.

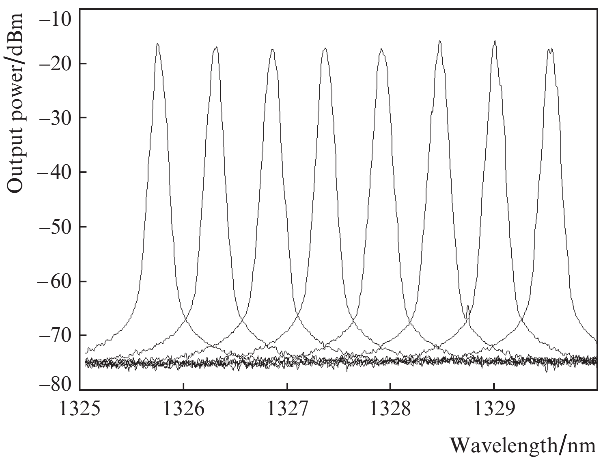

Figure 4. Continuous wavelength tuning spectra of a bismuth laser measured with an improved spectral resolution (0.02 nm). The distance between the lines (spectral channels) is 0.6 nm; the signal-to-noise ratio is no lower than 50 dB.

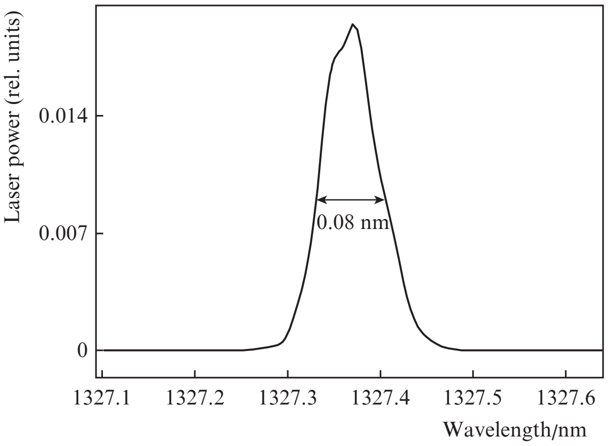

Figure 5. Single line of a bismuth fibre laser peaking near $\lambda = 1327.36$ nm recorded with a spectral resolution of ~ 0.01 nm.

4. Tunable bismuth laser emitting in the range 1350–1510 nm

Figure 6 shows the scheme of a continuously tunable bismuth laser emitting in the 1350–1510 nm range, which was developed and studied by us mainly in [5]. In the present work, we report the results of additional investigations. As well as in the previous case, we used the typical cavity scheme with broadband mirrors and a 600-line mm^{-1} diffraction grating for tuning the laser wavelength. Tuning was performed by rotating the grating, for which purpose the coupling-out and

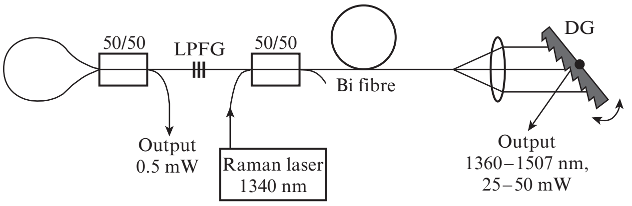

Figure 6. Typical scheme of a tunable fibre laser based on an LGSB fibre for the wavelength range 1360–1510 nm.

tuning unit was equipped with a motor controlled by electrical signals. The photograph of the motorised tuning system of the bismuth fibre laser emitting in the 1350–1510 nm range is shown in Fig. 7.

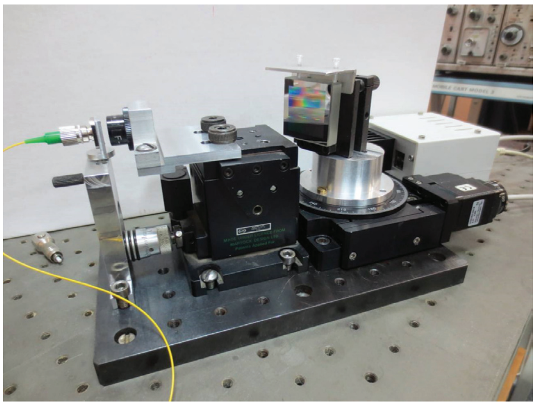

Figure 7. Photograph of the wavelength tuning unit of the bismuth fibre laser emitting in the range 1360–1550 nm, which consist of a diffraction grating and a motor for its rotation. The radiation is coupled out in the zero diffraction order (mirror-like with respect to the grating plane).

