Quantum Electronics **32** (11) 1017 – 1019 (2002)

PACS numbers: 42.55.Wd; 42.60.Fc
DOI: 10.1070/QE2002v032n11ABEH002339

Self-*Q*-switched ytterbium-doped cladding-pumped fibre laser

D.A. Grukh, A.S. Kurkov, I.M. Razdobreev, A.A. Fotiadi

***Abstract*. A self-*Q*-switched ytterbium-doped double-clad fibre laser is described. A samarium-doped fibre is used as a filter for protecting a pump source. A fibre coupler is employed to obtain a nonlinear feedback. The mechanism of pulse formation in the laser is considered, and the dependence of its output pulse on the coupler parameters is studied.**

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

1. Introduction

High-power double-clad fibre lasers have been extensively developed and studied in the last years [1]. One of the main applications of such lasers is pumping of Raman converters for fibreoptic communication systems [2]. The lasers operate usually in a continuos wave mode. Pulsed regime will expand the scope of applications of such lasers owing to a higher peak power. In the earlier methods for obtaining pulsed lasing, as a rule, discrete elements were used, for example, acoustooptic and electrooptical modulators, saturable absorber switches, etc. [3, 4].

The modern level of development of fibre optics assumes the absence of discrete elements in fibreoptic devices; therefore, it is interesting to develop a high-power all-fibre pulsed laser.

Such a laser can be created by suppressing a constant feedback and obtaining a variable feedback by using the nonlinear properties of a fibre. For this purpose, additional fibre elements are introduced the laser scheme. Thus, in [5], a fibre was spliced to the end of a fibre laser, and a fibre ring was introduced in the laser scheme in paper [6]. To suppress a constant feedback, an output fibre with a skewed end was used, which eliminated Fresnel reflection. In both schemes, a nonlinear feedback was produced due to backward Rayleigh scattering, resulting in SBS, which provided pulsed lasing [7, 8].

In paper [5], the active medium of the laser was a Nd^{3+}-doped double-clad fibre, and pump radiation was coupled with the help of a dichroic mirror. Because the presence of an additional fibre (to obtain a nonlinear feedback) resulted in a strong instability of the output parameters, an acousto-optic modulator was used at the output, which returned a part of the output power at the lasing frequency. A more stable laser with a fibre ring was studied in paper [6]. However, to achieve high output powers from Yb^{3+}-doped core-pumped fibre lasers, they should be pumped by a Ti : sapphire laser. The aim of this paper is to create and study a self-*Q*-switched ytterbium-doped double-clad all-fibre laser pumped by a diode laser.

2. Experimental

Fig. 1 shows the scheme of the laser under study. The laser was pumped by a diode laser developed by Sigma-Plyus (Moscow) and Melon (St. Petersburg). The 6-W radiation from the diode laser at 976 nm was coupled to a fibre of diameter 100 μm with the numerical aperture NA = 0.22. Note that one of the main problems encountered in the use of a diode laser for pumping a high-power pulsed laser is the coupling of the pump radiation. A direct coupling of the pump radiation into an active fibre can cause the damage of a diode laser by high-power pulses appearing at the wavelengths of the SRS components, which differ from the resonance wavelength of the input Bragg grating of the fibre.

We solved this problem by using two variants of the pump radiation coupling. In the first case, the pump radiation was coupled through an X-like coupler, which

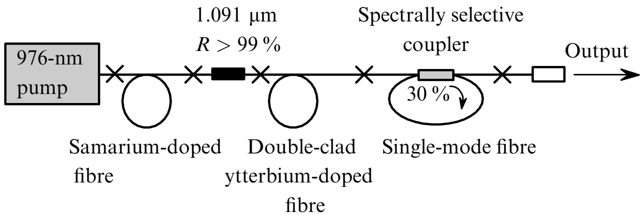

Figure 1. Scheme of the self-Q-switched fibre laser.

