Investigation of diode-pumped 2.8-μm laser performance in Er:BaY$_2$F$_8$

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Laser operation at 2.8 μm in BaY$_2$F$_8$ with erbium concentrations of 7.5% and 20% is investigated under laser-diode pumping at 967 nm. Output powers as high as 250 mW and slope efficiencies as high as 24% are obtained. Results are comparable with those of Er^{3+}:LiYF$_4$ under the same pump conditions. Slope efficiencies above 30% are predicted for optimized erbium concentrations.

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The investigation of erbium-doped lasers at 3 μm is stimulated by applications in medicine, especially in surgery. Fiber lasers are promising candidates in this field if single-mode operation at moderate output powers in the range of 100 mW is required.[1] Efficient diode pumping, however, can be more easily realized with crystal hosts. Continuous-wave output powers as high as 500 mW in Er^{3+}:YSGG (Ref. 2) and above 1 W in Er^{3+}:LiYF$_4$ (Ref. 3) have been reported.

The upper laser level of the erbium 3-μm transition has a shorter lifetime than the lower laser level. The interionic upconversion process that depletes the lower laser level and feeds the upper laser level is a significant process in the establishment of cw inversion.[4,5] This has been demonstrated by cw laser emission for pumping of the lower laser level.[6] Slope efficiencies of 36% in GSGG (Ref. 7) and 40% in LiYF$_4$ (Ref. 8) exceeding the Stokes limit have been obtained as a result of energy recycling through the upconversion mechanism. A second upconversion depletes the upper laser level, which is detrimental to lasing. The concentration dependence of both upconversion processes has been measured in Er^{3+}:LiYF$_4$ (Ref. 9) and Er^{3+}:BaY$_2$F$_8$.[10] The increase of the lower-state upconversion and its saturation above a 30% erbium concentration as well as the increase of the upper-state upconversion above a 30% erbium concentration suggest an optimum dopant concentration near 30%. Concentration-dependent laser experiments determined this concept for YSGG,[11] but in LiYF$_4$ the optimum concentration was found to be considerably lower.[3]

BaY$_2$F$_8$ is a promising candidate for efficient 2.8-μm laser performance. Owing to a small phonon energy of 415 cm^{-1} the ratio of upper-state to lower-state lifetime is very favorable.[10] Diode-pumped laser performance has been demonstrated[12] with slope efficiencies as high as 19% and an output power of approximately 100 mW. However, the erbium concentration has as yet not been optimized for maximum slope efficiency, which, in view of the results cited above, is important for efficient laser operation.

In this Letter the 2.8-μm laser performance of Er^{3+}:BaY$_2$F$_8$ with dopant concentrations of 7.5% and 20% is investigated. Our convention for the erbium concentration is atomic percent at the yttrium site. The 7.5% sample was grown at Hughes Research Laboratories, and the 20% sample was grown at the Massachusetts Institute of Technology. The crystal end faces are flat polished, but the reflection of He–Ne laser light indicates that the surfaces are not parallel to each other. The samples are uncoated, because difficulties have occurred in the past with industrial antireflection coatings at 2.8 μm.

The experimental arrangement reported in Ref. 11 is shown in Fig. 1 and is applied to the laser experiments with BaY$_2$F$_8$. Two IBM laser diodes specified at powers of 1 W, each with an emission zone of 1 μm × 50 μm and operating at 967 nm, are collimated and polarization combined. They provide a cw

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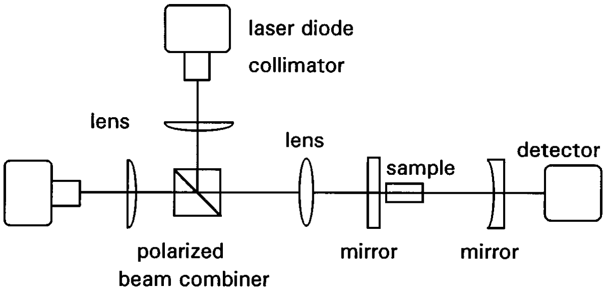

