Optica Applicata, Vol. XXXVIII, No. 4, 2008

Generation investigation of "eye-safe" microchip lasers pumped by 974 nm and 939 nm wavelength

JAROSŁAW MŁYŃCZAK*, KRZYSZTOF KOPCZYŃSKI, ZYGMUNT MIERCZYK

Institute of Optoelectronics, Military University of Technology, Kaliskiego 2, 00-908 Warsaw, Poland

*Corresponding author: jmlynczak@wat.edu.pl

The paper describes the results of spectroscopic and generation investigations of Concentrated and SELG glasses with different concentrations of dopants. Transmission spectra of the glasses were measured and absorption coefficients calculated. The laser generation was carried out using two different pump wavelengths of 974 nm and 939 nm in cw and quasi-cw regimes. Attempts to compare the efficiencies of pumping by these two different wavelengths and the evaluation of the optimal thickness of the active media were made.

Keywords: erbium glasses, microchip lasers, "eye-safe" laser radiation.

1. Introduction

The spectral range of „eye-safe" laser radiation wavelength results from the optical characteristics of the eye [1]. Radiation shorter than 400 nm and longer than 1400 nm is strongly absorbed by tissues so it does not penetrate the eye inside and does not cause retina damage. A wavelength of 1.5 μm is considered to be safe for direct looking at the radiation beam of energy density a hundred times higher than for 10.6 μm (CO_2 laser) and $2\cdot10^5$ times higher than for 1.06 μm (Nd:YAG laser) [2].

In the first laser system generating "eye-safe" radiation, a Raman shifter was used in the form of methane cell in which a conversion of radiation, generated by Nd:YAG laser (1064 nm), into radiation of 1.54 μm occurred. Molecular crystals (*e.g.*, $Ba(NO_3)_2$, $CaCO_3$, $CaSO_4$), in which the effect of stimulated Raman scattering (SRS) occurs, are competitive with high-pressure gaseous cells. Because the efficiency of SRS in these crystals is not high, they have not found practical applications [3]. However, such crystals as $BaWO_4$, $SrWO_4$ and $SrMoO_4$ have favorable properties for scattering the pump radiation with picosecond pulse duration and, as a result of high efficiency of this process, can be considered as an efficient Raman-active material for utilization in picosecond solid-state laser systems [4–6]. Moreover, these crystals can be doped with neodymium ions making possible laser operation and simultaneously stimulated Raman scattering in one medium [7–10].

Parametric generation of wavelength near 1.5 μm in nonlinear crystals was practically not used. The main obstacle in this case is the difficulty to ensure stable laser operation within a wide range of temperatures [11].

The first works concerning eye safe generation in erbium glasses were presented in 1965 [12]. For these experiments silicate glasses were used but soon phosphate glasses turned out to be much more efficient [13]. Laser action takes place in erbium ions in three level scheme between $^4I_{13/2}$ and $^4I_{15/2}$ energy levels. Codoping of the glasses with ytterbium Yb^{3+} ions increases the efficiency of pumping. Yb^{3+} ions have a 1200 cm^{-1} wide absorption band in 900–1030 nm spectrum range [14]. Excitation of erbium ions is through energy transfer from ytterbium ions: $Yb^{3+}(^2F_{5/2}) + Er^{3+}(^4I_{15/2}) \rightarrow Yb^{3+}(^2F_{7/2}) + Er^{3+}(^4I_{11/2})$. "Eye-safe" 1.5 μm lasers with this active media were used in many different applications [15, 16]. The development of new pumping laser diodes with very high output power has increased the requirements for mechanical, optical and thermal resistance of new active media. Higher concentrations of dopants are required especially for diode pumped lasers. Intensive research has been done to find a new type of laser glasses with very high thermal resistance and optimal concentrations of dopants.

So far QX/Er, QE-7 and QE-7S glasses, manufactured by KIGRE, have been most often applied to lasers generating at 1.5 μm. The concentrations of erbium and ytterbium ions in the QE-7S and in the QE-7 glasses are $1–1.2\cdot10^{19}$ cm^{-3} and $1–1.3\cdot10^{21}$ cm^{-3}, respectively. The chemical stability of QX/Er glasses is almost the same as the silicon glasses. They were optimised to resist very high thermal loads. These glasses are characterized by increased thermal conductivity and decreased thermal expansion. Durability of these glasses is almost three times higher than of the QE-7S glasses. The concentration of ytterbium ions is $1.8\cdot10^{21}$ cm^{-3} [17].

