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1 July 1997

Optics Communications 139 (1997) 215–218

OPTICS COMMUNICATIONS

Emission properties of an optimised 2.8 μm Er^{3+}:YLF laser

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Received 19 December 1996; accepted 6 March 1997

Abstract

A Ti:sapphire-pumped Er^{3+}:YLF laser is built. The samples are grown at our institute and are compared with a commercially available Er^{3+}:YLF. The dopant concentration and the polarisation of the pump beam is optimised. Slope efficiencies up to 50% and thresholds as low as 42 mW are achieved. The emission properties of the laser are studied. The cw laser emission is linearly polarised. More than 90% of the output power is emitted on a single Stark transition.

PACS: 42.55.–f; 42.55.Rz; 42.60.–v; 42.60.Lh

Keywords: Laser; Erbium; YLF; $LiYF_4$; Slope efficiency; Crystal

1. Introduction

In recent years much attention was paid to laser action in trivalent erbium. Depending on the laser host, the $^4I_{11/2} \rightarrow {}^4I_{13/2}$ laser transition emits light of 2.7 μm to 2.94 μm wavelength. This is the range of strong absorption due to OH-vibration in water vapour and liquid water. Therefore, the erbium laser is ideal for applications such as LIDAR measurements of atmospheric humidity or laser surgery. Modern surgical applications demand a compact laser system with high output power. Therefore, lasers with low threshold and high slope efficiency are needed.

Fluoride crystals promise to be laser hosts with high efficiency, due to their low phonon energies [1]. For Er^{3+}:YLF a maximum slope efficiency of 56% is theoretically predicted [2]. In experiments, however, only slope efficiencies up to 40% [3] with Ti:sapphire-pumping and 35% [4] with diode-pumping are realised as yet.

In our paper we report on the optimisation of an Er^{3+}:YLF laser with respect to a high efficiency. To ensure a high quality of the Er^{3+}:YLF, crystals of two different sources are compared. One sample is a commercially available Er^{3+}:YLF. The other samples were grown and polished at the Department of Chemistry and Biochemistry in Bern. With the goal to reach a high slope efficiency pump focus, the length of the resonator, thickness of the crystal, pump wavelength, temperature, polarisation of the pump beam and dopant concentration are optimised.

In view of future applications, the emission properties of the optimised laser are studied. The output power is measured as function of the polarisation. Further the spectral and temporal behaviour of the laser emission is studied.

2. Experimental setup

The experimental arrangement is shown in Fig. 1. A Ti:sapphire-laser (Spectra-Physics 3900) is pumped with an argon-ion laser (Spectra Physics 2570 E). Since direct pumping of the $^4I_{11/2}$ upper laser level is most efficient [5], the Ti:sapphire-laser is tuned to emit at $\lambda_p = 973$ nm wavelength. The beam passes a filter (RG 695) suited to block the remaining of the argon laser beam. With a neutral density filter of variable transmission the beam is

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PII S0030-4018(97)00130-2

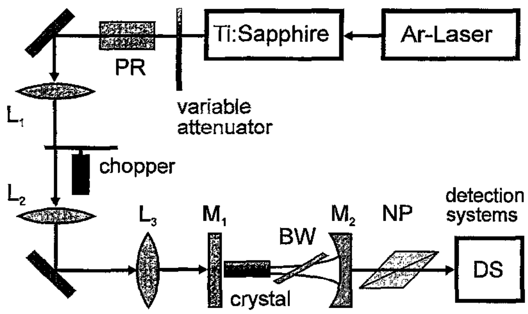

Fig. 1. Experimental arrangement.

attenuated to control the input power. The pump beam is linearly polarised. The polarisation is adjusted with a polarisation rotator PR (Spectra Physics 310-21). The beam is focused onto the blades of a chopper (duty cycle 50%, $f \approx 21$ Hz). This provides an excitation time of 24 ms. In view of the effective lifetimes of the laser levels in the order of 1 ms in YLF [1], the laser operates practically in cw regime [3]. Under true cw excitation, the slope efficiency is not changed. Chopping the beam reduces the thermal load of the crystal. Using a lens L_2, the parallelism of the chopped beam is re-established.

