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Transient processes and cross talk in an O-band bismuth-doped fibre amplifier

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Abstract. **This paper reports on transient processes and cross talk (cross modulation) in an O-band (1260 – 1360 nm) bismuth-doped phosphosilicate fibre amplifier. Times characterising dynamic parameters of the amplifier at a pump wavelength of 1.23 μm have been determined experimentally. Data have been obtained on the effect of the modulation frequency *Ω* of one of the channels in the range 10 Hz to 1 MHz on the cross-talk intensity in another channel. The data, in combination with numerical calculation results, show that the cross talk in the Bi-doped fibre amplifier is insignificant at modulation frequencies *Ω* above 100 kHz. Our results demonstrate that O-band Bi-doped fibre amplifiers are potentially attractive for practical application in multichannel high-speed data transmission systems.**

Keywords: *bismuth, amplifier, optical fibre, O band, data transmission.*

1. Introduction

Research interest in bismuth-doped optical fibre has been aroused by a need for active media capable of amplifying light in wavelength ranges where rare-earth-doped fibres are essentially inapplicable. In the almost fifteen years since the advent of the first Bi-doped fibre [1], a considerable amount of research has been done, which has made it possible to create a range of Bi-doped fibres intended mainly for near-IR optical amplifiers (see e.g. reviews in Refs [2 – 4] and references therein). In recent years, more and more research [5 – 7] has focused on a detailed analysis of the behaviour of such amplifiers in pilot communication systems due to the considerable attention paid to this issue by commercial companies (see e.g. Ref. [8]).

In this respect, bismuth-doped fibre amplifiers for the spectral region around 1.3 μm (O band) are of obvious interest because using them can considerably increase the transmission capacity and range of the existing intra-city communication systems. Recently, we have demonstrated a compact O-band bismuth-doped fibre amplifier (BDFA) which ensures a 20-dB gain under pumping at a wavelength of 1230 nm with a record high gain efficiency: 0.18 dB mW^{-1} [9]. Its performance has been improved owing to the use of a W index profile fibre [10]. The main characteristics of the BDFA suggest that it has considerable potential for practical application in data transmission. However, attempts to implement such amplifiers in wavelength-division multiplexing (WDM) systems that involve controlled WDM channel removal or addition processes, traffic redirection, protective switching, etc. may encounter problems related to dynamic amplifier characteristics because control of one channel may influence the power and noise in other channels. This may lead to cross talk related to gain saturation due to a decrease in population inversion in the optical amplifier.

This has stimulated research on the dynamic properties of the BDFA, in particular, analysis of the transient gain dynamics in the BDFA, and investigation of the cross talk resulting from inverted population modulation.

2. Experimental procedure and calculation

Figure 1 shows a schematic of the experimental setup used to study dynamic characteristics of the BDFA. The amplifier used a copropagating 1230-nm laser diode pump configuration, i.e. the signal and pump light propagated in the same direction. The length of the active fibre was 110 m [9]. To study the dynamic properties of the BDFA, we used two signals, at wavelengths of 1.31 (modulated) and 1.33 μm (continuous), which were coupled into the BDFA using a multiplexer (M). The possibility of using relatively widely spaced signals was due to the fact that the bismuth-doped active fibre had a homogeneously broadened gain profile.

Modulation of the signal at λ = 1.31 μm was controlled using an Agilent 33220A function generator (which modulated the drive current of the laser diode). To study transient processes, we used modulation by rectangular pulses; for cross-modulation effects, sinusoidal pulses were used. The power of the modulated signal (at λ = 1.31 μm) was varied from 0.1 to 0.8 mW, which was sufficient for varying the population of the metastable level (proportional to the gain and inversely proportional to the input signal intensity), i.e. for the transition of the BDFA from the small-signal regime to gain saturation (see Ref. [9] for details). Unlike the modulated signal, the continuous (test) signal at a wavelength of 1.33 μm had a power of just 50 μW and had no effect on the laser level population. Thus, the test signal propagating through the BDFA was expected to vary under the effect of the modulated signal. Both signals were detected by photodetectors, PDA 10D-EC and PDA 10CS-EC, connected to an Agilent DSO-X 2024A oscilloscope. To separate the signals transmitted