Taking into account the experience of working with the similar above-described bismuth laser tunable within the 1270–1370 nm wavelength range, we included in the scheme of the laser tunable from 1360 to 1510 nm (Fig. 6) the following changes necessary due to the change in the working wavelength range.

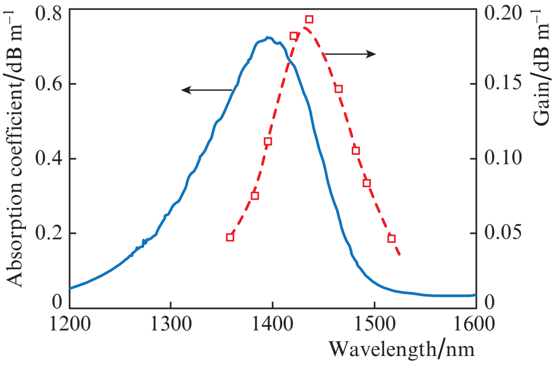

Figure 8. Working absorption and luminescence bands of an MCVD single-mode LGSB fibre with the composition 95% SiO_2, 5% GeO_2, 0.02% Bi_2O_3 for a laser tunable in the range 1360–1550 nm.

As a matrix of the single-mode waveguide, we used bismuth-doped LGSB glass with a low germanium concentration. The MCVD bismuth fibre was 65 m long. The fibre core consisted of 95% of SiO_2, 5% of GeO_2, and 0.02% of Bi_2O_3. The outer diameter of the fibre was 125 μm (without the polymer coating). The second mode cut-off wavelength was 1.1 μm. The absorption and gain spectra of the single-mode bismuth fibre are shown in Fig. 8. The length of the active bismuth-doped fibre was chosen from the condition of almost total absorption of ~ 300-mW radiation with $\lambda = 1340$ nm obtained at the output of the pumping system, which was similar to the system shown in Fig. 2 with the only difference that the Raman laser generated radiation at the required wavelength 1340 nm according to the absorption spectrum of bismuth centres.

To flatten the luminescence and gain profiles peaking at 1400 nm, we introduced into the cavity a long-period fibre grating (LPFG), which transformed the total profile as illustrated in Fig. 9 for the total spectrum of the bismuth fibre with the grating. This led to flattening of the total spectrum, suppression of lasing at wavelengths close to the luminescence band centre, and extension of the laser wavelength range at the tuning edges. Figure 10 shows the long-wavelength part of the comb of lines generated upon tuning. In fact, we obtained laser radiation up to wavelengths of 1540–1550 nm. Thus, the long-wavelength edge of the considered tuning range reached the gain band of Er^{3+} ions, which gives hope to obtain quasi-continuous wavelength tuning of bismuth lasers to $\lambda = 1550$ nm by using hybrid schemes.

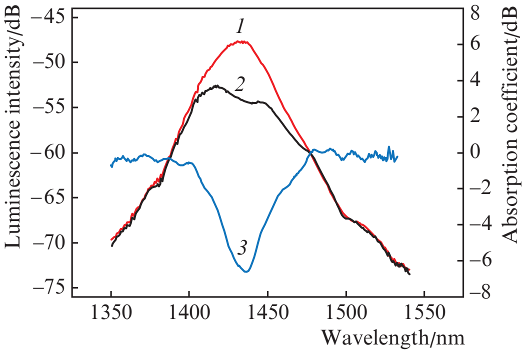

Figure 9. Luminescence spectra of (*1*) a single-mode LGSB fibre and (*2*) the same fibre with a built-in LPFG, as well as (*3*) LPFG absorption spectrum.

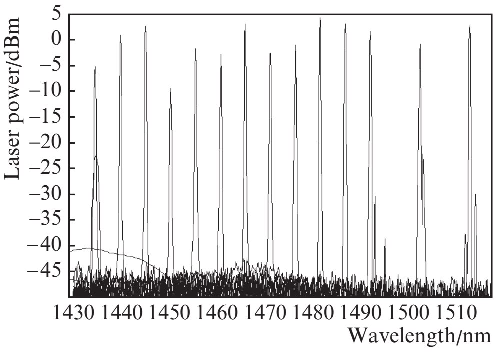

Figure 10. Typical shape of the spectral lines of a bismuth fibre laser upon wavelength tuning by the diffraction grating near the long-wavelength edge of the range 1360–1550 nm.

