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Self-*Q*-switched ytterbium-doped fibre laser with intracavity spectral conversion

D.A. Grukh, A.E. Levchenko, A.S. Kurkov, V.M. Paramonov

***Abstract*.** **A pulsed fibre laser is fabricated which is based on an active fibre with a multielement cladding and an additional single-mode fibre providing nonlinear feedback. The peak output power of the laser is ~ 1 kW for 20-ns pulses. The emission spectra of the laser with additional fibres having different nonlinear and dispersion properties are investigated.**

Keywords: *ytterbium-doped fibre laser, Q-switching, nonlinear feedback.*

1. Introduction

Fibre lasers of different configurations are being extensively investigated at present [1]. The most popular among them are ytterbium-doped fibre lasers pumped into a cladding by high-power semiconductor lasers. Due to their high efficiency and cw output power achieving $\sim 10^3$ W, ytterbium-doped fibre lasers have found applications in communication systems, material machining, medicine and other fields. At the same time, pulsed ytterbium-doped lasers provide high peak output powers, extending the scope of their applications. It should be emphasised that of most interest is a pulsed laser operating without using any bulk elements (modulators, switches, etc.) because it preserves the advantages of a fibre laser such as compactness and the absence of optical alignment units.

One of the types of pulsed all-fibre lasers is self-*Q*-switched fibre lasers. Their operation is based on the suppression of constant feedback and the use of nonlinear feedback appearing due to SBS caused by backward Rayleigh scattering [2]. Note that because, as a rule, the length of an active fibre forming the resonator is insufficient for obtaining feedback, additional fibre elements are used in a pulsed laser. Thus, in [3] the laser with an additional fibre loop in the resonator was used, the fibre being pumped in the fibre core. In [4], this principle was extended to cladding-pumped fibre lasers. In both cases, 2–10-ns pulses with the peak power amounting to 10 kW were generated. In [5], an undoped single-mode fibre was spliced to the output of a Nd^{3+}-doped active fibre. In this case, not only the development of pulsed lasing should be expected but also the conversion of the emission spectrum of the laser due to nonlinear effects appearing in the additional undoped fibre because of the high peak output power. It is obvious that the type of emission spectrum conversion depends on the output power of the laser and optical properties and length of the fibre used.

In this paper, we present the results obtained by using additional fibres of different types in the resonator of the pulsed laser. Note that the conversion of the emission spectrum of the laser increases the possibility of irradiation of a pump source by high-power laser radiation, which can result in the source damage. For this reason, we used a fibre with a multielement cladding for optical decoupling the laser and pump source.

2. Experimental

Figure 1 shows the scheme of a pulsed fibre laser. The active medium of the laser was a fibre with a mutielement cladding (GTWave fibre) [6], which consisted of two fibres in optical contact surrounded by a common polymer jacket with the refractive index lower than that of silica. One of the fibres has an active core doped with Yb^{3+} ions, where lasing appears. The second (passive) fibre is made of silica and serves to couple pump radiation, a part of which transfers then to the active fibre cladding. Because only the active fibre cladding is in optical contact with the passive fibre, laser radiation does not enter the passive fibre. Therefore, the pump source and fibre laser prove to be optically decoupled. Among the advantages of a multielement-clad fibre is also the possibility to control radiation emitted from both faces of the active fibre. The concen-

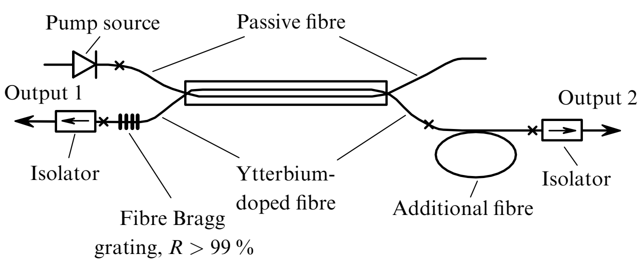

Figure 1. Scheme of a pulsed fibre laser (crosses indicate fibre splices).