With a lens L_3 of focal length $f(\lambda_p) = 65$ mm, the beam is focused into the crystal. Similar results are obtained with focal lengths $f(\lambda_p) = 80$ mm and $f(\lambda_p) = 50$ mm. The pump-beam waist at the crystal front face is $r \approx 40$ μm. The resonator consists of a plane, dielectric input mirror M_1 and a outcoupling mirror M_2 with a radius of curvature of $\rho_2 = 75$ mm. The transmission of the mirrors has only been optimised in coarse steps. Mirror M_1 transmits $T_1 = 2.1\%$ and for mirror M_2 $T_2 = 2.1\%$ at 2.81 μm. The erbium laser radiation is emitted in parts proportional to the mirrors transmission on both sides of the resonator. This is verified by placing identical beam splitters on each side outside the resonator, pumping through one of them, and measuring simultaneously the output power. The nearly hemiconcentric resonator has an optimised length of $L = 76$ mm [6]. The effective length of the resonator, due to the refractive index of YLF ($n_{YLF} = 1.47$), is about $L_{eff} \approx 74.5$ mm. The cylindrically shaped Er:YLF sample is placed close to the input mirror. The c-axis of the crystal is orthogonal to the beam axis. The rod is mounted on a copper heat sink ($T = 10$°C) to ensure a proper cooling. Output power, spectra and temporal behaviour of the laser emission are not changed by cooling the copper block down to $T = 0$°C or heating it up to $T = 50$°C. Three erbium doped YLF crystals with dopant concentrations of 15 at.% (two different crystals) and 20 at.% are investigated. One of the samples is a commercially available Er^{3+}(15 at.%):YLF with a length $L = 5.8$ mm (Lightning Optical Corp.). The other samples were grown and polished at the Department of Chemistry and Biochemistry using the vertical gradient freezing method

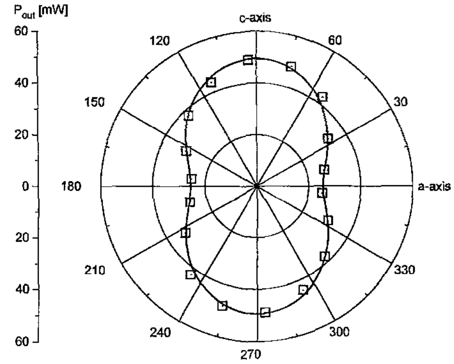

Fig. 2. Output power as a function of the angle between the crystallographic a-axis of Er^{3+} (15 at.%):YLF and the polarisation of the pump beam. The squares indicate the measurements, the solid line the fitted curve.

[7]. Both rods have a length $L = 4.5$ mm. More than 99% of the pump power is absorbed within the crystal.

A Brewster window BW (a sapphire plane plate) inside the cavity is used to force the laser to emit on only one polarisation. A filter (RL 2000) blocks the residual pump power. To study the two different states of polarisation of the laser emission, a Nicol-prism NP is used outside the cavity. The beam is detected with either a PbS-detector (Ealing Beck 28-7870), a power meter (Sensor Physics), an InAs diode or a monochromator (Sopra 1-F 1150) in connection with a PbS-detector.

3. Experimental results and discussion

3.1. Optimisation

Fig. 2 shows the output power as a function of the angle between the crystallographic a-axis of the sample and the polarisation plane of the pump beam. If the crystal is pumped with the electric vector parallel to the c-axis ($E \| c$), the output power is a factor of two higher than in

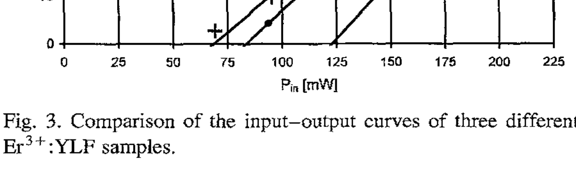

Fig. 3. Comparison of the input–output curves of three different Er^{3+}:YLF samples.