In General Physics Institute, at the Laser Materials and Technology Research Center of the Russian Academy of Sciences in Moscow, under Professor Denker's leadership, two new types of erbium glasses were developed. One of them is Concentrated Yb-Er laser glass (Concentrated) with concentration of ytterbium ions as high as $4.2\cdot10^{21}$ cm^{-3} [18]. The other one is strong erbium laser glass (SELG) especially developed for microlaser applications and characterized by enhanced thermal damage threshold [19]. These glasses have thermo-mechanical properties of silicate glasses as well as high generation efficiency of phosphate glasses. Comparing them with KIGRE QX/Er glass one can see that they have lower thermal expansion, higher deformation temperature and much higher hardness [20]. It results in higher resistance to thermal damages that can be further increased by ion exchange strengthening [21].

Laser generation in these glasses using 975 nm laser diode as a pump was achieved with very good parameters [18, 19]. But there is still a lack of literature concerning laser generation in these glasses pumped by 940 nm laser diode. In this paper we present generation investigations of Concentrated and SELG glasses pumped by 939 nm as well as 974 nm laser diode. We attempt to compare the efficiency of pumping by these two different wavelengths.

2. Spectroscopic investigations

Three samples of Concentrated glasses with thickness of 2 mm as well as three samples of SELG glasses with thickness of 1.5 mm were examined. All samples had 6 mm diameter. Concentrations of ytterbium and erbium ions were as follows:

I. GLASS-1: Yb $4\cdot10^{21}$ cm^{-3}, Er $1.5\cdot10^{20}$ cm^{-3},
II. GLASS-2: Yb $4\cdot10^{21}$ cm^{-3}, Er $0.5\cdot10^{20}$ cm^{-3},
III. GLASS-3: Yb $4\cdot10^{21}$ cm^{-3}, Er $0.3\cdot10^{20}$ cm^{-3},
IV. SELG-1: Yb $1.7\cdot10^{21}$ cm^{-3}, Er $0.75\cdot10^{20}$ cm^{-3},
V. SELG-2: Yb $1.7\cdot10^{21}$ cm^{-3}, Er $1\cdot10^{20}$ cm^{-3},
VI. SELG-3: Yb $1.7\cdot10^{21}$ cm^{-3}, Er $1.3\cdot10^{20}$ cm^{-3}.

Absorption coefficient spectra of the investigated media were calculated on the basis of measured transmission as a function of wavelength taking into account multiple reflections inside the probes. Measurements were made in the range of 200 nm to 3200 nm at room temperature using Lambda 900 spectrophotometer. Peaks of absorption at 916 nm and 975 nm relate to the $^2F_{7/2} \rightarrow {}^2F_{5/2}$ transition in Yb^{3+} ions. As a result of concentration of ytterbium, the absorption coefficient is higher for Concentrated glasses (32 cm^{-1} for 975 nm) [22] than for SELG glasses (22 cm^{-1} for 975 nm) [23].

Lifetimes of the $^4I_{13/2}$ level of the Er^{3+} ions were measured with the help of excitation from a pulsed 975 nm laser diode POLAROID 4300. Fall time of the laser pulse was much shorter than the measured lifetimes. The 1.5 μm luminescence was detected with an InGaAs photodiode and an oscilloscope. The measured lifetimes are presented in Tab. 1.

Table 1. Lifetimes of the $^4I_{13/2}$ level of the Er^{3+} ions.

Probes	τ [ms]	$\Delta\tau$ [ms]
GLASS-1	8.6	±0.1
GLASS-2	8.8	±0.1
GLASS-3	9.6	±0.1
SELG-1	9.1	±0.1
SELG-2	9.0	±0.1
SELG-3	8.9	±0.1

One can see that for higher concentration of Er^{3+} ions the lifetime is shorter, which may be caused by concentration quenching of luminescence.

Attempts at measuring the lifetimes of the $^4F_{5/2}$ level of the Yb^{3+} ions were carried out. For detection of 1030 nm luminescence, Si photodiode was used. However the signal was equal to zero, which may result from a very good energy transfer from ytterbium to erbium.

3. Experimental preparations

For excitation of the investigated media two fiber coupled laser diodes generating at 940 nm (LIMO25-F100-LD940) and at 976 nm (LIMO25-F100-LD976) in normal temperature were used. Taking into account the wavelength of the pumping and generated beam, the input mirror should have high transmission for 940–980 nm and high reflectivity for 1545 nm, while the output mirror should have high reflectivity for 940–980 nm and a few percent transmission for 1545 nm. So dichroic mirrors AR@940–980 nm, HR@1535 nm and HR@940–980 nm, R = 98%@1535 nm were put on the facets of the samples creating laser resonator [23]. Obtained in this way microchip lasers are presented in Fig. 1.