5. Bismuth lasers tunable in the wavelength range 1600–1800 nm

To obtain and study continuous wavelength tuning of bismuth lasers in the range 1600–1800 nm, we chose a ring scheme (Fig. 11), which is simpler than the scheme shown in Fig. 6 and emits a broader band. This scheme is commonly used for this scope of problems because it allows one to use the chosen active bismuth fibre and other elements, such as long-period gratings and/or FBG-based filters. The scheme can be designed without a highly reflecting mirror because the spectral broadbandness is determined only by the optical broadbandness of the single-mode fibre, and, as a spectrally selective element controlling the output wavelength, one can use one diffraction grating connected to the ring fibre cavity using a fibre circulator.

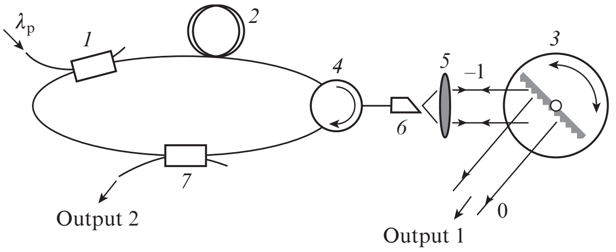

Figure 11. Ring scheme of a continuously tunable bismuth fibre laser for the wavelength range 1650–1800 nm [6]:
(*1*) 1480/1700 nm multiplexer for pump coupling; (*2*) bismuth HGSB fibre; (*3*) diffraction grating on a rotation stage; (*4*) fibre-optic circulator; (*5*) microobjective; (*6*) angle-polished connector; (*7*) 30/70 fibre output coupler.

The first results of investigations of a bismuth fibre laser tunable in the wavelength range 1600–1800 nm were obtained in [6]. In addition to the bismuth fibre laser scheme, we, for completeness of description, take from [6] the laser spectrum in the considered wavelength range (Fig. 12). For this range, we used a single-mode HGSB fibre with a high germanium concentration (50 mol% of SiO_2 and 50 mol% of GeO_2) doped with ~0.01 wt% of bismuth. The pump radiation with λ_p = 1564 nm was coupled into the cavity through a multiplexer fabricated by thin-film technology, which provides the maximum homogeneity of its spectral characteristic in the range 1600–1800 nm. The splice losses were 0.9 dB. The active bismuth fibre was 45 m long. The power coupled into the active fibre was limited by the radiation resistance of the multiplexer, which was 300 mW. A selective element formed by a plane diffraction grating was introduced into the cavity scheme using a fibre circulator. The laser radiation (30% of the optical power) was coupled out from the cavity through an X-type coupler. The total losses in the cavity were 10 dB, and the maximum output power was 6 mW.

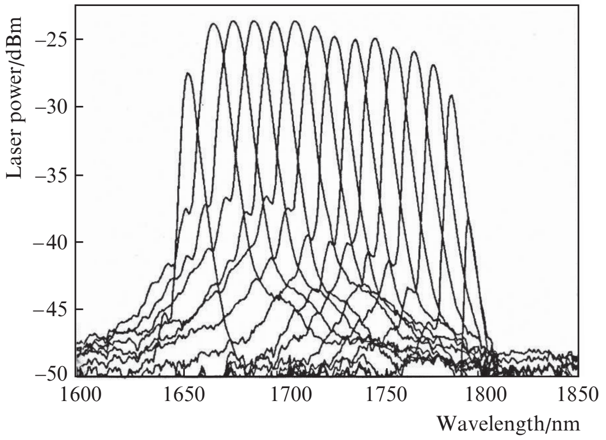

Figure 12. Spectrum of a tunable bismuth fibre laser with an HGSB core (50 mol% SiO_2, 50 mol% GeO_2, ~0.01 wt% Bi) [6].

The diffraction grating in the Littrow configuration was mounted on a motorised rotation stage, which provided the wavelength tuning accuracy of ~0.05 nm.

The width of the tuning range of the studied laser was 140 nm. Figure 12 presents the laser spectrum in the range 1654–1794 nm measured on a StellarNet spectrum analyser with a resolution of 10 nm.