D.A. Grukh, A.E. Levchenko, A.S. Kurkov, V.M. Paramonov Fiber Optics Research Center, A.M. Prokhorov General Physics Institute, Russian Academy of Sciences, ul. Vavilova 38, 119991 Moscow, Russia; e-mail: kurkov@fo.gpi.ru

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Table 1. Parameters of fibres used in the study.

Sample number	Core composition	GeO_2 molar concentration (%)	Core diameter/μm	Zero dispersion wavelength/μm	Optical losses at 1.1 μm/dB km^{-1}
1	SiO_2/GeO_2	6	5.5	1.45	1
2	GeO_2/SiO_2	75	2	>2	120
3	SiO_2	–	5	1.15	70

tration of ytterbium ions in the active fibre was 4×10^{19} cm^{-3}, the diameter of the fibre core was 6 μm, the diameter of the silica cladding was ~ 120 μm, and the length of the active fibre was 15 m.

To one of the ends of the active fibre, a fibre Bragg grating (FBG) with the high reflectivity was spliced, and to another – an additional fibre to enhance a backscattered signal. A constant feedback caused by reflection from the fibre ends was suppressed with the help of optical isolators spliced to fibre outputs. Pumping was performed by a 976-nm laser diode array ('Milon-Laser', St. Petersburg). The pump source power was limited by the rated maximum power transmitted by the isolator equal to 300 mW.

To enhance a backscattered signal, three different fibres of length 20 m were used: with the germanosilicate glass core, the germanate glass core, and the silica core and microstructure cladding formed by four layers of holes. The parameters of these fibres are presented in Table 1. The wavelength of the zero chromatic dispersion of germanosilicate and germanate glass fibres was estimated from the refractive index profile, and was measured by the interference method [7] for the fibre with a microstructure cladding.

3. Experimental results

We obtained repetitively pulsed lasing using fibre No. 1 with parameters close to those of telecommunication fibres (Table 1). The laser pulse duration at outputs 2 and 1 (Fig. 1) was ~ 20 and 3 ns, respectively. The oscillograms of pulses are shown in Fig. 2. The difference in their shape is explained by the fact that lasing at the output 1 is observed at wavelengths not coinciding with the reflection wavelength of a FBG, in particular, at wavelengths of the SBS components. The average output power at output 2 is 280 mW for the 1.8-W pump power, and the peak power is ~ 1.5 kW. The average power at output 1 is ~ 30 mW. The pulse repetition rate linearly depends on the pump power, achieving ~ 10 kHz for the maximum power. The pulse repetition rate instability is 10 % – 15%.

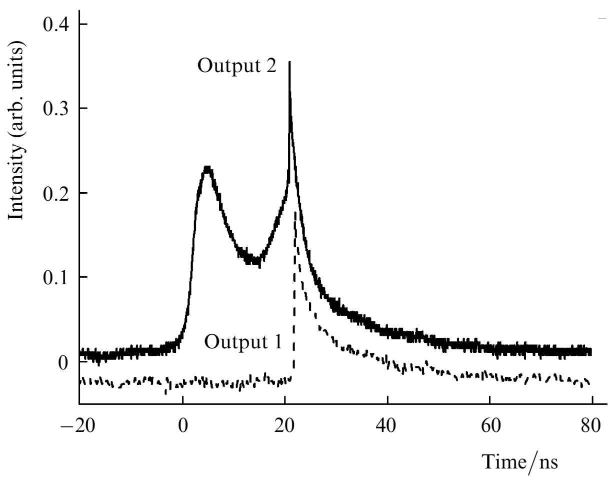

Figure 2. Oscillograms of pulses at different outputs of the laser.

Figure 3 shows the emission spectra of the laser measured at both outputs. One can see that new stimulated Raman components have appeared in the spectrum of emission propagated through the additional fibre (output 2). In this case, a part of the power corresponding to lasing is of about 70 %. The emission spectrum at output 1 is less distorted because it is formed in fact during one transit and the contribution of emission from the additional fibre is smaller.