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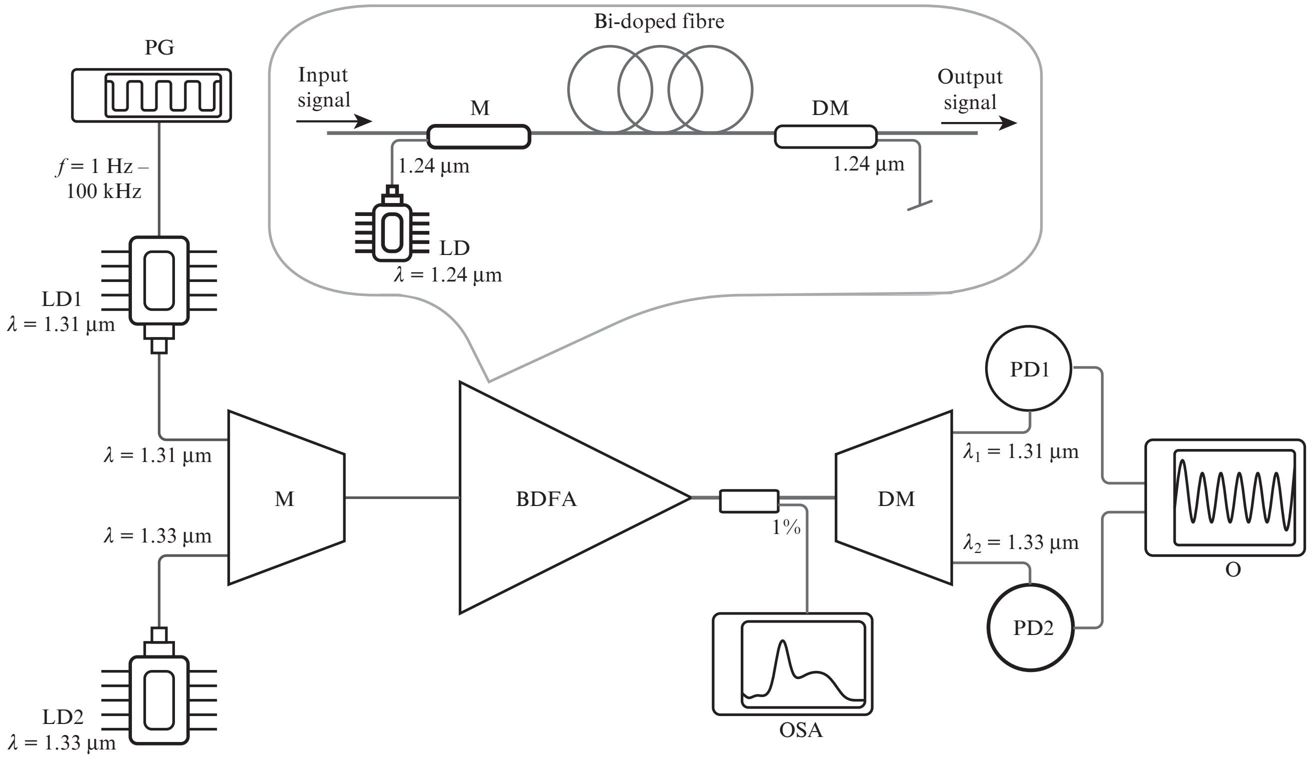

Figure 1. Schematic of the experimental setup: (PG) pulse generator; (PD1, 2) photodetectors; (LD, LD1, LD2) pump laser diodes for modulating and test light, respectively; (O) oscilloscope; (M) multiplexer; (DM) demultiplexer; (OSA) optical spectrum analyser. Inset: schematic of the BDFA.