It follows from Figs. 11 and 12 that the development of an active fibre waveguide or a hybrid fibre scheme for wavelength tuning from ~1540 nm to 1600 nm is still a technological and practical problem. It is this range in which the luminescence (lasing) band of Er^{3+} in different matrices lies. Let us consider the physical and technological possibilities that can be promising for tuning in the range 1540–1650 nm.

6. Possibilities of development of hybrid bismuth–erbium lasers for the wavelength range 1500–1650 nm

Figure 13 presents possible schemes of combined fibre systems for amplification and lasing in the range 1500–1650 nm. It is suggested to include the corresponding single-mode bismuth of bismuth–erbium fibre in a ring laser scheme similar to that shown in Fig. 11. Variants I, II, and III in Fig. 13 illustrate the possibility of using three types of active fibres, i. e., a fibre codoped with erbium and bismuth (I), a specially developed bismuth fibre (II), and a fibre with successive regions doped with bismuth and erbium.

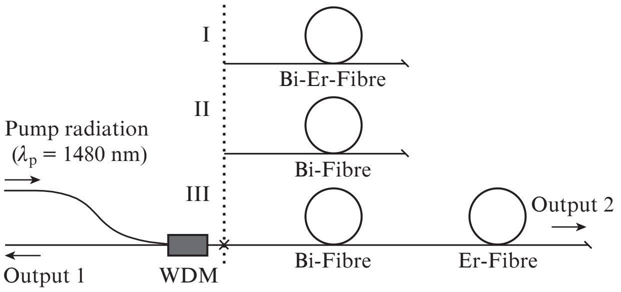

Figure 13. Possible variants of combined Bi–Er schemes of tunable lasers for the range 1500–1650 nm.

For simultaneous operation of different active centres in a single-mode fibre, one must use fibre optic spectral multiplexers and demultiplexers to couple in the pump radiation at λ = 1480 nm and couple out the tunable laser radiation, which will increase the device size. The ring scheme of a hybrid laser seems to be most convenient for searching for the best combination of active single-mode fibres and the configuration of their connection in the cavity. Therefore, an urgent problem is to develop and study fibres codoped with Er^{3+} ions and active bismuth centres (variant I). A serious technological problem is to develop a silica glass matrix for the single-mode fibre core and optimise the concentration of active bismuth and erbium centres for obtaining approximately identical luminescence and lasing intensities of these centres. The results obtained in [8] on the development and study of a broadband optical amplifier for the C+L+U ranges based on a single-mode fibre codoped with bismuth and erbium are promising for creating narrowband continuously tunable lasers for the range 1520 – 1650 nm.

We have studied the luminescence characteristics of one of the first single-mode fibres codoped with bismuth and erbium (variant I). Pumping was performed at λ = 1480 nm. Figure 14 shows the luminescence spectra of the single-mode fibre codoped with Bi and Er^{3+} at different pump powers. One can see that, at powers from 50 to 175 mW (Fig. 14a), the luminescence intensity insignificantly depends on the pump power and more strongly depends on the wavelength; in particular, the maximum difference in the luminescence intensity at different wavelengths exceeds 10 dB mainly due to the too intense luminescence of Er^{3+} in its spectral band (1530 – 1570 nm). The bismuth luminescence wing with a maximum at λ = 1700 nm is rather gradual and can be used for uniform and smooth wavelength tuning of lasers or optical amplifiers. The results presented in Fig. 14 indicate that further investigations should be focused mainly on the improvement of the fabrication technology of active fibres and on the optimisation of the bismuth and erbium concentrations, as well as, probably, on the matrix composition and the impurity distribution over the fibre length.

