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Development and characterization of Yb-Er laser glass for high average power laser diode pumping

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ABSTRACT A new strong erbium laser glass (SELG) based on a boro-alumo-phosphate composition is reported. We discuss the synthesis and chemical properties together with spectroscopic and thermo-mechanical data. The new glass composition shows excellent laser performance and withstands high-average power pump radiation. We present laser results at 1.54 μm from flashlamp and laser pumping. In tests with laser-diode pumped Q-switched Er-Yb microchip lasers, we have achieved up to 150 mW of average output power and generated 1.2 kW in peak power. Co^{2+}:$MgAl_2O_4$ was here used as the saturable absorber.

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1 Introduction

Interest in ytterbium-erbium glass lasers has increased recently. Progress in strained-layer InGaAs laser diode (LD) technology has made it possible to obtain efficient laser action from miniature Yb-Er:glass elements under LD pumping into the Yb absorption band (see, for example, [1]). This can be useful in a wide range of applications where radiation in the eye-safe wavelength region of 1.54 μm is beneficial, as in range-finding, optical communication and microsurgery, for example. The laser-diode pumped concept, together with glass as the bulk material for the lasers, allows for good efficiency, compactness, and low cost when mass-produced.

The main drawback of existing Yb-Er phosphate laser glasses today is their low thermal damage threshold under intense optical pumping. This limits the average output power of the erbium-glass lasers, both in flashlamp and in LD pumped operation. The highest thermal damage resistance nowadays among commercially available Yb-Er laser glasses is obtained with Kigre's QX-Er glass [2]. This glass can be further surface strengthened by an ion exchange process [3].

A number of attempts have been made to develop an Yb-Er-doped crystalline material for 1.5 μm lasers. The main advantage of such a material would be a high thermal conductivity in comparison with glasses, and thus, potentially, a high thermal damage threshold. Room temperature laser action has been obtained under Ti:Al_2O_3 or LD pumping in Yb-Er-doped YAG, Y_2SiO_5 and $Ca_2Al_2SiO_7$ crystals [4, 5]. Unfortunately, the efficiency of these crystal materials is unable to compete with that of the phosphate glasses. The main reason is that these crystalline materials have a considerably longer $^4I_{11/2}Er^{3+}$ lifetime than that observed for phosphate glasses. It leads to strong reverse energy transfer and enhanced up-conversion losses. (See the energy level scheme and the main energy transformation processes in Yb-Er laser media in Fig. 1.). Furthermore, relatively long $^4I_{11/2}Er^{3+}$ lifetime in Yb-Er-doped silicate glasses (that are generally stronger and chemically more stable than phosphate glasses) will not allow efficient lasing at 1.54 μm. Hence, until now, phosphate-based glasses have remained a unique host for Yb-Er 1.5 μm lasers. In these, the Er^{3+} ions combine a long fluorecent lifetime ($\tau_e = 7$–8 ms) of the upper laser level, $^4I_{13/2}$, a high Yb→Er energy transfer quantum yield

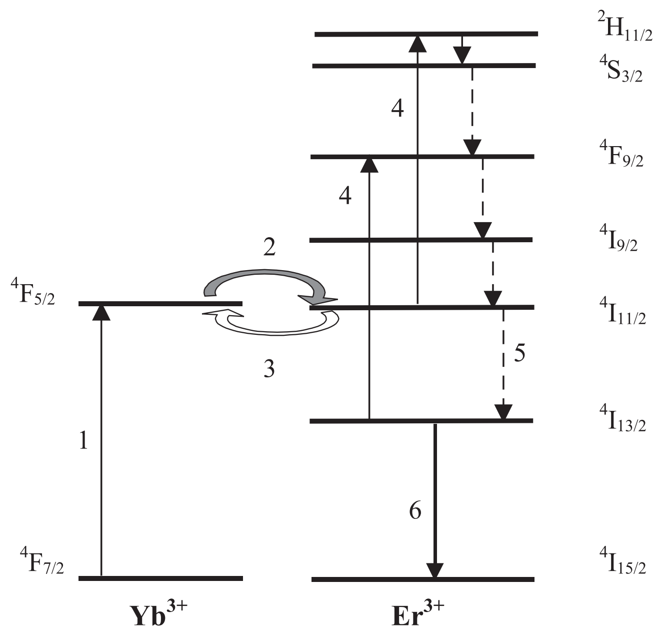

FIGURE 1 The principal energy level scheme and the energy transformation processes in Yb-Er-doped media. 1: optical pumping into the Yb absorption band; 2, 3: direct and back-wards Yb-Er energy transfer; 4: up-conversion losses; 5(−− →): multiphonon relaxation; 6: lasing transition

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($\eta \approx 90\%$), and a very short lifetime (2–3 μs) of the $^4I_{11/2}$ level. The fast non-radiative multi-phonon relaxation from the $^4I_{11/2}$ to the $^4I_{13/2}$ level greatly decreases the back-energy transfer and the up-conversion losses due to the interaction between the Yb^{3+} and the Er^{3+}, excited at the $^2F_{5/2}$ and the $^4I_{11/2}$ levels, respectively.