D.A. Grukh, A.S. Kurkov Fiber Optics Research Center, A.M. Prokhorov General Physics Institute, Russian Academy of Sciences, ul. Vavilova 38, 119991 Moscow, Russia; e-mail: rayoflight@fo.gpi.ru; kurkov@fo.gpi.ru;
I.M. Razdobreev Laboratoire de Physique des Lasers, Atomes et Molecules, UMR 8523, Centre d'Etudes et de Recherches Lasers Applications, Universite des Sciences et Technologies de Lille, F-59655 Villeneuve d'Ascq Cedex, France;
A.A. Fotiadi A.F. Ioffe Physico-Technical Institute, Russian Academy of Sciences, Politekhnicheskaya 26, 194021 St. Petersburg, Russia

Received 17 May 2002
Kvantovaya Elektronika **32** (11) 1017 – 1019 (2002)
Translated by M.N. Sapozhnikov

combined single-mode radiation entering the fibre core with multimode radiation entering the fibre cladding. In the second case, the pumping was performed through a piece of a single-mode Sm^{3+}-doped fibre. The absorption spectrum of this fibre is shown in Fig. 2. One can see that this fibre provides absorption of light equal to several tens of decibels in the spectral range from 1030 to 1300 nm. In this case, additional losses of the pump radiation do not exceed 0.5 dB and are determined first of all by the fact that the radiation propagates mainly outside the core doped with absorbing ions. Note that both pumping schemes gave similar results. Below, we will consider the results that were obtained by pumping the fibre laser through a Sm^{3+}-doped fibre.

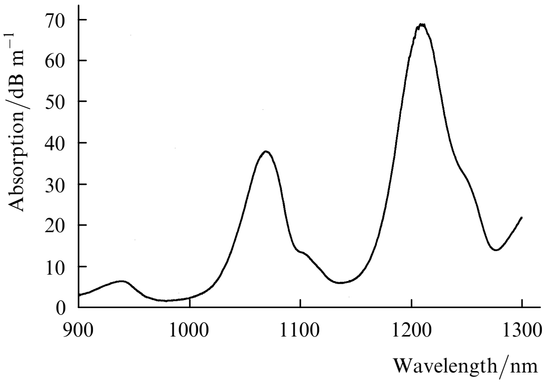

Figure 2. Absorption spectrum of a Sm^{3+}-doped fibre.

A photoinduced Bragg grating with the reflectivity of more than 99 % at 1091 nm and the selectivity of 0.5 nm was used as the input mirror of the laser. A spectrally selective coupler was spliced to the active fibre output end, which provided the coupling of about 30 % of the laser power to a fibre ring made of pieces of a standard fibre of length from several metres to 1 km. The output radiation of the laser was detected with an avalanche diode with the time resolution less than 1 ns.

3. Results

Continuous wave lasing with a maximum power of 2.1 W upon 4.2-W pumping was observed when the output end of the coupler was cleaved perpendicular to fibre axis, providing the 4 % reflectivity. A relatively low lasing efficiency (about 50 %) was explained by additional radiation losses at splicings of the fibre coupler with the active fibre and the fibre ring.

If the output end of the coupler was skewed, which eliminated a constant feedback, pulsed lasing was developed. Fig. 3 shows the dependence of the average output power and the pulse repetition rate of the laser on the pump power. One can see that the pulse repetition rate linearly depends on the pump power and varies from several kilohertz at the lasing threshold up to 40 kHz at the maximum pump power. The maximum average output power of the laser was 1.4 W. The high-resolution measurements of the temporal parameters of lasing showed that a train of pulses was generated with parameters depending on the length of the fibre ring. Fig. 4 shows the oscillogram for the ring of length 8 m.

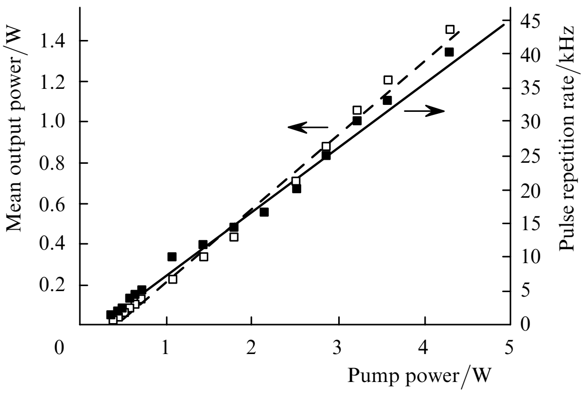

Figure 3. Dependences of the mean output power and the pulse repetition rate of the laser on the pump power.