Table 1
Slope efficiencies and thresholds of three different Er^{3+}:YLF samples

	Slope efficiency	Threshold
Er(15 at.%):YLF (Lightning Optical)	50%	123 mW
Er(15 at.%):YLF (grown at our institute)	38%	68 mW
Er(20 at.%):YLF (grown at our institute)	42%	83 mW

the orthogonal state of polarisation. For $E \| c$, the absorption coefficient at 973 nm is a factor of two higher than for $E \| a$ [5]. The overlap between pump and laser mode is better at the crystal end where the pump beam enters. Therefore, for $E \| c$ the population density is higher and the overall spatial overlap becomes better, which results in a higher output power.

The input–output curves of the three samples are shown in Fig. 3. The slope efficiencies and the thresholds are listed in Table 1. The highest slope efficiency of 50% is achieved with the commercially produced Er^{3+}(15 at.%):YLF. This value clearly exceeds the Stokes limit of $\eta_{st} = \lambda_{pump}/\lambda_{laser} = 35\%$. This results from energy recycling into the upper laser level via interionic upconversion ($^4I_{13/2}$, $^4I_{13/2} \rightarrow {}^4I_{15/2}$, $^4I_{9/2}$) [2]. Nevertheless, very high slope efficiencies are achieved with the crystals grown at our institute. The Er^{3+}(20 at.%):YLF has a slightly higher slope efficiency than the Er^{3+}(15 at.%):YLF [8]. The high threshold of the commercial YLF can be explained in part by the fact that the angle between the two faces of the crystal is $\alpha = 0.25°$.

3.2. Emission properties

The input–output curve of the optimised laser is shown in Fig. 4. The Er^{3+}(15 at.%):YLF sample was grown at our institute. The measurements are carried out with a different set of mirrors. The transmission of the mirrors at the laser wavelength are $T_1 = 1.2$ and $T_2 = 2.7\%$. With respect to absorbed pump power the slope efficiency is 46% and the threshold is 42 mW. The improvement of the slope efficiency is mainly due to the better quality of the mirrors.

The laser emission is linearly polarised with the electric vector parallel to the c-axis of the crystal. The spectrum of the laser emission is shown in Fig. 5. The spectra are not changed by pump power, polarisation of the pump beam or the temperature of the sample ($T = 0°C$ to $50°C$). The inset [9] in Fig. 5 shows the Stark level scheme of the upper and the lower laser levels with assigned transitions. More than 90% of the output power is emitted on a single Stark transition (X2 → Y4). The peak is located around 2809 nm and has a FWHM of 2.2 nm.

The temporal behaviour of an Er^{3+}:YLF laser pulse is shown in Fig. 6. The duration of the pulse is 25 ms

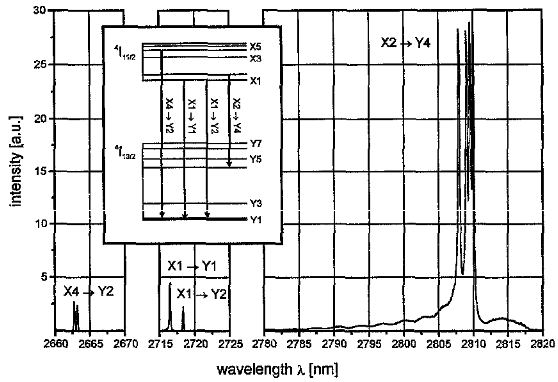

Fig. 5. Spectrum of the laser emission of Er^{3+}:YLF pumped. The inset shows the Stark level scheme [9] with assigned transitions. More than 90% of the output power is emitted on a single Stark transition (X2 → Y4) located around 2809 nm.