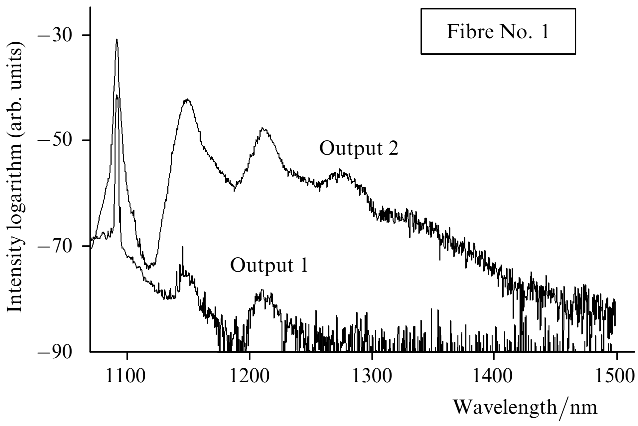

Figure 3. Emission spectra of the laser with an additional germanosilicate glass fibre.

Of great interest is the use of fibres with high nonlinearity (in particular, germanate glass fibre No. 2, Table 1) in the laser resonator [8]. Due to a high concentration of GeO_2 and a small core diameter, such fibres have a high Raman gain of ~ 300 dB km^{-1}W^{-1} in the spectral region at 1.1 μm [9] (for fibre No. 1, the gain is ~ 5 dB km^{-1}W^{-1}). The average output power of a laser with additional germanate glass fibre No. 2 was 260 mW for the pump power of 1.8 W. The temporal and frequency characteristics of the laser were similar to those for the laser with fibre No. 1, whereas the emission spectrum was substantially transformed so that the radiation power was distributed among discrete Stokes components over the entire spectral range studied (Fig. 4). The discreteness of the spectrum is explained by the fact that the wavelength of the zero chromatic aberration in fibre No. 2 lies in the wavelength range above 2 μm, i.e., the spectrum is transformed in the region of normal group-velocity dispersion. The Stokes components contain ~ 70 % of the total power. The power is quite uniformly distributed among the six components, the relative fraction in each of the components being from 9 % to 15 %. The absence of the characteristic decrease in power with increasing number of the Stokes component can be caused by the decrease in optical losses from 120 dB km^{-1} at a wavelength of 1.1 μm down to 25 dB km^{-1} at a wavelength of 1.7 μm. Therefore, this

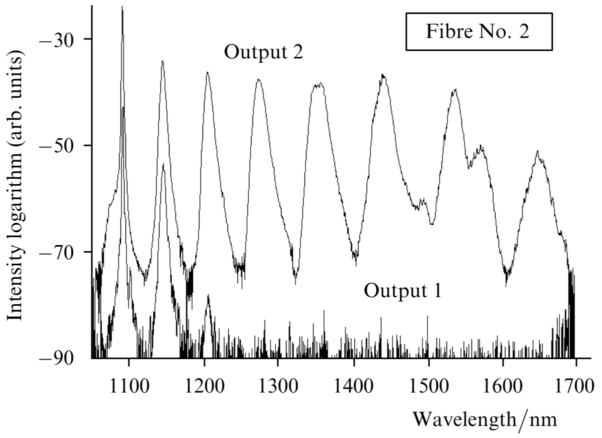

Figure 4. Emission spectra of the laser with an additional germanate glass fibre.

laser represents a radiation source emitting simultaneously at several wavelengths. At output 1, emission was mainly observed at the laser wavelength and its power was an order of magnitude lower than that at output 2.

The last of the additional fibres used in the laser resonator had a microstructure cladding (fibre No. 3, Table 1). Note that this fibre had no high nonlinear properties due to a large core diameter and the absence of dopants. However, the closeness of the laser wavelength to the wavelength of zero chromatic dispersion leads to some specific properties of spectral transformation.

