Quantum Electronics **48** (11) 989–992 (2018)

LETTERS

https://doi.org/10.1070/QEL16887

25 Gb s^{-1} data transmission using a bismuth-doped fibre amplifier with a gain peak shifted to 1300 nm

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Abstract. **Using a bismuth-doped aluminosilicate fibre laser tunable in the range 1130–1210 nm, we have examined the effect of pump wavelength on the gain spectrum of bismuth-doped phosphosilicate fibres in the range 1220–1400 nm. At a pump wavelength of 1195 nm, we obtained a peak gain wavelength of 1300 nm, which is near the centre of the standard range for O-band transmission (1270–1320 nm) in fibre-optic communication links, in particular between data centres. Using a bismuth-doped phosphosilicate fibre amplifier pumped at 1195 nm, we have demonstrated that the transmission distance for a signal from a semiconductor laser diode directly modulated at 25 Gb s^{-1} [on–off keying (OOK) modulation] can be increased for G.652 fibre from the standard 10 to 80 km or even more.**

Keywords: *bismuth-doped fibre amplifier, data transmission, tunable laser, bismuth-doped fibre laser, gain spectrum.*

1. Introduction

One transmission window of silica-based optical fibres, widely used in telecommunication systems for data transmission, is located in the 1.3 μm range. In optical communications, this range is commonly referred to as the O band.

At present, the O band is utilised for point-to-point data transmission over distances shorter than 120 km because, owing to the relatively low cost of optical fibre, this type of connection ensures a substantial reduction in capital and operating expenditures due to the absence of expensive dense wavelength division multiplexing (DWDM) components and the simple configuration of the communication system. The zero-dispersion point of silica glass and, accordingly, the zero-dispersion wavelength of many silica-based optical fibres in communication links already in use or being deployed are located in about the same range. Owing to this, in the case of O-band transmission there is no need for dispersion compensation in the optical or electronic domain, which also substantially reduces expenditure.

Because of the increase in data transmission rate due to the increase in both the number of channels in coarse wavelength division multiplexing (CWDM) systems and the channel data rate, the available power per channel decreases, as does the receiver sensitivity, which in turn leads to a decrease in the maximum transmission distance without optical amplification. Thus, an O-band fibre amplifier would allow for a further increase in data transmission rate, without passing into the C or L band (1530–1610 nm).

For this reason, interest in bismuth-doped phosphosilicate fibre amplifiers operating near 1.3 μm has continued unabated since the first report [1]. Nevertheless, the use of such amplifiers for data transmission has long been significantly limited by the fact that the peak gain wavelength, in the range 1320–1340 nm at the pump wavelengths used previously [2, 3], did not meet the standards accepted in the field [4], according to which the transmission range should be 1270–1310 nm. Note that the O band extends from 1270 to 1350 nm.

This paper examines the effect of the pump wavelength on the peak gain wavelength of active bismuth centres in phosphosilicate fibres at excitation wavelengths in the range 1130–1210 nm, which has not been used previously to pump amplifiers based on such fibres. For our experiments, we built what appears to be the first bismuth-doped aluminosilicate fibre laser tunable over this wavelength range. It was tuned using a diffraction grating. The need for such a laser stems from the lack of commercially available single-mode cw laser diodes with sufficient power (200–300 mW) and wavelengths covering the entire range in question. Note that there are commercially available laser diodes emitting in some portions of this range, but they are very expensive.

Data obtained by us were used to make a bismuth-doped fibre amplifier with a 19-dB gain at $\lambda \approx 1300$ nm and a pump wavelength of 1195 nm. With this amplifier, we demonstrated the feasibility of test signal transmission at an on–off keying (OOK) modulation rate of 25 Gb s^{-1}.

2. Tunable bismuth-doped aluminosilicate fibre laser

Figure 1 shows a schematic of the tunable bismuth-doped aluminosilicate fibre laser. The laser cavity was formed by a diffraction grating mounted on a rotation stage and a loop mirror produced using a fibre coupler. The 3-dB width of the spectrum returned by the grating (ruled at 600 lines mm^{-1}) to the cavity was ~0.5 nm, and the loop mirror ensured a broad reflection spectrum. To minimise the optical loss in the grating, we used a polarisation controller, which allowed us to adjust the plane of polarisation of light in the cavity. The

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Received 25 October 2018
Kvantovaya Elektronika **48** (11) 989–992 (2018)
Translated by O.M. Tsarev

pump source used was a single-mode Yb-doped fibre laser delivering 6 W of output power at $\lambda = 1.08$ μm in continuous mode. The active fibre was core-pumped through a fusion spliced wavelength-division multiplexer (WDM). The maximum pump power used was limited by the optical damage threshold of the coupler: ~2 W.