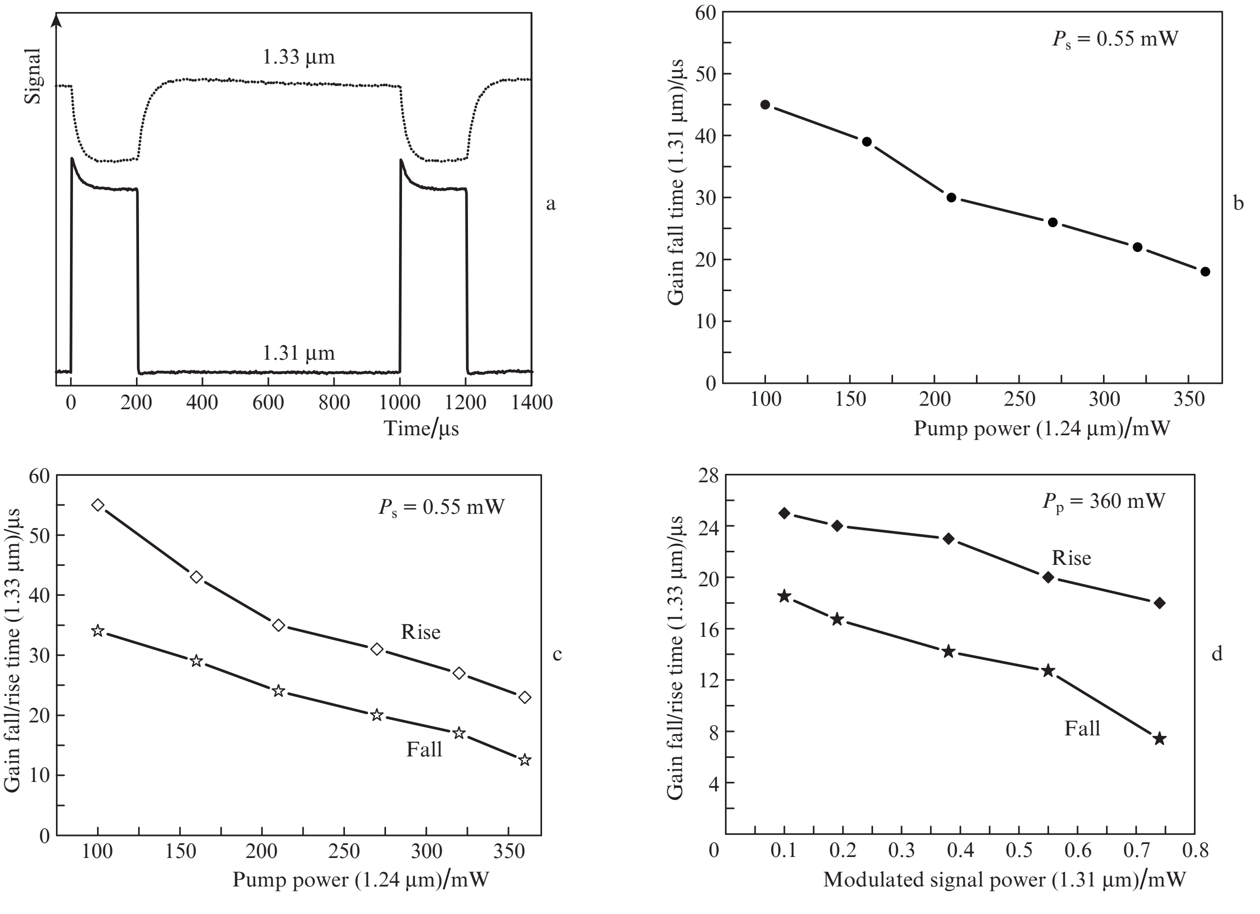

Figure 2. Oscilloscope traces of the signals at the amplifier output (a), signal fall/rise times at wavelengths of 1.31 (b) and 1.33 μm (c) as functions of pump power, and 1.33-μm signal fall/rise times as functions of 1.31-μm signal power at constant pump power (d).

through the BDFA, a demultiplexer (DM) was placed at the amplifier output (Fig. 1). Variations in the test signal were measured at various modulation frequencies (from 10 Hz to 1 MHz) of the signal at $\lambda = 1.31$ μm. The output spectra of the BDFA were recorded using an Agilent 86140B optical spectrum analyser.

