15 November 1996

ELSEVIER

Optics Communications 132 (1996) 107–110

OPTICS COMMUNICATIONS

Performance of a diode-pumped $BaY_2F_8:Er^{3+}$(7.5 at.%) laser at 2.8 μm

S. Wittwer [a], M. Pollnau [a], R. Spring [a], W. Lüthy [a], H.P. Weber [a], R.A. McFarlane [b], Ch. Harder [c], H.P. Meier [c]

[a] *Institute of Applied Physics, University of Bern, Sidlerstrasse 5, CH-3012 Bern, Switzerland*
[b] *Hughes Research Laboratories, 3011 Malibu Canyon Road, Malibu, CA 90265, USA*
[c] *IBM Research Division, Zürich Research Laboratory, Säumerstrasse 4, CH-8803 Rüschlikon, Switzerland*

Received 13 February 1996; accepted 24 April 1996

Abstract

An Er^{3+}-doped BaY_2F_8 laser crystal with a dopant concentration of 7.5 at.% is quasi-cw-pumped longitudinally with the combined beams of two diode lasers. The pump wavelength is 967 nm, the output wavelength ranges from 2.7 to 2.8 μm. The dependence of slope efficiency and threshold power on the reflectance of the resonator mirrors, on the focus of the pump light, and on the resonator length is investigated. The best results are 24% for the slope efficiency and 16 mW for the threshold.

1. Introduction

The strong absorption of 2.8-μm radiation in water and thus in biological tissue makes many surgical applications possible. This is a strong motivation for the investigation of laser operation in erbium-doped host materials. Modern surgical applications demand a compact laser system with high output power. GaInAs diode lasers at 970 nm are an excellent pump source for Er^{3+} lasers and allow the desired compactness. The best pump wavelength for an erbium 3-μm laser is 970 nm leading to a transition into the upper laser level [1]. From computer simulations [2] we know that fluoride hosts promise high efficiency.

This has been confirmed by several experiments, that have been raising the efficiency in $LiYF_4:Er^{3+}$ [3,4] up to 40% [5] with Ti:sapphire-pumping and 35% [6] with diode-pumping. The optimization of the slope efficiency for $LiYF_4:Er^{3+}$ lasers is still assumed to proceed towards the theoretically predicted efficiency maximum of 56% [7]. Efficient lasers are also reported in erbium-doped YSGG [8,9], YAG [10], and BaY_2F_8 [11]. For $BaY_2F_8:Er^{3+}$ we expect a similar efficiency as in $LiYF_4:Er^{3+}$, especially for optimized erbium concentrations of 10 to 15 at.% [12].

However, with the exception of the results reported in Ref. [12] to our knowledge no experiments are reported so far on laser-diode-pumped $BaY_2F_8:Er^{3+}$. Also the spectral properties of such a diode-laser pumped system have not yet been described. With the goal to reach a high slope efficiency resonator parameters, mirror reflectances and pump focus have to be optimized.

In our report we describe the optimization of a $BaY_2F_8:Er^{3+}$ laser with respect to a high slope efficiency. The measurements were carried out with

PII S0030-4018(96)00313-6

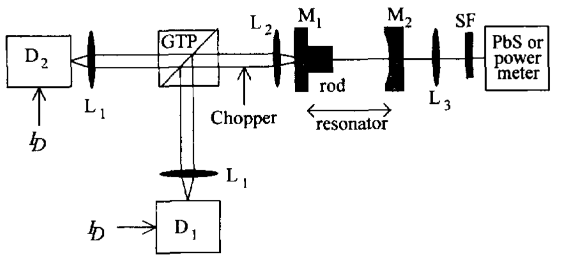

Fig. 1. Experimental arrangement with laser diodes $D_{1,2}$, collimated with lenses L_1, polarization-combined with a Glan-Thompson prism GTP and focused with lens L_2 onto the surface of the $BaY_2F_8:Er^{3+}$ sample. The hemiconcentric resonator consists of a flat mirror M_1 and a mirror M_2 with 75 mm radius of curvature. The laser emission is filtered with a low-pass filter SF and focused onto a PbS detector or an InAs diode or a powermeter.

a nearly hemiconcentric resonator. Resonator length, cavity reflectance and the focus of the pump beam have been optimised. The spectrum of the emitted wavelengths at 2.7 to 2.8 μm is measured as a function of absorbed pump power.