This investigation focuses on the development of a new Yb-Er activated glass that combines good laser efficiency and better thermo-mechanical properties than presently existing phosphate laser glasses.

2 Selection of glass composition

It is well known (for example, see [6]) that silicate glasses have a much higher chemical stability and better mechanical properties than phosphate glasses. Both types consist of tetrahedrons (SiO_4 or PO_4, respectively) with strong covalent chemical bonds between the central ion and the oxygen anions. However, the glass properties are strongly determined by the bonds combining the tetrahedrons with each other. In the case of fused silica glass, each SiO_4 tetrahedron is bonded to four others by bridging oxygen ions (i.e. ions having bonds with two different glassforming Si^{4+} ions). These bonds form a strong three-dimensional net, resulting in a superb thermo-mechanical property of the SiO_2 glass (hardness, low thermal expansion, relatively high thermal conductivity and high softening temperature). In the case of phosphate glasses, the PO_4 tetrahedrons are bonded together by not more than three other PO_4 tetrahedrons. Thus, the physical properties of phosphate glasses such as those mentioned above are much poorer.

The situation with phosphate-based materials can be changed by the addition of trivalent glass-forming ions (B^{3+}, Al^{3+}), which also can form strong tetrahedral complexes with oxygen. It is well known that alternating the PO_4 and BO_4 or AlO_4 groups in crystalline BPO_4 and $AlPO_4$ forms a strong three-dimentional lattice similar to that of crystalline SiO_2 with four bridging oxygen ions in each tetrahedron. As for the phosphate glasses, it is also known that even a small addition of boron can significantly improve mechanical hardness [7]. With regard to vitreous aluminum metaphosphate, it exhibits the highest thermal conductivity among the phosphate glasses, which is also combined with an excellent stability to air moisture [8]. The idea behind this paper is that a strong Yb-Er laser glass should be composed of a mixture composition with large amounts of aluminum and boron. The main demands for the glass we have designed are (1) it should have thermo-mechanical properties similar to those of silicate glass, and (2) it should exhibit exited state relaxation rates of erbium ions close to those in the phosphate glasses in order to have good laser efficiency. The last statement needs to be elucidated.

It is also recognized that B^{3+} ions in borate glasses can have both tetrahedral and trigonal coordination. The phonon spectrum of BO_4 is similar to that of PO_4. Usually, the presence of the BO_3 groups leads to a phonon spectrum extending into the 1.5-μm luminescence band for the Er^{3+} ions, strongly quenching the luminescence lifetime ($\tau_e =$ 500–600 μs) in the borate glasses. Fortunately, in mixed borophosphate glass, even very large amounts of boron (up to quantities four times bigger than the amount of phosphorus) do not lead to significant quenching of the Er^{3+} luminescence. We interpret this fact as indicating a tetrahedral coordination of the B^{3+} ions in these glasses.

Thus, the search for a strong glass composition was carried out within the B_2O_3-Al_2O_3-P_2O_5-Yb_2O_3 system. All the tested glass compositions included $\sim (1.5-2) \times 10^{21}\,cm^{-3}$ of Yb^{3+}. The test batches (~ 20 g) were melted in air in small alumina crucibles. After the melting process, the crucibles were left in the furnace for slow cooling. During the cooling process, some test samples were partially or completely devitrificated, but some remained quite transparent. This simple procedure enabled us to select the compositions that were stable enough to be crystallized. A good example of such a composition is:

Al_2O_3 – 10%mol., B_2O_3 – 15%mol., Yb_2O_3 – 7%mol., P_2O_5 – 69%mol.

Unfortunately, the melting temperature (1400–1450 °C) of these glasses was too high for synthesis in the ∼1 liter platinum crucibles with the rather thin (1.5–2 mm) walls that we have. (Platinum becomes too soft and will deform under its own weight and that of the crucible and of the glass melt). To reduce the melting temperature to a more practical value (1340–1360 °C), a certain amount of Li_2O was added to the chosen composition, resulting in the following mol-values:

Li_2O – 9%mol., Al_2O_3 – 7%mol., B_2O_3 – 12%mol., Yb_2O_3 – 7%mol., P_2O_5 – 65%mol. The appropriate erbium-oxide doping was then added to this composition.