Figure 2a shows typical oscilloscope traces of signals at the BDFA output in the case of modulation by rectangular pulses at a frequency of 1 kHz. It is seen that, after amplification in the BDFA, the leading edges of the output pulses at a wavelength of 1.31 μm have gain spikes (followed by an exponential fall-off) due to changes in laser level population [11]. Turning on the signal at $\lambda = 1.31$ μm reduced the continuous (test) signal at $\lambda = 1.33$ μm by 25% to 30%, whereas after turning it off the test signal returned to its original level. The observed changes can be accounted for by variations in inverted population. From the decay of the 1.31-μm signal, we can estimate characteristic times needed for the BDFA to reach a steady state, which is related to gain saturation.

Figure 2b shows the gain saturation time as a function of pump power. As expected, with increasing pump power the gain saturation time (the time needed for the amplifier to reach a steady state) decreases from 45 to about 18 μs. The gain saturation time of the test signal was determined in a similar manner. Its variation with pump power (Fig. 2c) proved to be similar to that for the modulated signal. After the modulated signal (of 0.55-mW power) was turned off, the gain of the test signal returned to its original level in 25–50 μs (depending on the pump power), which slightly exceeded the gain recovery time. Figure 2d shows the gain saturation time of the test signal as a function of input modulated signal power. It is seen that, with increasing 1.31-μm signal power, the gain saturation/recovery time of the test signal at a given pump power decreases, as would be expected. In this case, the gain saturation and recovery times of the test signal also differed little.

Knowing parameters of the bismuth-doped fibre (saturation power at the pump wavelength $P_{\rm p}^{\rm sat} = 0.9$ mW, and lifetime of active centres at the laser level $\tau = 720$ μs), we can estimate the limiting gain recovery time using the following relation [11]:

$$\tau_{\rm rec} = \frac{\tau}{1 + P_{\rm p}/P_{\rm p}^{\rm sat}} = \frac{720}{390} \approx 1.8\ \mu\text{s}.$$

An estimate of the time needed for the BDFA to reach a steady state showed that $\tau_{\rm sat} \approx \tau_{\rm rec}$. The estimated limiting parameters correlate with experimental data.

To study cross talk (cross modulation) effects in the bismuth-doped fibre amplifier, the signal at a wavelength of 1.31 μm was modulated using a sinusoidal pulse generator. Figure 3 shows the shapes of the modulated and test signals at frequencies $\Omega = 100$ Hz and 1 MHz. It is seen that the sine modulation ($\Omega = 100$ Hz) of the 1.31-μm signal leads to the corresponding modulation of the 1.33 μm test signal. As expected, the observed effect strongly depends on Ω: at the higher frequency, test signal modulation is markedly weaker, and vice versa.

To assess the effect of cross-modulation processes on the operation of any amplifier, we use the dependence of the ratio of the minimum and maximum optical powers of the signal, G, on modulation frequency. Such a dependence (Fig. 4) was obtained experimentally for the BDFA under consideration. It is seen that the cross-modulation process has a marked effect on the test signal for $\Omega < 10$ kHz and is insignificant for $\Omega > 100$ kHz. Analogous results were obtained by Taengnoi et al. [12] for a similar amplifier.