2. Experimental

The experimental arrangement is shown in Fig. 1. The two IBM diode lasers D_1 and D_2 (type 3716C-C-13) are driven with current I_D. They emit a maximum power of 500 mW each at 967 nm in a bandwidth (FWHM) of 2 nm. The emission area of the diodes is 30 μm wide by 1 μm high. The divergence angles (FWHM) are 9.7° and 27°. Each beam is collimated with an antireflection-coated microscope objective L_1 with a numerical aperture NA = 0.53 and a focal length $f = 12.5$ mm. The two linearly polarized pump beams are polarization-combined with a Glan-Thompson prism (GTP). The pump beam is chopped with a frequency of 16.7 Hz and a duty cycle of 0.5. Lenses L_2 ($f_1 = 20$ mm and $f_2 = 30$ mm) are used to focus the emission zones onto the front surface of the crystal. The focused pump light appears as two crossed rectangles with dimensions of about 50×2 μm^2 (f_1) and 70×3 μm^2 (f_2). The length of the nearly hemiconcentric resonator is varied between 61 mm and 75 mm. The properties of the mirrors is listed in Table 1. The 4.7 mm long $BaY_2F_8:Er^{3+}$ (7.5 at.%) crystal is uncoated (reflectance $R \approx 10\%$ at 970 nm). It is positioned close to the input mirror and pumped parallel to the x-axis. The lowest threshold power is 16 mW.

The 2.8-μm laser is collimated with a lens L_3, filtered with a 2-μm low pass filter SF and detected with a lead-sulphide detector PbS. The detector signal is monitored on an oscilloscope (LeCroy 9450A).

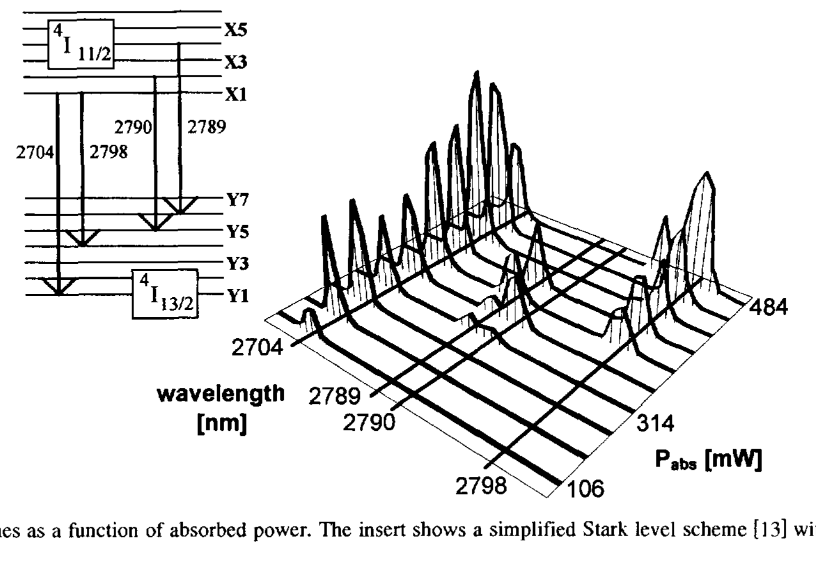

Fig. 2. Emitted laser lines as a function of absorbed power. The insert shows a simplified Stark level scheme [13] with tentatively assigned transitions.

Table 1
Reflectances and combinations of resonator mirrors: The reflectance R_{970} at the pump wavelength and the reflectance at 2.8 μm R_{in} of the flat mirror M_1 and R_{out} of the curved mirror M_2 are given in the table. The cavity reflectance $R = R_{in} R_{out}$ is given in the last column of the table

R_{970}	R_{in} ($\rho = \infty$)	R_{out} (ρ = 75 mm)	R
0.25	0.988	0.988	0.976
0.05	0.9985	0.988	0.987
0.05	0.9985	0.9955	0.994
0.05	0.9985	0.9985	0.997

The laser spectrum is analysed with a monochromator of 1 nm resolution.

3. Results and discussion

Fig. 2 shows the spectrum of the laser emission as a function of absorbed pump power. The insert [13] shows schematically the Stark level scheme of the upper and lower laser levels. Near threshold lasing begins on the $X_1 \rightarrow Y_1$ transition at 2704 nm. With an absorbed power of about 300 mW the higher population of the $^4I_{13/2}$ levels forces laser emission also to $X_1 \rightarrow Y_4$ and $X_2 \rightarrow Y_5$ at 2789 nm and 2790 nm. At even higher pump power emission occurs mainly on the $X_4 \rightarrow Y_6$ transition at 2798 nm.