Figure 5 shows the emission spectra of the laser with the additional microstructure fibre. The spectrum at output 2 exhibits one Raman component at the wavelength virtually coinciding with the wavelength of zero chromatic dispersion. In the region of anomalous group-velocity dispersion, a continuous spectrum was observed. The supercontinuum was also generated at wavelengths shorter than the laser wavelength, which is explained by the influence of parametric processes. The fraction of radiation power outside the main laser line was $\sim 25\,\%$. It can be expected that the use of a fibre with a smaller core diameter will result in the increase in power converted to the supercontinuum. The emission spectrum at output 1 is similar to spectra observed for other additional fibres.

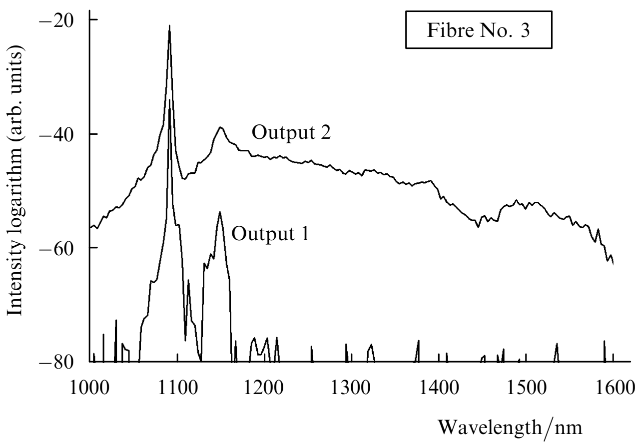

Figure 5. Emission spectra of the laser with an additional fibre with a microstructure cladding.

4. Conclusions

By using an active fibre with a multielement cladding and an additional single-mode fibre, we have fabricated a pulsed fibre laser emitting 1-kW nanosecond pulses. The emission spectra of the laser with different additional fibres have been studied. The use of a germanate glass fibre in the laser resonator leads to the distribution of the output power among several discrete Raman components. By using a fibre with a microstructure cladding, the supercontinuum generation has been obtained.

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References

1. Kurkov A.S., Dianov E.M. *Kvantovaya Elektron.*, **34**, 881 (2004) [*Quantum Electron.*, **34**, 881 (2004)].
2. Chernikov S.V., Fotiadi A.A. *Proc. Conf. on Laser and Electro-Optics* (Baltimore, 1997) p. 477.
3. Chernikov S.V., Zhu Y., Taylor J.R., Gapontsev V.P. *Opt. Lett.*, **22**, 298 (1997).
4. Grukh D.A., Kurkov A.S., Razdobreev I.M., Fotiadi A.A. *Kvantovaya Elektron.*, **32**, 1017 (2002) [*Quantum Electron.*, **32**, 1017 (2002)].
5. Chen Z.J., Grudinin A.B., Porta J., Minely J.D. *Opt. Lett.*, **23**, 454 (1998).
6. Grudinin A.B., Payne D., Turner P.W., Zervas M.N., Ibsen M., Durkin M.K. International patent WO 00/67350, priority date 30.04.1999.
7. Belov A.V., Dianov E.M., Kurkov A.S. *Kvantovaya Elektron.*, **13**, 1680 (1986) [*Sov. J. Quantum Electron.*, **16**, 1096 (1986)].
8. Mashinsky V.M., Medvedkov O.I., Neustruev V.B., Dvoyrin V.V., Vasiliev S.A., Dianov E.M., Khopin V.F., Guryanov A.N. *Proc. 29th ECOC/14th IOOC* (Rimini, 2003) Vol. 2, p. 210.
9. Bufetov I.A., Mashinsky V.M., Neustruev V.B., Shubin A.V., Medvedkov O.I., Dianov E.M., Guryanov A.M., Khopin V.F., Salgansky M.Yu. *Proc. CLEO'2004* (San Francisco, 2004) p. CMD1.