To numerically assess the effect of cross modulation on the operation of the BDFA at a pump wavelength of 1240 nm,

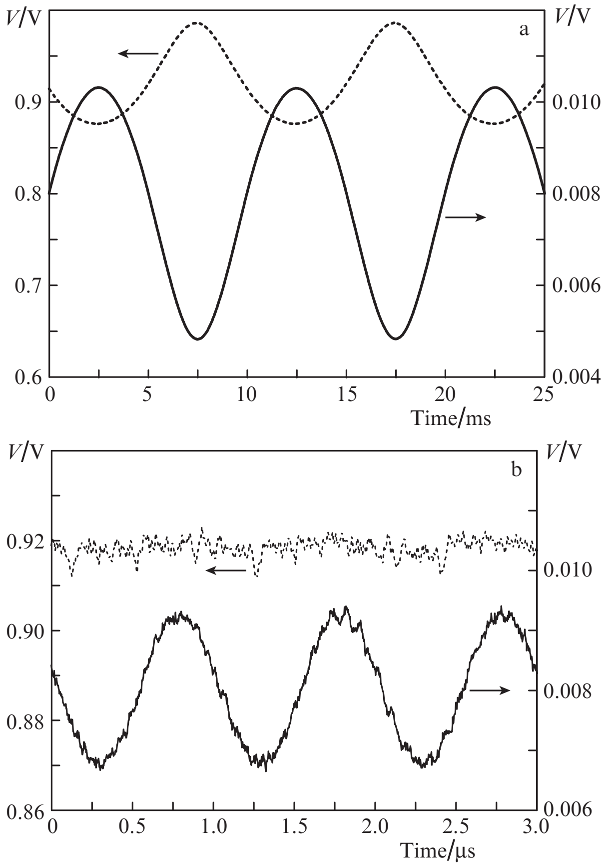

Figure 3. Oscilloscope traces of the modulated (solid line, $\lambda = 1.31$ μm) and test (dashed line, $\lambda = 1.33$ μm) signals at the BDFA output at modulation frequencies Ω = (a) 100 Hz and (b) 1 MHz.

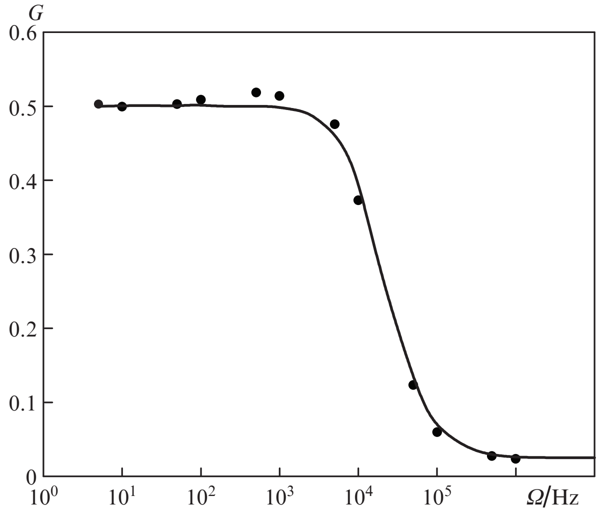

Figure 4. Ratio of the minimum and maximum optical powers of the test signal, G, as a function of input signal modulation frequency, Ω (the solid line represents the calculation results and the filled circles represent the experimental data).

we used a typical quasi-two-level system of energy levels in which the population density of the excited-state level can be described by the standard equation [11]

$$\frac{\mathrm{d}N_2(z,t)}{\mathrm{d}t} = \frac{1}{\tau}[\tau W_{12}N - \tau(W_{12} + W_{21})N_2(z,t) - N_2(z,t)], \quad (1)$$

where

$$\tau W_{12} = \sum_{i=P,S_1,S_2} \frac{1}{1+\eta_i}\frac{P_i(z,t)}{P_{\mathrm{sat}}(\nu_i)}; \quad \tau(W_{12} + W_{21}) = \sum_{i=P,S_1,S_2} \frac{P_i(z,t)}{P_{\mathrm{sat}}(\nu_i)};$$

$$\eta_i = \frac{\sigma_{\mathrm{e}}(\nu_i)}{\sigma_{\mathrm{a}}(\nu_i)}; \quad P_{\mathrm{sat}}(\nu_i) = \frac{h\nu_i}{\tau[\sigma_{\mathrm{e}}(\nu_i) + \sigma_{\mathrm{a}}(\nu_i)]}A_{\mathrm{eff}};$$

τ is the excited-state lifetime of the active centres; $\sigma_{\mathrm{e,a}}(\nu_i)$ is the emission (e) or absorption (a) cross section at frequency ν_i; N is the active centre concentration; $A_{\mathrm{eff}} = \pi\bar{\omega}_i^2/\Gamma_i$ is the effective area taking into account the fundamental mode field diameter $(\bar{\omega}_i^2)$ and the overlap Γ of the given mode profile with the active centre distribution profile; P, S_1 and S_2 are the pump, test signal, and main signal powers, respectively; and W_{12} and W_{21} are the probabilities of stimulated transitions from the ground state to an excited state and back, respectively.