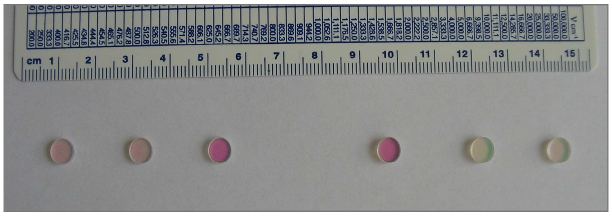

Fig. 1. Active media with dichroic mirrors.

Generation investigations were carried out in an experimental setup in which radiation from the laser diode was focused into the active media while the microchip laser was placed inside the copper holder to avoid any thermal damage [22].

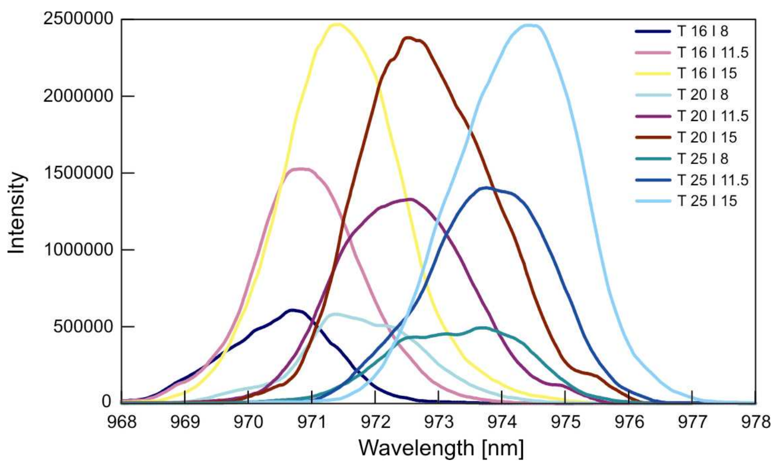

Fig. 2. Emission spectra of LIMO20-F100-DL976 laser diode.

Wavelength generated by a laser diode strongly depends on the temperature and the current (increase in the current causes increase in the temperature). For high pumping efficiency, the laser diode wavelength should fit into the absorption band of an active media. For this reason, the generation spectrum of the laser diodes for three different temperatures (16 °C, 20 °C, 25 °C) and three currents (8 A, 11.5 A, 15 A) were measured with the use of ARC AM-510-M1 spectrometer. Figure 2 shows emission spectra of LIMO20-F100-DL976 laser diode, while Fig. 3 presents emission spectra of LIMO20-F100-DL940 laser diode. In these two figures one can see that for higher temperatures, the emission spectra shift towards longer wavelengths of about 0.35 nm per 1 degrees centigrade. The same situation is for higher currents.

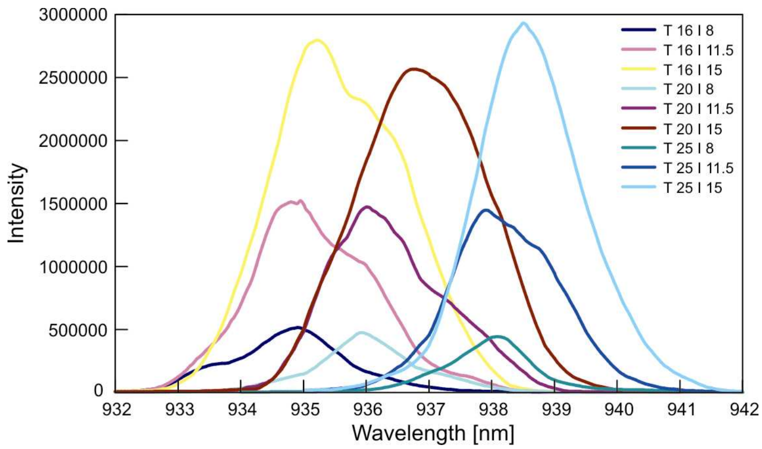

Fig. 3. Emission spectra of LIMO20-F100-DL940 laser diode.