Fig. 1. Experimental arrangement.

power of 1.3 W incident upon the crystal. The pump-beam spot at the front surface of the crystal is approximately a cross with two bars of 90 μm × 20 μm. The sample is mounted on a water-cooled copper block. The nearly hemiconcentric resonator consists of a planar input mirror and an output mirror with a radius of 50 mm. Mirror reflectivities at 2.8 μm are measured to be 99.8% on each side. The resulting transmission of 0.4% led to higher slope efficiencies than did 1.2% transmission.[3] No degradation of the mirror coatings has occurred during several months of operation. The resonator length is adjusted for the highest output power.

The 7.5% sample is oriented and polished for transmission along the x axis of the index ellipsoid (using the convention of Dinndorf *et al.*[13]), whereas the 20% sample is oriented along the y axis. The ground-state-absorption cross sections of the 7.5% and 20% samples at the pump wavelength are 1.3×10^{-21} and 6.4×10^{-22} cm^2, respectively, resulting in comparable absorption coefficients of 1.3 and 1.7 cm^{-1} at laser threshold. The absorption coefficients increase with rising pump power because of a temperature shift of the diode pump wavelength with rising pump power toward the absorption peak at 967 nm. Excited-state absorption from the upper laser level[14] that is due to increased excitation of the sample at higher pump power plays only a minor role, because the excitation of the laser levels is small compared with the ground-state population. Ground-state absorption is, therefore, significantly stronger than excited-state absorption.[8]

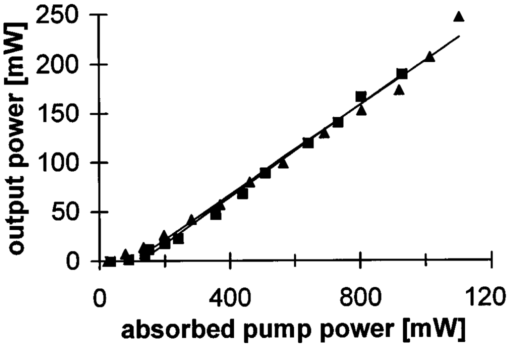

Fig. 2. Input–output curves for Er^{3+}:BaY_2F_8 with dopant concentrations of 7.5% (squares) and 20% (triangles).

The input–output curves for both samples are shown in Fig. 2. After relaxation oscillations laser emission at 2.80 μm is truly cw. Thresholds in the range of 30 mW and slope efficiencies of 23% and 24%, respectively, are achieved (see Table 1). The beam is linearly polarized with the electric-field vector **E** parallel to the z axis for the 7.5% sample, whereas the 20% sample lases with **E** parallel to the x axis. Since the emission cross section is a factor of 1.2 higher for **E** parallel to the x axis,[10] the threshold is smaller for the 20% sample. The output power approaches 250 mW and is limited by the pump power available from the two laser diodes. We obtain a slight enhancement of the efficiency by providing a nitrogen flow into the partly closed resonator, thus reducing the reabsorption losses owing to water vapor in the cavity.

In Fig. 3 the Er^{3+}:BaY_2F_8 results of the present experiments are compared with results of Er^{3+}:$LiYF_4$ with several dopant concentrations[3] under the same pump and resonator conditions and with the same resonator mirrors. Losses are small in both materials, and the overlap between pump and laser modes is similar. The spectroscopic data of lifetimes and upconversion parameters are comparable in Er^{3+}:$LiYF_4$ (Ref. 9) and Er^{3+}:BaY_2F_8.[10] In addition, 1% erbium on the yttrium site corresponds to erbium concentrations of 1.32×10^{20} cm^{-3} in BaY_2F_8 and 1.38×10^{20} cm^{-3} in $LiYF_4$, which are also comparable. Therefore similar laser performance is expected for identical erbium concentrations in both host materials. The slope efficiency versus absorbed pump power in $LiYF_4$ increases with increasing dopant concentration but drops significantly above 15% erbium concentrations.[3] The data for BaY_2F_8 fit well into this scenario, with possibly a slight shift toward smaller concentration. Thus we dare the prediction that an optimum erbium concentration may be in the range of 12–15% with slope efficiencies exceeding 30%.