Under the assumptions that the BDFA self-saturation is negligible and that the time needed for the excited state population to change is longer than the time needed for light to pass through the BDFA, the rate equations for the pump and signal powers can be represented as follows [11]:

$$\frac{\mathrm{d}P_i(z,t)}{\mathrm{d}z} = \left[(1+\eta_i)\frac{N_2(z,t)}{N} - 1\right] \times \alpha(\nu_i)P_i(z,t) - \alpha_{\mathrm{BG}}(\nu_i)P_i(z,t), \quad (2)$$

where $\alpha(\nu_i) = \Gamma_i\sigma_{\mathrm{a}}(\nu_i)N$ is the small-signal absorption by the bismuth-related active centres (active absorption) and $\alpha_{\mathrm{BG}}(\nu_i)$ is the optical background loss. Equations (1) and (2) were solved numerically for pumping and forward propagation signals in the Python ecosystem, which involves ScyPy libraries containing algorithms, in particular those for solving differential equations (see www.scipy.org). In numerical calculation, we used the parameters given below. The cross-sectional active centre distribution and the profile of the fundamental mode of the bismuth-doped fibre were taken from a previous report [9].

Absorption cross section at the pump wavelength (1.24 μm), $\sigma_{\mathrm{a}}(\nu_{\mathrm{p}})$/m^2	2.36×10^{-24}
Emission cross section at the pump wavelength (1.24 μm), $\sigma_{\mathrm{e}}(\nu_{\mathrm{p}})$/m^2	8.75×10^{-25}
Absorption cross section at the modulated signal wavelength (1.31 μm), $\sigma_{\mathrm{a}}(\nu_{S_1})$/m^2	1.86×10^{-24}
Emission cross section at the modulated signal wavelength (1.31 μm), $\sigma_{\mathrm{e}}(\nu_{S_1})$/m^2	1.86×10^{-24}
Absorption cross section at the test signal wavelength (1.33 μm), $\sigma_{\mathrm{a}}(\nu_{S_2})$/m^2	1.47×10^{-24}
Emission cross section at the test signal wavelength (1.33 μm), $\sigma_{\mathrm{e}}(\nu_{S_2})$/m^2	1.94×10^{-24}
Luminescence lifetime, τ/μs	720
Length of the active fibre, L/m	110
Active absorption at the pump wavelength, $\alpha(\nu_{\mathrm{p}})$/dB	0.45
Active absorption at the modulated signal wavelength, $\alpha(\nu_{S_1})$/dB	0.41
Active absorption at the test signal wavelength, $\alpha(\nu_{S_2})$/dB	0.4
Optical loss at the pump wavelength, $\alpha_{\mathrm{BG}}(\nu_{\mathrm{p}})$/dB	0.06
Optical loss at the modulated signal wavelength, $\alpha_{\mathrm{BG}}(\nu_{S_1})$/dB	0.03
Optical loss at the test wavelength, $\alpha_{\mathrm{BG}}(\nu_{S_2})$/dB	0.03
Pump power, P/mW	350
Modulated signal power, S_1/mW	1
Test signal power, S_2/ μW	100
Overlap integral of the fundamental mode and dopant profile, A_{eff}/μm^2	20

The calculation results are presented in Fig. 4. Good agreement between the calculation results and experimental data suggests that the model under consideration adequately describes processes in the BDFA. Subsequently, it can be used for analysis of the operation modes of the BDFA and more detailed optimisation of its parameters.