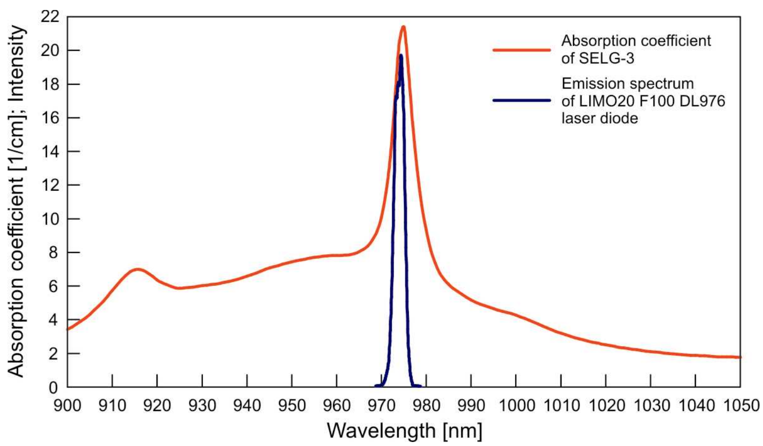

Fig. 4. Emission band of LIMO20-F100-DL976 laser diode at temperature 27 °C on the background of absorption coefficient of SELG-3 sample.

The highest absorption coefficient of the investigated glasses is for the wavelength of 975 nm [22, 23]. The absorption peak for this band is about 6 nm wide at FWHM so the wavelength of the pumping laser diode should be precisely adjusted. To meet this requirement, LIMO20-F100-DL976 laser diode for output power up to 1 W should be kept in temperature of 30 °C. However, because of the restrictions imposed by the manufacturer of this laser diode, the temperature was fixed at the level of 27 °C with the central generated wavelength of 974 nm. In this case the emission band of the laser diode still fits into the absorption band of the investigated glasses. It was shown in Fig. 4 for SELG-3 sample.

Because the absorption coefficient of the glasses close to the wavelength of 940 nm is at the same level in quite wide range, there is no need to adjust precisely the wavelength emitted by the LIMO20 F100 DL940 laser diode. However, during the experiments the laser diode was kept at the temperature of 27 °C with the central generated wavelength of 939 nm.

4. Results and discussion

The dependence of the output power on the incident pump power in cw and quasi--cw regime was examined. In quasi-cw regime the pumping pulses had duration of 10 ms with the frequency of 50 Hz. The measured results along with approximation by linear function are presented in Figs. 5–8 for Concentrated glasses and in Figs. 9–12 for SELG glasses. In the figures there are also shown equations of the approximating linear function. During all the experiments the saturation effect was not observed.

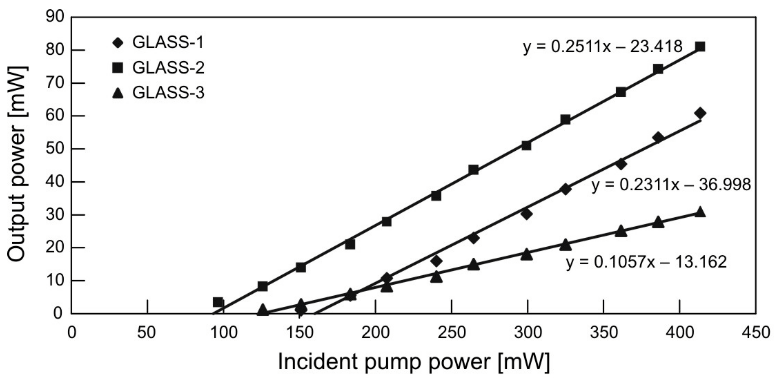

Fig. 5. Output power versus incident pump power of 974 nm wavelength for quasi-cw regime.

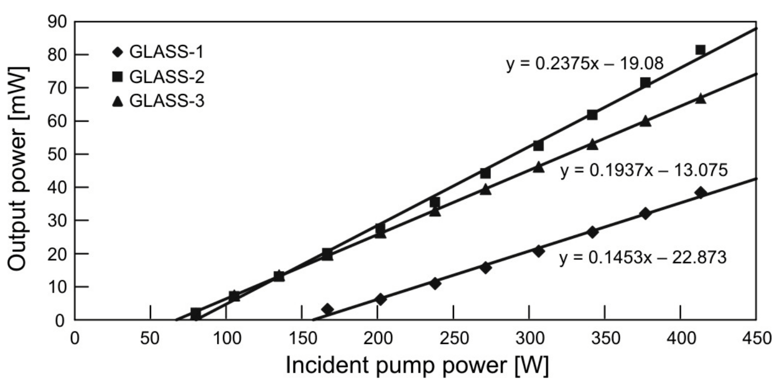

Fig. 6. Output power versus incident pump power of 974 nm wavelength for cw regime.