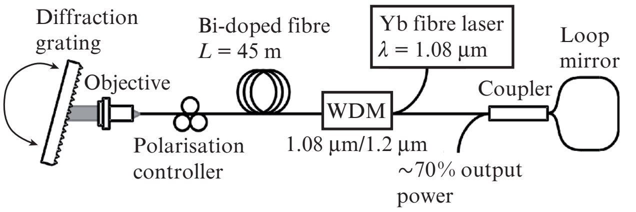

Figure 1. Schematic of the tunable bismuth-doped fibre laser.

As the gain medium of the laser, we used aluminosilicate fibre produced by the MCVD process and doped with less than 0.01 wt % bismuth. It was similar to that described previously [5], but its absorption coefficient at $\lambda = 1.06$ μm (in the band of active bismuth centres) was increased to 0.7 dB m^{-1}. The length of the active bismuth-doped fibre was 45 m, which ensured pump absorption above 10 dB.

At room temperature, we were able to tune the laser wavelength over the range 1130–1210 nm. As a result, the output power varied from 30 mW at the edges of this range to 55 mW in its centre. This power was obviously insufficient for measuring gain spectra of bismuth-doped phosphosilicate fibres. Taking into account that the lasing efficiency of bismuth-doped aluminosilicate fibres is a strong function of temperature [6], we decided to cool the active fibre to liquid nitrogen temperature (77 K). To this end, the active fibre was coiled and immersed in liquid nitrogen in a vessel. Figure 2a shows laser emission spectra at different angles of the diffraction grating. Like at room temperature, the spectral tuning range was ~80 nm (1130–1210 nm). A typical lasing linewidth was 0.2 nm. At grating orientations corresponding to the edges of the tuning range, we observed not only the main line but also free-running laser operation in the range 1.14–1.16 μm (in Fig. 2a, such spectra are represented by dotted lines).

Figure 2b shows the laser output power as a function of wavelength for the liquid nitrogen cooled fibre at a pump power of 2 W. Note that, in the range 1130–1206 nm, the output power exceeded 200 mW, which was sufficient for measuring gain spectra.

3. Effect of pump wavelength on the gain spectrum

Using the tunable bismuth-doped fibre laser and a Raman laser emitting at 1230 nm, we measured gain spectra of a bismuth-doped phosphosilicate fibre having parameters similar to those reported elsewhere [2]. Figure 3 shows the gain spectra and peak gain wavelengths ($\lambda_{\max}$) at different pump wavelengths (λ_p). It is seen that, with decreasing λ_p, the gain peak shifts to shorter wavelengths. Note that, at pump wavelengths in the range 1200–1230 nm, the peak height remains unchanged. The use of shorter pump wavelengths reduces the gain peak height. Our data demonstrate a considerable inhomogeneous broadening in the absorption and gain spectra of the bismuth-doped phosphosilicate fibres. The present results have the important implication that, using pump wavelengths near 1200 nm, one can obtain a gain spectrum well overlapping with the O band, which is used for data transmission in fibre-optic communication links. Another important consequence of the large inhomogeneous broadening of the bismuth band is that simultaneous pumping at a few wavelengths, e.g. at 1200 and 1270 nm, would be expected to cause an almost twofold increase in gain bandwidth: from 40 to ~75 nm.