3. Conclusions

In this paper, we have presented experimental data and numerical calculation results for transient amplification processes and gain modulation-induced cross talk in a BDFA. Characteristic gain fall and recovery times have been determined as functions of modulated signal power and pump power. We have shown that, by varying the pump and signal powers, the characteristic gain fall and rise times can be tuned over the ranges 10–30 and 20–60 μs, respectively. Cross-modulation experiments have demonstrated that the BDFA is essentially insensitive to cross talk at frequencies above 100 kHz, which suggests that the amplifier has considerable potential for use in high-speed data transmission.

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References

1. Dianov E.M., Dvoyrin V.V., Mashinsky V.M., Umnikov A.A., Yashkov M.V., Gur'yanov A.N. *Quantum Electron.*, **35**, 1083 (2005) [*Kvantovaya Elektron.*, **35**, 1083 (2005)].
2. Bufetov I.A., Melkumov M.A., Firstov S.V., Riumkin K.E., Shubin A.V., Khopin V.F., Guryanov A.N., Dianov E.M. *IEEE J. Sel. Top. Quantum Electron.*, **20**, 0903815 (2014).
3. Firstov S.V., Alyshev S.V., Riumkin K.E., Khegai A.M., Kharakhordin A.V., Melkumov M.A., Dianov E.M. *IEEE J. Sel. Top. Quantum Electron.*, **24**, 0902415 (2018).
4. Thipparapu N., Wang Y., Wang S., Umnikov A., Barua P., Sahu J. *Opt. Mater. Express*, **9**, 2446 (2019).
5. Mikhailov V., Melkumov M.A., Inniss D., Khegai A.M., Riumkin K.E., Firstov S.V., Afanasiev F.V., Yan M.F., Sun Y., Luo J., Puc G.S., Shenk S.D., Windeler R.S., Westbrook P.S., Lingle R.L., Dianov E.M., DiGiovanni D.J., in *Proc. Optical Fiber Communication Conference (OFC) 2019, OSA Techn. Digest* (Optical Society of America, 2019) paper M1J.4.
6. Taengnoi N., Bottrill K.R.H., Thipparapu N.K., Umnikov A.A., Sahu J.K., Petropoulos P., Richardson D.J. *J. Lightwave Technol.*, **37**, 1826 (2019).

7. Melkumov M.A., Mikhailov V., Khegai A.M., Riumkin K.E., Firstov S.V., Afanasiev F.V., Guryanov A.N., Yan M.F., Sun Y., Luo J., Puc G.S., Shenk S.D., Windeler R.S., Westbrook P.S., Lingle R.L., DiGiovanni D.J., Dianov E.M. *Quantum Electron.*, **48**, 989 (2018) [*Kvantovaya Elektron.*, **48**, 989 (2018)].
8. https://www.bbcmag.com/breaking-news/ofs-demonstrates-o-band-amplification-with-bismuth-doped-fiber.
9. Firstov S.V., Khegai A.M., Kharakhordin A.V., Alyshev S.V., Firstova E.G., Ososkov Y.J., Melkumov M.A., Iskhakova L.D., Evlampieva E.B., Lobanov A.S., Yashkov M.V., Guryanov A.N. *Sci. Rep.*, **10**, 11347 (2020).
10. Firstov S., Khegai A., Riumkin K., Ososkov Y., Firstova E., Melkumov M., Alyshev S., Evlampieva E., Iskhakova L., Lobanov A., Khopin V., Abramov A., Yashkov M., Guryanov A. *Opt. Lett.*, **45**, 2576 (2020).
11. Desurvire E. *Erbium-Doped Fiber Amplifiers: Principles and Applications* (New Jersey: Wiley, 2002).
12. Taengnoi N., Bottrill K.R.H., Hong Y., Wang Y., Thipparapu N.K., Sahu J.K., Petropoulos P., Richardson D.J., in *Proc. Conference on Lasers and Electro-Optics, OSA Techn. Digest* (Optical Society of America, 2020) paper SW3R.2.