Despite the similar lasing properties at comparable dopant concentrations, $LiYF_4$ has two advantages over BaY_2F_8. First, it is lasing on a slightly different wavelength with smaller reabsorption losses owing to water vapor. This ensures efficient performance without the need to keep the resonator dry. Second, in one of the BaY_2F_8 samples thermal problems, e.g., a smaller slope efficiency without sample cooling, already occurred at 1.3 W absorbed pump power, whereas in $LiYF_4$ thermal problems are present only above 6 W absorbed pump power[3] but in a hardly comparable setup with less tight focusing of the pump beam.

Table 1. Parameters of the Investigated BaY_2F_8 Crystals Under Diode Pumping at 967 nm[a]

Er^{3+} Concentration (%)	Length (mm)	α (cm^{-1})	Threshold (mW)	Polarization	Slope Efficiency (%)
7.5	4.8	1.3	33	$\mathbf{E} \parallel z$ axis	24
20	4.1	1.7	25	$\mathbf{E} \parallel x$ axis	23

[a] The erbium concentration is given in atomic percent at the yttrium site. The absorption coefficient α is given for the 967-nm pump wavelength at laser threshold but increases with rising pump power.

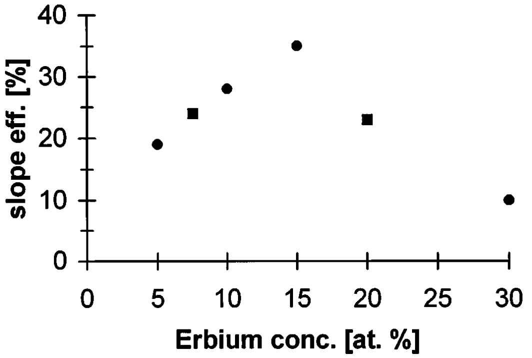

Fig. 3. Concentration-dependent slope efficiencies of Er^{3+}:BaY_2F_8 (squares) and Er^{3+}:$LiYF_4$ (circles) in the same experimental arrangement. Data for $LiYF_4$ are taken from Ref. 3.

The complicated population dynamics of the erbium 3-μm crystal laser has been extensively investigated.[15,16] The concentration dependence of the slope efficiency, however, is still in question. All crystals investigated so far exhibit a maximum slope efficiency at a certain erbium concentration. This concentration is approximately 50% for flash-lamp-pumped YAG,[17] 30% for other diode-pumped garnets,[2,11] and 15% for diode-pumped fluorides.[3] Using the rate-equation system of Ref. 16, the measured or estimated concentration dependence of the interionic parameters in Er^{3+}:$LiYF_4$ (Ref. 9) and Er^{3+}:BaY_2F_8,[10] and including the inverse interionic processes with parameters[18] different from those of the normal processes, we calculate an optimum output power for a 20% erbium concentration. This value is in reasonable agreement with the experimental result[3] of 15% for Er^{3+}:$LiYF_4$. The decrease in slope efficiency toward lower or higher dopant concentration, however, is much less pronounced in the simulation than in the experiment. This indicates that either further two-ion or even three-ion processes, which have not yet been included in the model, may contribute to the population dynamics in erbium or that the parameters of the relevant interionic processes have to be remeasured.

In conclusion, laser operation at 2.8 μm in BaY_2F_8 with erbium concentrations of 7.5% and 20% has been investigated under laser-diode pumping at 967 nm. With two polarization-coupled laser diodes, output powers as high as 250 mW and slope efficiencies as high as 24% are obtained, although a considerable fraction of the pump light is lost owing to the noncircular shape of the pump beam and the resulting nonoptimal overlap between the pump and the laser beams. Results are comparable with those of investigations of Er^{3+}:$LiYF_4$ under the same pump and resonator conditions. The highest slope efficiency, which may exceed 30%, is predicted for an erbium concentration of approximately 12–15%. Thermal problems may occur at a lower pump power than in $LiYF_4$.