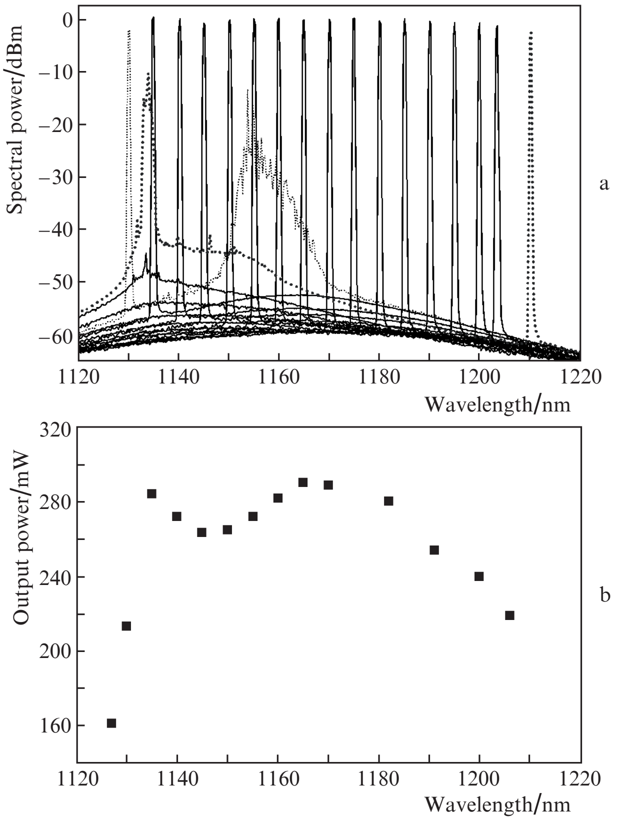

Figure 2. (a) Output spectra of the bismuth-doped fibre laser measured with a 1-nm resolution at different angles of the diffraction grating; (b) laser output power as a function of wavelength for the liquid nitrogen cooled fibre.

Using the present data on the optimal pump wavelength, we carried out an experiment aimed at test signal transmission over a fibre-optic link using a bismuth-doped fibre amplifier.

4. O-band transmission using a bismuth-doped fibre amplifier

Test signal transmission using a bismuth-doped fibre amplifier was first demonstrated in the 1.45 μm range [7]: an optical signal OOK-modulated at a rate of 10.6 Gb s^{-1} using an electro-optical modulator was transmitted over 80 km. Taengnoi et al. [8] recently reported a test transmission of a set of signals at a few wavelengths in the range 1.32–1.37 μm, modulated at 9.9 Gb s^{-1} by electro-optical modulators. Transmission over 100 and 120 km was performed using a 150-m-long bismuth-doped phosphosilicate fibre amplifier. They used pumping at two wavelengths, 1240 and 1267 nm, which allowed them to reach a gain of 22 dB at $\lambda = 1.35$ μm (maximum of the band). However, the wavelengths used for trans-

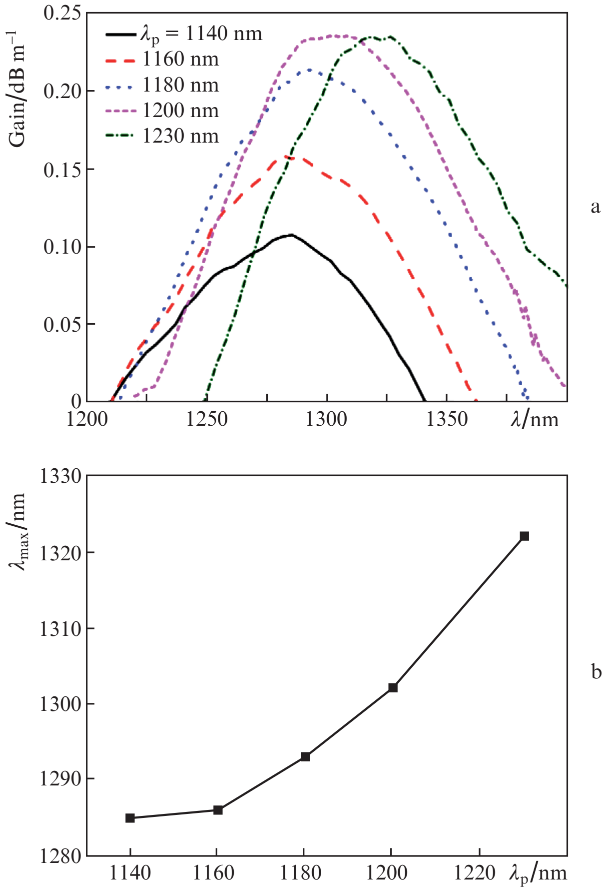

Figure 3. (a) Gain spectra and (b) peak gain wavelengths at different pump wavelengths.

mission do not meet the standards accepted in the field, which restrict the operating range to 1270–1310 nm.

In this paper, we report the fabrication of a bismuth-doped phosphosilicate fibre amplifier with a gain band optimised according to relevant standards and describe testing of the amplifier for data transmission. Such an amplifier, pumped at 1195 nm, was used by us for test signal transmission at 25 Gb s^{-1} through G.652 fibre. A semiconductor laser (SL) with an emission wavelength of 1310 nm and output power of 6 dBm was directly OOK-modulated by a $2^{31} - 1$ pseudorandom binary sequence (Fig. 4a). The electrical signal was provided by a Viavi ONT-604 optical network tester [a device for pseudorandom sequence generation and bit error rate (BER) testing]. The optical signal was launched into an ~80 km length of the fibre (loss, 0.33 dB km^{-1}; zero dispersion wavelength, ~1320 nm) and, after passing the transmission link, was amplified in a bismuth-doped fibre amplifier (BDFA). For simplicity, we used an amplifier comprised of four components: optical isolator (ISO), wavelength division multiplexer (WDM), pump laser (800 mW of output power, λ_p = 1195 nm) and 80-m length of bismuth-doped phosphosilicate fibre (Fig. 4b). Note that the peak transmission wavelength of the WDM was chosen to be near 1272 nm, so the WDM acted as a gain flattening filter as well and ensured a uniform gain at a level of 2 dB in the range 1270–1310 nm.