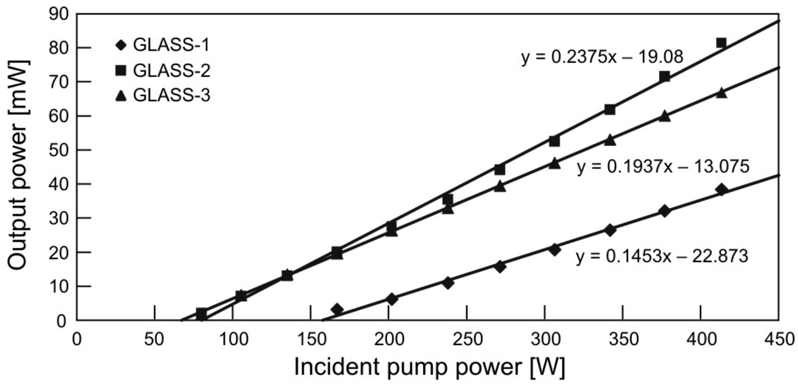

Fig. 7. Output power versus incident pump power of 939 nm wavelength for quasi-cw regime.

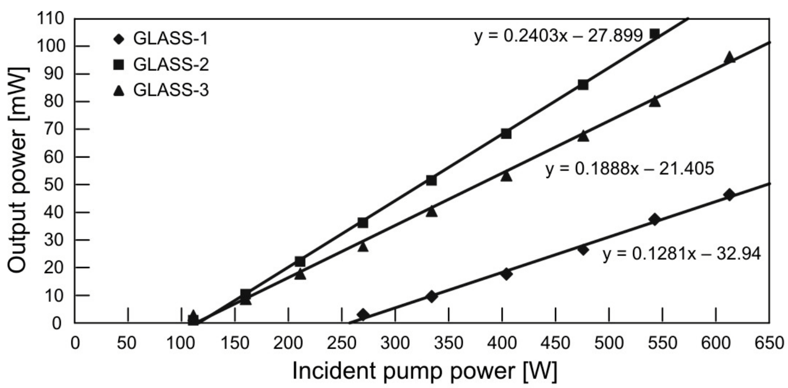

Fig. 8. Output power versus incident pump power of 939 nm wavelength for cw regime.

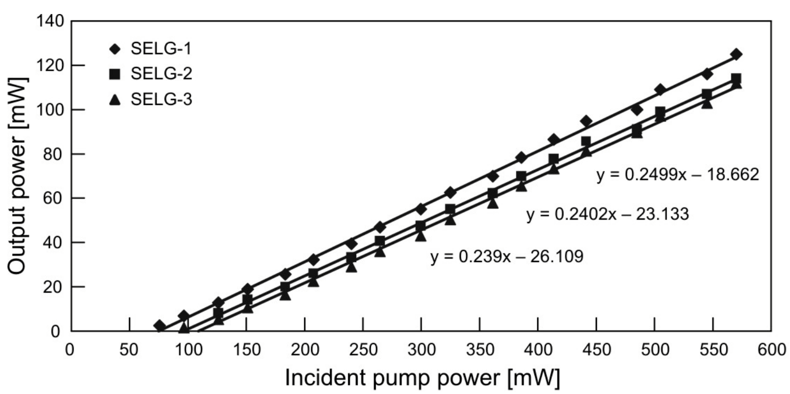

Fig. 9. Output power versus incident pump power of 974 nm wavelength for quasi-cw regime.

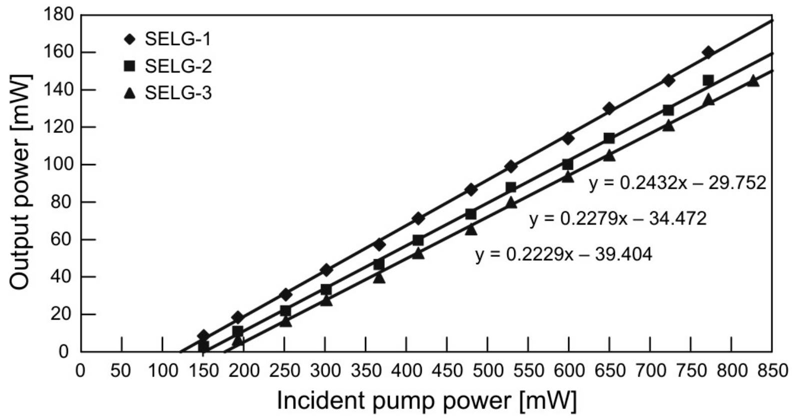

Fig. 10. Output power versus incident pump power of 974 nm wavelength for cw regime.