The temporal shape of a $BaY_2F_8{:}Er^{3+}$ laser pulse is shown in Fig. 3. The duration of the pulse is 30 ms according to the chopped pump pulse. Spiking occurs only during about 3 ms in the leading edge of the pulse, then cw-lasing is established. The laser emission is linearly polarized with E parallel to the z-axis.

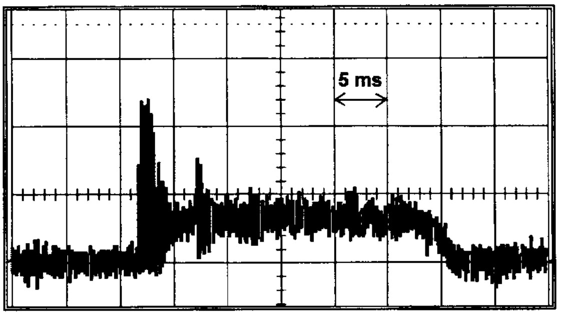

Fig. 3. Temporal shape of a 30 ms laser pulse showing a short period of spiking and transition to cw operation.

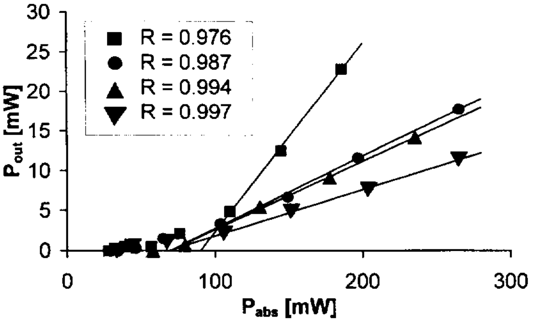

Fig. 4. Output power as a function of absorbed power for different cavity reflectances $R_{in} R_{out}$. The pump-beam is focused with a lens of f_1 = 20 mm. The resonator is nearly hemiconcentric.

The laser output power as a function of absorbed pump power is shown in Fig. 4 for different mirror reflectances ranging from 97.6% to 99.7%. The pump light is focused with a lens L_2 of f_1 = 20 mm. From Fig. 4 it is seen that the best slope efficiency of η = 24% is reached with mirrors $R_{in} R_{out}$ = 97.6% (higher efficiencies are possible with lower $R_{in} R_{out}$). With higher reflectances of $R_{in} R_{out}$ = 98.7%; 99.4% and 99.7% slope efficiencies of only η = 9%; 8%, and 6% are achieved, respectively. Comparing these values with results obtained in $LiYF_4$ [5] and YSGG [14], where reflectances of $R_{in} R_{out}$ = 99.6% proved to be superior to 98.8% leads to the conclusion that internal losses in our $BaY_2F_8{:}Er^{3+}$ laser are somewhat higher than in $LiYF_4$ or YSGG.

With a reflectance of $R_{in} R_{out}$ = 97.6% the slope efficiency is compared for focal lengths of L_2 of f_1 = 20 mm and f_2 = 30 mm. The result is shown in

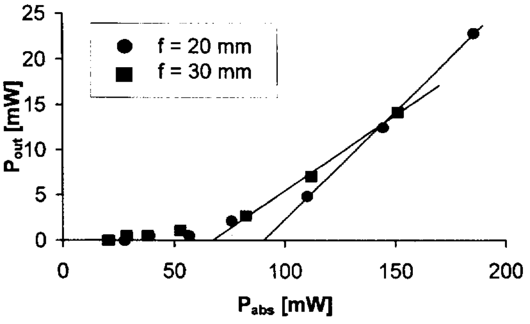

Fig. 5. Output power as a function of absorbed power for two differently focused pump beams (f_1 = 20 mm and f_2 = 30 mm). The cavity reflectance is $R_{in} R_{out}$ = 97.6% and the resonator is nearly hemiconcentric.

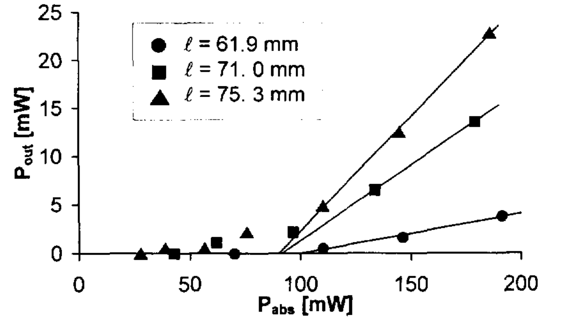

Fig. 6. Output power as a function of the absorbed power for different resonator lengths of 61.9 mm, 71 mm and 75.3 mm. The pump-beam is focused with $f_1 = 20$ mm, the cavity reflectivity is $R_{in} R_{out} = 97.6\%$.