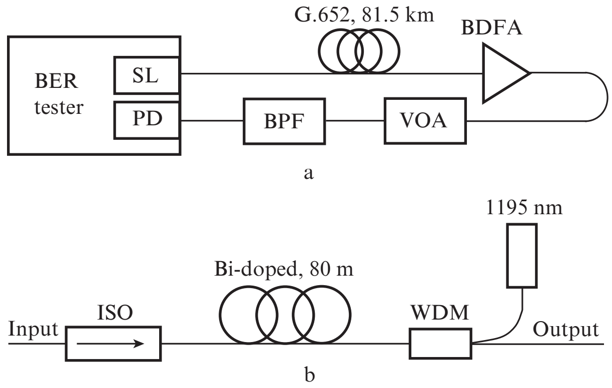

Figure 4. Schematics of the (a) test transmission configuration and (b) bismuth-doped fibre amplifier.

The gain in the amplifier was 19 dB, its maximum power was 20 dBm, and the noise figure was 5 dB. Before detection, the signal was passed through a variable optical attenuator (VOA), and spontaneous emission was filtered off by a 4-nm optical bandpass filter (BPF) (such filters are used in CWDM and LAN WDM systems). Next, the signal was detected by a photodetector (PD). Figure 5 shows the bit error rate (BER) as a function of the signal power at the receiver input. Even though the curve obtained in a test configuration containing an 81.5-km length of the fibre differs from that obtained with no fibre, near the limit of the error correction algorithm in the KP4 FEC standard (BER = 2.6×10^{-4}) the signal transmitted through the fibre segment has a power penalty under 0.5 dB.

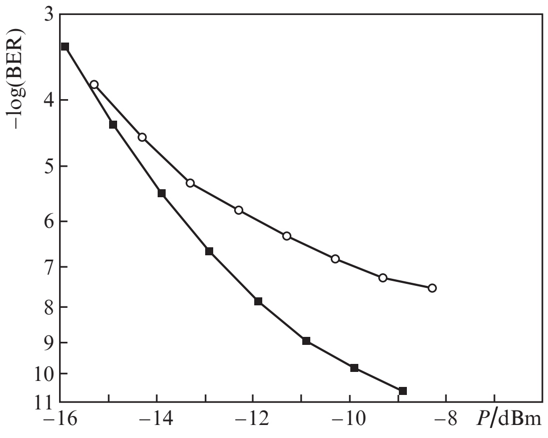

Figure 5. Bit error rate as a function of the signal power at the receiver input in the test configuration containing an 81.5-km length of the fibre (○) and with no fibre (■).

In the near future, we will complete our work and present results of testing such an amplifier in a link consisting of eight standard LAN WDM channels in the O band using ~25 GBd four-level pulse amplitude modulation (PAM-4) signals, which will ensure an overall transmission capacity of ~400 Gb s^{-1}.

5. Conclusions

Using a bismuth-doped aluminosilicate fibre laser tunable in the range 1130–1210 nm, we have examined the effect of pump wavelength on the gain spectrum of bismuth-doped phosphosilicate fibres. The results indicate that pump wavelength optimisation allows the gain peak of such fibres to be shifted to ~1300 nm. Using an optimised amplifier and directly modulated laser diode, we have demonstrated 25 Gb s^{-1} test signal transmission over ~80 km at a wavelength of 1310 nm. The measured power penalty near the limit of the error correction algorithm in the KP4 FEC standard ($BER = 2.6 \times 10^{-4}$) was under 0.51 dB, with a minimum BER of $\sim 2 \times 10^{-7}$, which leaves an appreciable reserve in designing a communication system, suggesting that further increase in transmission distance is possible. The amplifier demonstrated here offers the possibility of increasing the signal transmission distance in the IEEE 802.3bs-2017 standard at the indicated rate from the standard 10 to 80 km. It is important to note that, in the experiment described here, we used commercially available transmit/receive components for the range in question, which are already employed in fibre-optic communication links. Therefore, the use of such an amplifier will not require adopting new standards or designing new components.

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