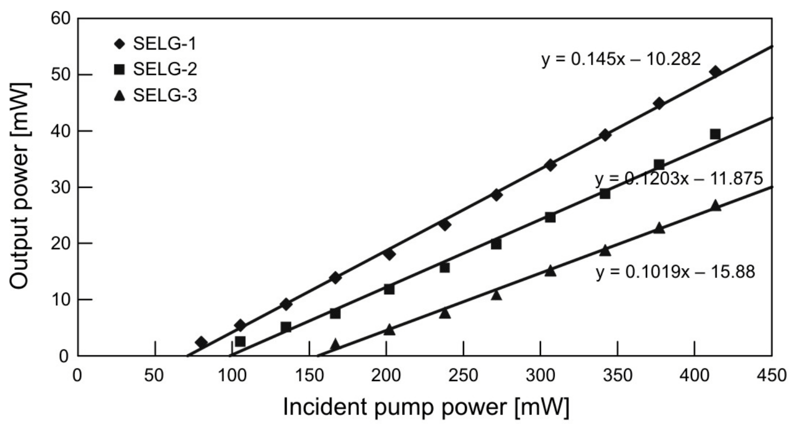

Fig. 11. Output power versus incident pump power of 939 nm wavelength for quasi-cw regime.

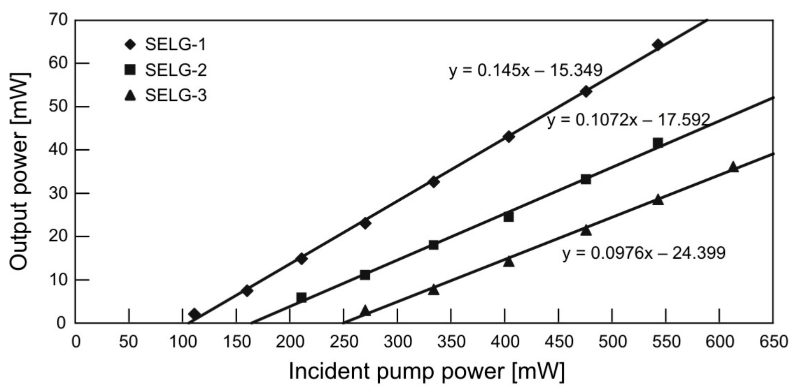

Fig. 12. Output power versus incident pump power of 939 nm wavelength for cw regime.

Thresholds and slop efficiencies of the microchip lasers are presented in Tab. 2. The maximum output powers were intentionally limited so as to avoid damaging the samples.

Table 2. Thresholds and slop efficiencies of the microchip lasers.

	Pump wavelength [nm]	CW		Q-CW	
		Slop efficiency [%]	Threshold [mW]	Slop efficiency [%]	Threshold [mW]
Glass-1	939	12.81	257	14.53	157
	974	20.37	255	23.11	160
Glass-2	939	24.03	116	23.75	80
	974	20.78	150	25.11	93
Glass-3	939	18.88	113	19.37	67
	974	10.33	217	10.57	125
SELG-1	939	14.50	106	14.50	71
	974	24.32	122	24.99	75
SELG-2	939	10.72	164	12.03	99
	974	22.79	151	24.02	96
SELG-3	939	9.76	245	10.19	156
	974	22.29	177	23.90	109

In the case of the same pump wavelength of 974 nm for Concentrated glasses (Figs. 5 and 6) and for SELG glasses (Figs. 9 and 10), higher slop efficiencies and lower thresholds are for SELG glasses because Concentrated glasses are thicker causing additional losses in not pumped part of the sample.

Taking into account the pump wavelength of 939 nm for Concentrated glasses (Figs. 7 and 8) and for SELG glasses (Figs. 11 and 12), higher slop efficiencies are for Concentrated glasses. It is caused by the fact that thickness of SELG glasses is 1.5 mm which is too small for total absorption of pumping wavelength despite the fact that this thickness is equal to absorption length (1.5 mm).