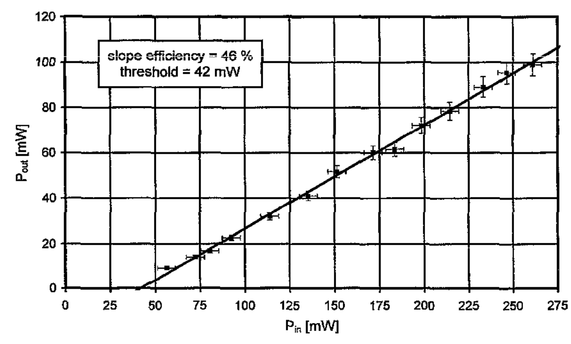

Fig. 4. Output power as a function of absorbed power at 2.8 μm of an optimised Er^{3+} (15 at.%):YLF laser. The crystal was grown at the Department of Chemistry and Biochemistry.

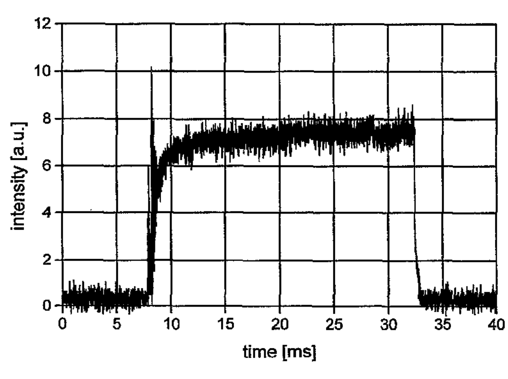

Fig. 6. Temporal behaviour of the laser emission showing a short period of spiking and transition to cw operation.

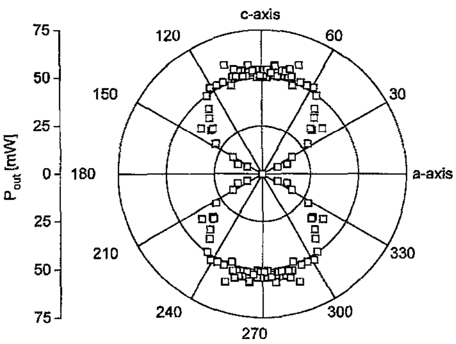

Fig. 7. Output power as a function of the angle between an intercavity Brewster window and the *a*-axis of an Er^{3+}:YLF.

according to the chopped pump pulse. Spiking occurs only during about 1 ms in the leading edge of the pulse, then cw-lasing is established. Without chopper, true cw-lasing occurs. Only the ripples in the pump source intensity due to instabilities of power source are modulating the laser output.

A Brewster window BW (Fig. 1) inside the cavity is used to force the laser to emit on only one polarisation. Fig. 7 shows the output power as a function of the angle between the electric vector and the crystallographic *a*-axis. The maximum output is achieved if the window transmits the polarisation parallel to the *c*-axis. On the orthogonal state of polarisation, no laser action is achieved.

4. Conclusions

A Ti:sapphire-pumped Er^{3+}:YLF laser has been built. The polarisation of the pump beam and the dopant concentration have been optimised. The highest slope efficiency was obtained with the polarisation of the pump beam parallel to the *c*-axis. A dopant concentration of 20 at.% erbium shows to be slightly better than 15 at.%. The highest slope efficiency achieved with a crystal grown at our institute is 46% and the threshold is 42 mW. This value clearly exceeds the Stokes limit of 35% due to energy recycling from the lower into the upper laser level. With a commercially produced Er(15 at.%):YLF a slope efficiency of 50% and a threshold of 123 mW was achieved.

The temporal and the spectral behaviour was measured. The cw laser emission is linearly polarised. More than 90% of the output power is emitted on a single Stark transition (X2 → Y4). The peak is located around 2809 nm (FWHM = 2.2 nm).

Acknowledgements

We would like to thank Christian Auchli for his help setting up the experimental arrangement. This work was supported in part by the Swiss Priority Program "OPTIQUE II".

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