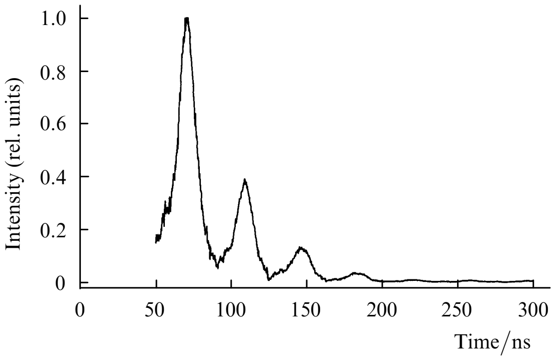

Figure 4. Dynamics of laser pulses in the ring of length 8 m.

The use of fibre rings of different lengths (up to 1 km) showed that the pulse interval in a train was determined by the ring length, more exactly, by the round-trip transit time for radiation in the ring. Therefore, lasing occurs at the resonance frequencies of a ring interferometer. Note that, when the ring length was increased to 1 km, only two pulses were observed in the train, more than 90 % of a total energy being accumulated in a more intense pulse. The pulse duration in the train was 5 – 10 ns, which yields the estimate of the pulse peak power as 5 kW.

We found that, when the laser passed to the pulsed regime, its emission spectrum was broadened and shifted to the red (Fig. 5). The spectral shift was ~ 0.18 nm (the

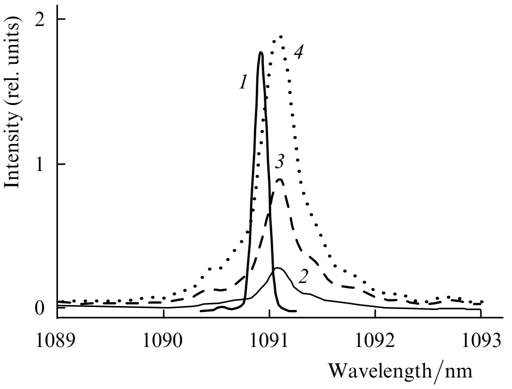

Figure 5. Emission spectrum of the laser in the cw (*1*) and pulsed regimes for pump powers 0.7 (*2*), 2.1 (*3*), and 3.6 W (*4*).

spectral resolution was 0.1 nm). This means that generation in such a fibre laser occurs mainly at the second SRS component.

4. Discussion

We will interpret the experimental results presented in Figs 4 and 5 by using the dynamic model of a laser [9], which is based on the cascade process of Rayleigh scattering and SRS in a fibre laser. The inverse population in an ytterbium-doped fibre increases at the beginning of each cycle, but the absence of reflection from the end of the output fibre of the laser prevents the development of lasing. Amplified spontaneous emission from an ytterbium-doped fibre enters the ring through the coupler and, circulating in it counter-clockwise, is accumulated in the fibre ring interferometer at its resonance frequencies. Rayleigh (linear, without frequency shift) backscattering of this emission results in the formation of a counterpropagating wave. This wave circulates in the ring clockwise and a part of it provides feedback in the laser through the fibre coupler. Therefore, the reflectivity of a ring Rayleigh mirror has a resonance frequency dependence with maxima at the eigenfrequencies of the ring interferometer. Reflection of light from this mirror performs the spectral selection of an amplified spontaneous noise and determines narrow-band initial lasing.

The initial lasing appears due to Rayleigh scattering in the ring, at the frequency near the maximum of reflectivity of the Bragg grating. This frequency should be resonant both for the ring and a linear resonator. An increase in the power of a narrow-band laser radiation, propagating in the ring counter-clockwise, results in the generation of a counterpropagating SBS pulse in the ring. The optical frequency of the pulse is shifted to the Stokes region with respect to the initial lasing frequency by the value of the SBS shift (~ 16 GHz) [10]. The pulse enters the ytterbium-doped fibre through the coupler, where, after being amplified, generates a new SBS pulse in the amplifier fibre in the direction of the laser output. The SBS signal propagating in the amplifier depletes the inversion population, terminating the cycle.