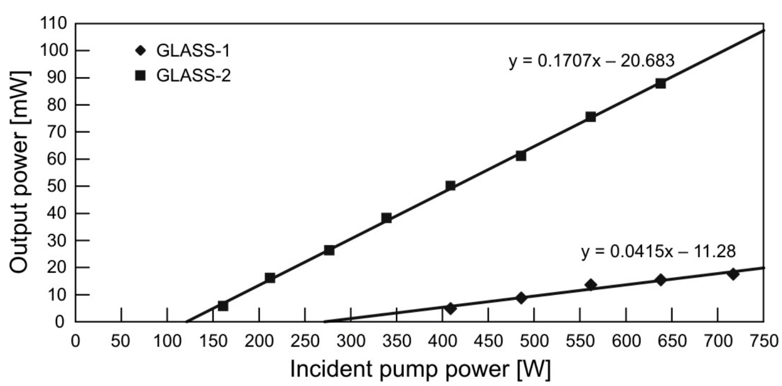

Fig. 13. Output power versus incident pump power of 939 nm wavelength for cw regime without optics.

To avoid any mistakes that could result from different adjustment of optical elements all generation experiments were repeated for pumping without optics. In this case active media were placed inside a specially developed copper holder while a fiber of the pumping laser diode was screwed to it by SMA905 coupling so as the face of the fiber was about 0.5 mm from the sample. Thanks to such approach, active media and fiber were always at the same place. Achieved results of generation turned out to have the same relationships between each other as in the case of pumping with optics. The only differences were lower slop efficiencies and higher thresholds. To prove this, the output power versus the incident pump power of 939 nm along with approximation by linear function for Concentrated glasses are presented in Fig. 13. The results for GLASS-3 are not shown because this sample was damaged during experiments.

From the analysis of the generation results, the SELG-1 and GLASS-2 probes are characterized by the best output parameters. Taking into consideration the cw generation of these microchip lasers (Tab. 2), one can calculate the dependence of slop efficiency and threshold on the ratio of the length of active medium to the absorption length for the given wavelength. This dependence is presented in Tab. 3.

Table 3. Dependence of slop efficiency and threshold on the ratio of the length of active medium to the absorption length for the given wavelength.

	Pump wavelength [nm]	Absorption length [mm]	Ratio of the length of active medium to the absorption length	Slop efficiency [%]	Threshold [mW]
Glass-2	939	1	2	24.03	116.10
	974	0.33	6	20.78	149.56
SELG-1	939	1.5	1	14.50	105.86
	974	0.5	3	24.32	122.34

As can be seen from Tab. 3, the highest slop efficiencies and the lowest thresholds can be achieved for the length of the active medium 2 and 3 times higher than the absorption length. The optimal lengths of the active media are shown in Tab. 4.

Table 4. Optimal lengths of the active media.

Active medium	Pump wavelength [nm]	Optimal lengths of the active medium [mm]
Glass	939	2–3
	974	0.66-0.99
SELG	939	3–4.5
	974	1–1.5

From the above described results of investigations one can conclude that the most efficient samples are SELG-1 and Glass-2. These may also indicate the most efficient concentrations of erbium ions. As can be seen from Tab. 4, the choice of the most efficient pump wavelength is determined by the thickness of the active media.

5. Conclusions

Looking at the absorption coefficient of the investigated active media, one can conclude that they are especially developed for high average-power diode-pumped eye-safe microchip lasers for the sake of high absorption coefficients. Measurements of the lifetimes of the $^4F_{5/2}$ level of the Yb^{3+} ions proved that efficiency of energy transfer from ytterbium to erbium is very high. For 974 nm pump wavelength the temperature of a laser diode should be precisely adjusted to fit into the absorption band of active media. This requirement is not necessary in the case of 939 nm pump wavelength.

From the results of generation investigations the most efficient concentration of erbium ions seems to be possessed by SELG-1 and Glass-2 samples. The most efficient pumping wavelength depends on the length of the active medium. The optimal lengths of the active media for 974 nm and 939 nm pump wavelengths were estimated.

Acknowledgements – Authors would like to thank Professor Borys Denker for preparing all the active media and Mrs. Jadwiga Mierczyk for measuring the transmission spectra of the laser glasses.

References

[1] GEERAETS W.J., BERRY E.R., *Ocular spectral characteristics as related to hazards from lasers and other light sources*, Journal of Ophthalmology **61**, 1968, pp. 15–20.

[2] ANSI Z-136.1-1993, *American National Standard for the Safe Use of Lasers*, 1993.

[3] ZVEREV P.G., BASIEV T., MURRAY J.T., POWELL R.C., REEVES R.J., *Stimulated Raman scattering of picosecond pulses in $Ba(NO_3)_2$ crystals*, OSA Proceedings in Advanced Solid-State Lasers, **15**, 1993, pp. 156–60.

[4] HAOHAI Y., DAWEI H., HUAIJIN Z., ZHENGPING W., WENWEI G., XINGUANG X., JIYANG W., ZONGSHU S., MINHUA J., *Picosecond stimulated Raman scattering of $BaWO_4$ crystal*, Optics and Laser Technology **39**, 2007, pp. 1239–42.

