LETTERS

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Bismuth/erbium-doped germanosilicate fibre amplifier with a bandwidth above 200 nm

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Abstract. **Using bismuth/erbium-doped optical fibre, we have fabricated the first optical amplifier with a gain of ~10 dB in a wide spectral range (1520–1770 nm), which covers the C-, L- and U-bands.**

Keywords: *fibre-optic communication, fibre amplifier, bismuth.*

1. Introduction

The transmission capacity of state-of-the-art optical fibre communication systems reaches 10 Tbit s^{-1}. Prototype systems may have an order of magnitude higher capacity (up to ~100 Tbit s^{-1}). Nevertheless, it is becoming clear that, to meet the need in contemporary society for information, which grows every year by 30% to 40%, the available transmission capacity will be insufficient in a few years. It is worth noting that the transmission capacity of the existing communication systems probably cannot be significantly increased because there is a fundamental limit determined by a number of factors, including the Shannon limit, the optical nonlinearity of fibres and the bandwidth of optical amplifiers [1–3]. All the above suggests that research effort should focus on ways of increasing the transmission capacity of optical fibre communication systems.

As a consequence, possible ways of raising the fibre transmission capacity to a level of ~1 Pbit s^{-1} and above have recently been the subject of extensive discussion (see e.g. Dianov [4] and references therein). At the 42nd European Conference on Optical Communication (ECOC 2016, 18–22 September 2016, Düsseldorf, Germany), this issue received a great deal of attention. One of the proposed ways to resolve it is to employ a broader spectral range for information transfer through optical fibres. It is known that, at present, the vast majority of the long-haul high-speed optical fibre communication systems use a rather narrow spectral range, 1530–1610 nm, which includes the C-band (1530–1565 nm) and L-band (1565–1625 nm) and is determined by the gain band of the erbium-doped fibre amplifier (EDFA). Note that, in principle, information can be transferred throughout the spectral range 1300–1700 nm (400 nm in width), where the optical loss in standard telecom fibres is sufficiently low, under 0.4 dB km^{-1}. Until recently, however, there were no efficient fibre amplifiers for this spectral range. Such optical amplifiers – key elements of modern optical fibre communication systems – have been demonstrated only recently, using thulium- and bismuth-doped fibres [5–8]. Unfortunately, these optical amplifiers have not attracted considerable interest of optical fibre communication network designers because they have a rather narrow gain band, which does not overlap with the gain band of the EDFA. From this point of view, optical amplifiers having a bandwidth larger than that of the EDFA (~80 nm) and covering both the C- and L-bands are of most practical interest. It is worth noting that the available basic components of existing communication networks will then be sufficient for successful implementation of such an amplifier, without considerable financial investments.

Given that this issue is of great current interest, we have carried out a study aimed at making a prototype of such an optical amplifier. To this end, we fabricated a germanosilicate fibre doped with bismuth and erbium ions to concentrations of ~100 ppm, using a bismuth-doped GeO_2-rich (~50%) germanosilicate fibre (whose basic characteristics were described in detail elsewhere [9]), which was used previously to make an optical amplifier operating in the 1700-nm range [7]. The erbium concentration in the fibre was low for two reasons: to prevent concentration quenching of luminescence and reach an optical gain approaching the level of active bismuth centres. The latter condition was essential for obtaining a broad optical gain band without parasitic lasing in the gain region of the erbium ion.

2. Results

Figure 1a shows the absorption spectra of the bismuth-doped fibre and a bismuth/erbium-doped fibre of similar composition. It is seen that the addition of erbium ions to the bismuth-doped fibre produces a characteristic absorption band centred around 1535 nm. The absorption bands observed in the spectra of both fibres at 1400 and 1650 nm are known to be due to active bismuth centres.

Figure 1b presents characteristic luminescence spectra of the fibres. The luminescence band of the fibre codoped with bismuth and erbium is broader than that of the bismuth-doped fibre by more than 70 nm. As a result, the overall width (FWHM) of the luminescence band of the bismuth/erbium-doped fibre reaches more than 200 nm. The present results

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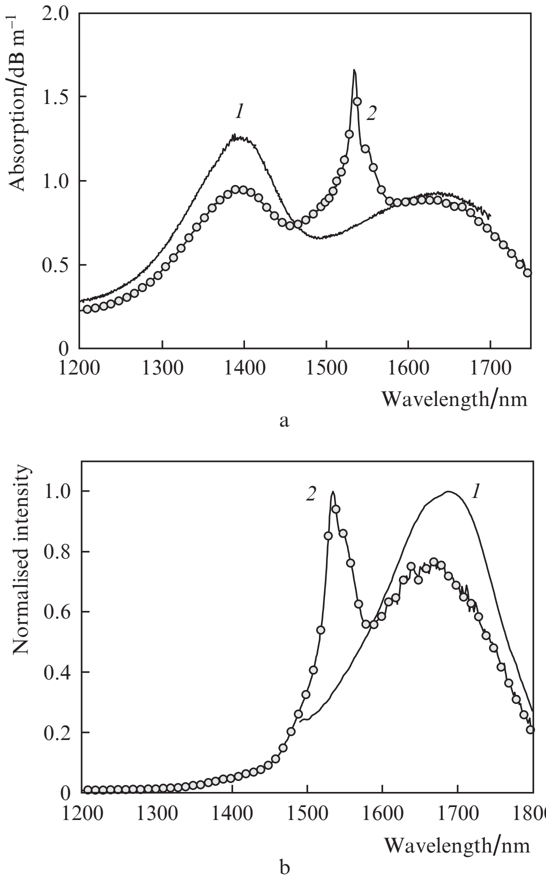