Therefore, output radiation of the laser is the radiation scattered in the last SBS process. Its frequency corresponds to the frequency of the second Stokes component and is shifted by ~ 32 GHz (~ 0.18 nm) to the red with respect to the initial lasing frequency (Fig. 5). Because the SBS signal is generated in an ytterbium-doped fibre from the amplified spontaneous noise, and the noise spectrum is determined by the coefficient of Rayleigh scattering from the ring, the SBS radiation represents a train of pulses separated by the round-trip transit time of radiation in the ring (Fig. 4).

When the fibre length in the ring is increased up to 1 km, the efficiency of Rayleigh scattering during a single trip in the ring becomes sufficient for providing the necessary feedback in the laser, which forms a single SBS pulse. The second (weak) pulse is a main pulse coupled to the ring after a round trip in it.

5. Conclusions

The Yb^{3+}-doped cladding-pumped fibres can be used in high-power pulsed fibre lasers. We proposed an original scheme of pumping through Sm^{3+}-doped fibre, which protects the pump source from backscattered high-power laser pulses. The maximum mean power of the laser is 1.4 W and its pulsed power is 5 kW. Note that, as other passively *Q*-switched lasers, our laser cannot provide a variation of the output pulse parameters in a broad range. At the same time, the laser can be tuned by using the intensity-modulated pumping. However, this question requires a separate study. In addition, we intend to develop in the future the SRS converters and supercontinuum sources based on the pulsed radiation source described above. It is also interesting to create pulsed radiation sources based on fibres doped with other rare-earth elements, in particular, erbium.

Acknowledgements. The authors thank V.M. Paramonov for consultations and great help in this study. One of the authors (A.A. Fotiadi) thanks the Russian Foundation for Basic Research for support (Grant No. 00-02-16903).

References

1. Kurkov A.S., Karpov V.I., Laptev A.Yu., Medvedkov O.I., Dianov E.M., Gur'yanov A.N., Vasil'ev S.A., Paramonov V.M., Protopopov V.N., Umnikov A.A., Vechkanov N.I., Artyushenko V.G., Fram Yu. *Kvantovaya Elektron.*, **27**, 239 (1999) [*Quantum Electron.*, **29**, 516 (1999)].
2. Kurkov A.S., Paramonov V.M., Egorova O.N., Medvedkov O.I., Dianov E.M., Yashkov M.V., Gur'yanov A.N., Zalevskii I.D., Goncharov S.E. *Kvantovaya Elektron.*, **31**, 801 (2001) [*Quantum Electron.*, **31**, 801 (2001)].
3. Clarkson W.A., Richardson D.J. *Opt. Lett.*, **25** (1), 37 (2000).
4. Paschotta R., Haring R., Gini E., Melchior H., Keller U., Offerhaus H.L., Richardson D.J. *Opt. Lett.*, **24** (6), 388 (1999).
5. Chen Z.J., Grudinin A.B., Porta J., Minely J.D. *Opt. Lett.*, **23** (6), 454 (1998).
6. Chernikov S.V., Zhu Y., Taylor J.R., Gapontsev V.P. *Opt. Lett.*, **22**, 298 (1997).
7. Chernikov S.V., Fotiadi A.A. *Proc. Conf. on Laser and Electro-Optics* (Baltimore, 1997) p. 477.
8. Fotiadi A.A., Kiyan R.V., Shakin O.V. *Pis'ma Zh. Tekh. Fiz.*, **27**, 79 (2001).
9. Fotiadi A.A., Ikiades A., Deparis O., Kiyan R., Chernikov S. *Proc. SPIE Int. Soc. Opt. Eng.*, **4354**, 125 (2000).
10. Smith R.G. *Appl. Opt.*, **11** (11), 2489 (1972).