Fig. 5. With a focal length $f_1 = 20$ mm the maximum slope efficiency is 24% and for $f_2 = 30$ mm the slope efficiency is reduced to 17%. Two mechanisms can explain this reduction of the slope efficiency with lower pump intensity: (i) Interionic processes (upconversion) that are quadratically dependent on pump intensity and support laser operation [2,7]. (ii) The geometrical overlap of pump mode and laser mode.

Fig. 6 shows the output power as a function of absorbed power for three different resonator lengths: Starting with the best configuration, a nearly hemiconcentric resonator with a length of 75.3 mm, pump light focussing $f_1 = 20$ mm and $R_{in} R_{out} = 97.6\%$ the resonator length was decreased to 71 mm and 61.9 mm. The slope efficiency decreases from 24% to $\eta = 16\%$ and $\eta = 4\%$, respectively. The shorter resonators lead to a larger beam waist of the output beam and the average pump intensity into the laser mode is reduced.

4. Conclusion

A laser-diode-pumped $BaY_2F_8:Er^{3+}$ laser has been built and spectral and temporal properties of the emission have been measured. The threshold was as low as 16 mW. The emission spectrum of the cw laser output consists of lines at 2704 nm, 2789 nm, 2790 nm and 2798 nm that can be assigned to transitions between $X_1 \rightarrow Y_1$; $X_1 \rightarrow Y_4$; $X_2 \rightarrow Y_5$, and $X_4 \rightarrow Y_6$, respectively. Input-output characteristics have been measured for four different mirror configurations, three different resonator lengths and two different focus lengths of the pump beam. The best slope efficiency of $\eta = 24\%$ has been obtained for a nearly hemiconcentric resonator with reflectance of $R_{in} R_{out} = 97.6\%$ and a pump beam focused with a lens of $f_1 = 20$ mm.

Acknowledgements

This work was supported in part by the Swiss Priority Program Optique. R.A. McFarlane acknowledges support by the U.S. Air Force Office of Scientific Research under Contract No. F49620-94-C-0018.

References

[1] R.C. Stoneman, J.G. Lynn and L. Esterowitz, IEEE J. Quantum Electron. 28 (1992) 1041.
[2] M. Pollnau, Th. Graf, J.E. Balmer, W. Lüthy and H.P. Weber, Phys. Rev. A 49 (1994) 3990.
[3] G.J. Kintz, R. Allen and L. Esterowitz, Appl. Phys. Lett. 50 (1987) 1553.
[4] F. Auzel, S. Hubert and D. Meichenin, Appl. Phys. Lett. 54 (1989) 681.
[5] R. Spring, M. Pollnau, S. Wittwer, W. Lüthy and H.P. Weber, in: Advanced Solid-State Lasers, Technical Digest (Optical Society of America, Washington, DC, 1996) pp. 262–264.
[6] T. Jensen, A. Diening and G. Huber, A diode-pumped 1.1 W cw Er:YLF laser at 2.8 μm, Conf. on Lasers and Electro-Optics 15, OSA Technical Digest Series (Optical Society of America, Washington DC, 1995), postdeadline paper CPD29.
[7] M. Pollnau, R. Spring, Ch. Ghisler, S. Wittwer, W. Lüthy and H.P. Weber, IEEE J. Quantum Electron. 32 (1996) 657.
[8] B.J. Dinerman and P.F. Moulton, Optics Lett. 19 (1994) 1143.
[9] R. Waarts, D. Nam, S. Saunders, J. Harrison and B.J. Dinerman, Optics Lett. 19 (1994) 1738.
[10] C.E. Hamilton, R.J. Beach, S.B. Sutton, L.H. Furu and W.F. Krupke, Optics Lett. 19 (1994) 1627.
[11] D.S. Knowles and H.P. Jenssen, IEEE J. Quantum Electron. 28 (1992) 1197.
[12] M. Pollnau, W. Lüthy, H.P. Weber, T. Jensen, G. Huber, A. Cassanho, H.P. Jenssen and R.A. McFarlane, Optics Lett. 21 (1996) 48.
[13] A.A. Kaminskii, S.E. Sarkisov, F. Below and H.-J. Eichler, Opt. Quantum Electron. 22 (1990) 95.
[14] T. Jensen, V.G. Ostroumov and G. Huber, in: OSA Proc. on Advanced Solid-State Lasers, eds. B.H.T. Chai and S.A. Payne (Optical Society of America, Washington D.C. 1995) Vol. 24, p. 366–370.