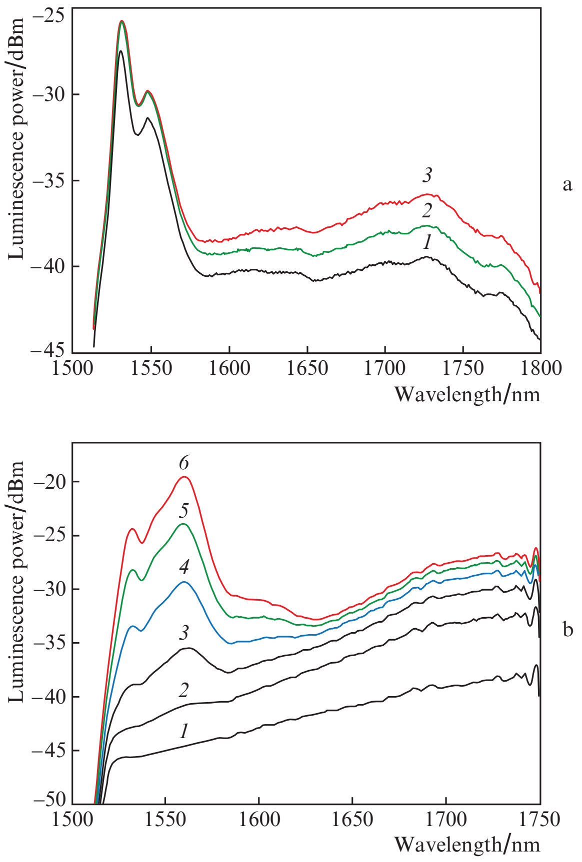

Figure 14. Luminescence spectra (a) of single-mode fibre №238 codoped with Bi and Er^{3+} at pump powers of (*1*) 50, (*2*) 100, and (*3*) 175 mW and (b) of an active fibre composed successively of single-mode bismuth (65 m) and erbium (7 m) fibres (variant III) in the case of luminescence excitation and recording from the side of the Bi fibre at pump powers of (*1*) 100, (*2*) 130, (*3*) 160, (*4*) 190, (*5*) 220, and (*6*) 250 mW; λ_p = 1480 nm.

For comparison with the considered variant, Fig. 14b shows the luminescence spectra of a combined active fibre composed of successively connected single-mode bismuth (65 m) and erbium (7 m) fibre segments (variant III) in the case of luminescence excitation and recording from the side of the Bi fibre. One can see that the luminescence power at a pump power of 200 mW (curve 4) changes in the spectral range 1530 – 1650 nm by no more than 5 dB and that it is possible to obtain continuous wavelength tuning in this range. As was shown in the previous section, the gain in the ring scheme of the tunable bismuth laser in this case must exceed the losses (10 dB) related to the use of fibre-optic elements.

Figure 14 b shows that the luminescence band at a pump power of 100 mW is broad, rather smooth, and belongs to only bismuth active centres, while backward luminescence of the erbium-doped fibre segment is absent. Thus, in scheme III (Fig. 13) pumped from the side of the Bi fibre, it is possible to use only the bismuth-doped HGSB fibre without the erbium-doped segment, because the bismuth luminescence in this case occurs in a wide spectral range including the luminescence band of Er^{3+} ions. The bismuth luminescence band in a single-mode fibre with a high germanium concentration is denoted by a grey rectangle in Fig. 1 as a promising variant for tunable bismuth lasers. The short-wavelength edge of this band lies at λ = 1525 nm (Fig. 14b), because of which variant II (Fig. 13) of tunable lasers with only a single-mode bismuth-doped HGSB fibre seems to be real.

Figures 13 and 14 indicate that the main problems in creating hybrid or combined tunable bismuth – erbium lasers will be the choice and optimisation of the composition of single-mode silica glass fibre cores for matching the working spectral ranges, the level of doping with active impurities, and the topology of the fibre laser scheme with separation of active regions and pumping directions. We plan to report the results of the study of these problems in a separate publication.

7. Conclusions

We have analysed the progress in fabricating continuously tunable bismuth fibre lasers of moderate powers (1 – 10 mW) emitting in the wavelength range 1200 – 1800 nm. It is shown that this range can be covered by four main luminescence bands of bismuth active centres near 1300, 1400, and 1700 nm and Er^{3+} bands in the range 1500 – 1600 nm. The optimum scheme for broadband wavelength tuning of bismuth fibre lasers is the ring fibre scheme with a minimum number of elements and one tuning element based on a diffraction grating controlling the spectrum. The spectra of continuously tunable narrowband laser radiation in the partially overlapping ranges 1270 – 1370, 1360 – 1540, and 1650 – 1800 nm are presented. It is shown that the fourth tuning range, i. e., 1500 – 1650 nm, which includes the Er^{3+} luminescence band, can be covered using one of the hybrid schemes of fibre lasers based on a single-mode fibre codoped with bismuth and erbium or on one HGSB fibre. It is also possible to use successively connected segments of bismuth and erbium fibres.

It is necessary to perform additional studies of the technology of active fibres doped with bismuth and erbium, as well as to develop and optimise the schemes of tunable fibre lasers, especially for the wavelength range 1500–1650 nm.

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