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References

1. M. Pollnau, Ch. Ghisler, G. Bunea, M. Bunea, W. Lüthy, and H. P. Weber, Appl. Phys. Lett. **66,** 3564 (1995).
2. B. J. Dinerman and P. F. Moulton, Opt. Lett. **19,** 1143 (1994).
3. T. Jensen, A. Diening, and G. Huber, in *Conference on Lasers and Electro-Optics,* Vol. 15 of 1995 OSA Tecnical Digest Series (Optical Society of America, Washington, D.C., 1995), paper CPD29.
4. K. S. Bagdasarov, V. I. Zhekov, V. A. Lobachev, T. M. Murina, and A. M. Prokhorov, Kvantovaya Elektron. (Moscow) **10,** 452 (1983) [Sov. J. Quantum Electron. **13,** 262 (1983)].
5. M. A. Noginov, S. G. Semenkov, V. A. Smirnov, and I. A. Shcherbakov, Opt. Spectrosk. **69,** 120 (1990) [Opt. Spectrosc. (USSR) **69,** 74 (1990)].
6. S. A. Pollack, D. B. Chang, and N. L. Moise, J. Appl. Phys. **60,** 4077 (1986).
7. R. C. Stoneman and L. Esterowitz, Opt. Lett. **17,** 816 (1992).
8. M. Pollnau, R. Spring, Ch. Ghisler, S. Wittwer, W. Lüthy, and H. P. Weber, "Efficiency of erbium 3-μm crystal and fiber lasers," submitted to IEEE J. Quantum Electron.
9. H. Chou and H. P. Jenssen, in *Tunable Solid State Lasers,* M. L. Shand and H. P. Jenssen, eds., Vol. 5 of OSA Proceeding Series (Optical Society of America, Washington, D.C., 1989), pp. 167–174.
10. D. S. Knowles and H. P. Jenssen, IEEE J. Quantum Electron. **28,** 1197 (1992).
11. T. Jensen, V. G. Ostroumov, and G. Huber, in *Advanced Solid-State Lasers,* B. H. T. Chai and S. A. Payne, eds., Vol. 24 of OSA Proceedings Series (Optical Society of America, Washington, D.C., 1995), p. 366.
12. B. J. Dinerman and P. F. Moulton, in *Proceedings of 1992 LEOS Annual Meeting* (Institute of Electrical and Electronics Engineers, New York, 1992), paper SSLT2.5.
13. K. M. Dinndorf, D. S. Knowles, M. Gojer, and H. P. Jenssen, in *Advanced Solid State Lasers,* L. L. Chase and A. A. Pinto, eds., Vol. 13 of OSA Proceedings Series (Optical Society of America, Washington, D.C., 1992), pp. 270–274.
14. M. Pollnau, W. Lüthy, H. P. Weber, K. Krämer, H. U. Güdel, and R. A. McFarlane, "Excited-state absorption in Er:BaY_2F_8 and $Cs_3Er_2Br_9$ and comparison to Er:$LiYF_4$," Appl. Phys. A (to be published).
15. V. Lupei, S. Georgescu, and V. Florea, IEEE J. Quantum Electron. **29,** 426 (1993).
16. M. Pollnau, Th. Graf, J. E. Balmer, W. Lüthy, and H. P. Weber, Phys. Rev. A **49,** 3990 (1994).
17. R. Gross, D. G. Matthews, and G. Huber, in *International Conference on Quantum Electronics Technical Digest Series* (Optical Society of America, Washington, D.C., 1992), pp. 338–339.
18. M. Pollnau, W. Lüthy, and H. P. Weber, J. Appl. Phys. **77,** 6128 (1995).