[5] CERNY P., JELINKOVA H., *Near-quantum-limit efficiency of picosecond stimulated Raman scattering in $BaWO_4$ crystal*, Optics Letters **27**, 2002, pp. 360–62.

[6] CERNY P., ZVEREV P.G., JELINKOVA H., BASIEV T.T., *Efficient Raman shifting of picosecond pulses using $BaWO_4$ crystal*, Optics Communications **177**, 2000, pp. 397–404.

[7] SULC J., JELINKOVA H., BASIEV T.T., DOROSCHENKO M.E., IVLEVA L.I., OSIKO V.V., ZVEREV P.G., *Nd:$SrWO_4$ and Nd:$BaWO_4$ Raman lasers*, Optical Materials **30**, 2007, pp. 195–97.

[8] JELINKOVA H., SULC J., BASIEV T.T., ZVEREV P.G., KRAVTSOV S.V., *Stimulated Raman scattering in Nd:$SrWO_4$*, Laser Physics Letters **2**, 2004, pp. 4–11.

[9] JELINKOVA H., SULC J., DOROSCHENKO M.E., SKORNYAKOV V.V., KRAVTSOV S.B., BASIEV T.T., ZVEREV P.G., *Nd:$SrWO_4$ Raman laser*, Proceedings of SPIE 5460, 2004, pp. 99–109.

[10] SULC J., *Eye-safe Nd:$SrMoO_4$ Raman laser*, Conference on Lasers and Electro-Optics Europe, Munich, Germany, 2007.

[11] MIERCZYK Z., *New materials for coherent pumped laser systems, active media, frequency conversion systems and non-linear elements*, Proceedings of SPIE 3186, 1997, pp. 22–31.

[12] SNITZER E., WOODCOCK R., *Yb^{3+}-Er^{3+} glass laser*, Applied Physics Letters **6**, 1965, pp. 45–8.

[13] SNITZER E., WOODCOCK R., SEGRE J., *Phospate glass Er^{3+} laser*, Journal of Quantum Electronics **4**, 1968, pp. 360–64.

[14] GAPONTSEV V.P., MATISIN S.M., ISINEEV A.A., KRAVCHENKO V.B., *Erbium glass lasers and their applications*, Optics and Laser Technology **14**, 1982, pp. 189.

[15] Laser Rangefinders, *JANE's Armour and Artillery Upgrades*, Eleventh Edition 1998–1999, Jane's Information Group Ltd., Couldson, Surrey, UK, 1998.

[16] MIERCZYK Z., *Investigations of saturable absorbers for "eye safe" giant-pulse laser systems*, Optics and Opto-electronics, Theory, Devices and Applications **2**, 1998, pp. 1033–36.

[17] KIGRE catalogue, 2005.

[18] DENKER B., GALAGAN B., OSIKO V., SVERCHKOV S., *Materials and components for miniature diode-pumped 1.5 μm erbium glass lasers*, Laser Physics **12**, 2002, pp. 697–701.

[19] KARLSSON G., LAURELL F., TELLEFSEN J., DENKER B., GALAGAN B., OSIKO V., SVERCHKOV S., *Development and characterization of Yb-Er laser glass for high average power laser diode pumping*, Applied Physics B: Lasers and Optics **75**, 2002, pp. 41–46.

[20] JIANG S., MYERS J., RHONEHOUSE D., MYERS M., BELFORD R., HAMLIN S., *Laser and thermal performance of new erbium doped phosphate laser glass*, Proceedings of SPIE 2138, 1994, pp. 166–174.

[21] JIANG S., MYERS J., WU R., BISHOP G.M., RHONEHOUSE D., MYERS M., HAMLIN S., *Chemically strengthened* Er^{3+}, Nd^{3+} *doped phosphate laser glasses*, Proceedings of SPIE 2379, 1995, pp. 17–25.

[22] MLYNCZAK J., KOPCZYNSKI K., MIERCZYK Z., *Generation of 1.54 μm laser radiation in Er, Yb:glass*, Proceedings of SPIE 6599, 2007, 65990E.

[23] MLYNCZAK J., KOPCZYNSKI K., MIERCZYK Z., *Investigations of optical and generation properties of Yb-Er laser glasses (SELG) designed for 1.5 μm microlasers*, Proceedings of SPIE 6599, 2007, 65990D.

Received July 01, 2008
in revised form August 27, 2008