Figure 1. (a) Absorption and (b) luminescence spectra of the (*1*) bismuth- and (*2*) bismuth/erbium-doped fibres.

suggest the possibility of making a fibre-optic amplifier with an extremely large gain bandwidth [10].

Using the codoped fibre, we made an optical amplifier schematised in Fig. 2. The signal and pump light were coupled into and outcoupled from the fibre using a wavelength-division multiplexer. To suppress undesirable lasing, optical isolators were placed at the amplifier input and output. The pump source used was a commercially available laser diode emitting at a wavelength of 1460 nm with 350 mW of output power. This wavelength was chosen because it falls in the absorption bands of both the erbium ion and active bismuth centres, so no additional pump sources are needed.

The gain spectrum of the optical amplifier was measured with a signal source that was fabricated by us using superluminescent bismuth- and erbium-doped fibre sources and had

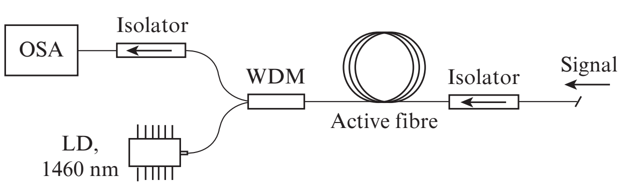

Figure 2. Schematic of the bismuth/erbium-doped fibre amplifier: (WDM) wavelength-division multiplexer; (LD) laser diode; (OSA) optical spectrum analyser.

an emission spectrum in the range from 1500 to 1800 nm. The signal at the amplifier input had the form of a comb consisting of 1-nm-wide peaks, which was 'cut' from the emission spectrum of the signal source as a result of reflection from a set of Bragg gratings with reflectivity near 100% at different wavelengths (the emitter design was described in detail elsewhere [7]). The input signal power was 30 μW, i.e. the amplifier operated in the small-signal regime.

The optical gain was evaluated by comparing the input and amplified signal intensities. The emission spectra of the input and amplified signals were measured with an optical spectrum analyser. The resultant gain spectrum of the bismuth/erbium-doped fibre under pumping at 1460 nm and 300 mW is presented in Fig. 3. Even though the optical gain has a maximum (~30 dB) near 1535 nm, it is seen that an optical gain near 10 dB can be obtained in a rather wide spectral range (1520–1770 nm). For comparison, Fig. 3 shows the gain spectrum of the bismuth-doped fibre. The decrease in the optical gain of the bismuth/erbium codoped fibre in the range 1650–1750 nm, which leads to a smoother shape of the optical gain spectrum, is due to signal absorption by erbium ions in an excited state [10].

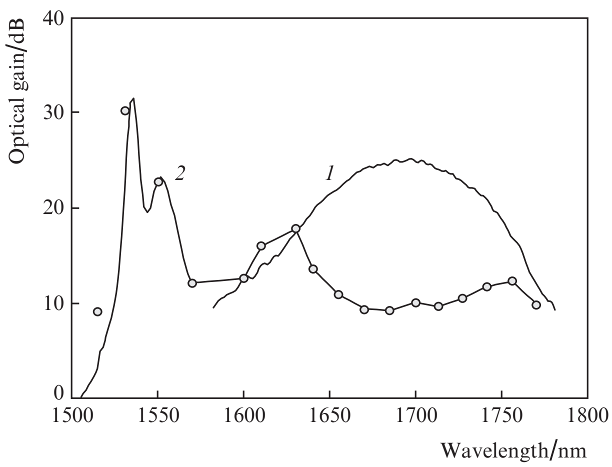

Figure 3. Optical gain spectra of the (*1*) bismuth- and (*2*) bismuth/erbium-doped fibres.

It should be noted that this communication presents pioneering work in the area in question. We believe that further research aimed at producing fibres with an optimal relationship between active elements (erbium and bismuth) will allow media with improved output characteristics to be obtained.

Thus, we have demonstrated the first optical amplifier with a gain bandwidth over 200 nm in the spectral range 1500–1800 nm under laser diode pumping at a wavelength of 1460 nm and power of ~300 mW. The amplifier was made using a bismuth/erbium-doped germanosilicate fibre.

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