3 Laser glass synthesis

We started our investigations with the technology basis for the synthesis of phosphate-based Nd and Yb-Er laser glasses developed at the General Physics Institute several years ago. The main step of the process is glass melting in a radio-frequency heated platinum crucible with a platinum stirrer in a dry atmosphere. The dry atmosphere was prepared by placing bowls with P_2O_5 powder into the closed chamber together with the crucible. One of the serious problems in laser glass technology is reaching a high level of dehydration. Glasses with excessive residual water content (in the form of OH^- groups) exhibit serious absorption losses at the laser wavelength of 1.54 μm as well as Er^{3+} luminescence quenching. In the case of the glass composition investigated, the water evaporation was too slow during the synthesis. This was probably due to the high viscosity of the melt. Very long synthesis periods (∼ 100 hours or more) did not help, since it caused glass devitrification (partial crystallization) due to evaporation of the glass components and subsequent changes of the original composition. To overcome this problem, the initial composition had to be modified. By partially substituting the metal oxides by some fluorides, hydrogen can evaporate in the form of HF. Most of the excess fluorine will evaporate in the form of BF_3, PF_5 and POF_3 gases [6, 9]. Substituting ∼ 4% of the oxygen in the glass batch by fluorine resulted in a glass with an excellent optical quality, displaying good crystallization stability, and with a concentration of residual water, corresponding to an optical absorption of 1–1.5 cm^{-1} at 3.33 μm wavelength. This is the normal residual water concentration in Yb-Er laser glasses.

Rare-earth components of the glass are not volatile, unlike many other components. That is why the rare-earth concentration increased during the synthesis process. The synthesized laser glass (referred to as the Strong Erbium Laser Glass, SELG) had a Yb^{3+} concentration of 1.7×10^{21} ions/cm^3. The Er^{3+} concentration was varied over the range of $(2.5-10) \times 10^{19}$ ions/cm^{-3}.

4 Chemical and thermo-mechanical properties of the glass

Some of the physical properties of the synthesized glass are presented in Table 1, and compared with the QX-Er laser glass from Kigre Inc. [2, 3]. The thermal shock resistance in the synthesized glass was measured in the same way as described in [3] for the QX-Er glass: hot chemically etched cylindrical glass rods (∅5 mm) were dropped into room temperature water. The figures in Table 1 represent the ensemble-averaged temperature shock causing fracture in three samples of each type.

The ion exchange strengthening experiments with the synthesized glass were also made with these samples by treating them for 1 hour in $NaNO_3$ molten salt, just above the melting temperature of 308 °C. A significant increase of the thermal shock resistance due to the larger Na^+ ions replacing the smaller Li^+ ions in the SELG surface layer was observed (see Table 1). Unfortunately, the treated surface looked matt due to glass surface corrosion. This is not a big obstacle for optical pumping through the glass, since the ion-exchanged layer is very thin (∼ 20 μm). However, it should be noted that this ion exchange procedure spoils the optically polished surfaces.

5 Damage from pump radiation

The measurements of the pump power damages of the new synthesized glass, in comparison with the phosphate Yb-Er laser glasses, were performed with flashlamp and $Ti:Al_2O_3$ laser pumping.

The threshold for optical damage from the flashlamp pumping was tested on chemically etched cylindrical glass rods (∅ 5 × 50 mm). No effort to obtain any lasing was made. Three types of rods were compared: rods from the GPI produced Yb-Er phosphate glass [10]; SELG rods; and surface-strengthened ion exchanged SELG rods. The rods were mounted in a distilled water-cooled pump chamber. The pump power was slowly increased until the rods fractured. Three rods of each type were tested in a flashlamp pumped mount (see Table 2). The SELG glass withstood four times more optical pump power than ordinary phosphate glass. The surface-strengthened sample further endured 35% more pump power.

Optical damage from CW $Ti:Al_2O_3$ laser pumping at the absorption peak (975 nm) of the ytterbium were induced on round glass chips (∅ 5 × 1 mm) with polished surfaces. Two types of glasses were compared: GPI-developed concentrated Yb-Er glass chips for efficient diode pumping (Yb^{3+} concentration of 4×10^{21} cm^{-3} [10], and SELG chips (Yb^{3+} concentration of 2×10^{21} cm^{-3}). The $Ti:Al_2O_3$ laser was focused into a spot 80 μm in diameter. Some of the samples were freely suspended, and some were mounted with a thin layer of heat-conductive paste on a copper heat-sink plate with a 2 mm hole in it. The results are presented in Table 3. No damage has been observed on the SELG chips from the available pump source, which in this experiment was limited to 1.4 W. The concentrated glass usually melted at pump powers of about 740 mW.

Apparently, the thermo-mechanical and chemical properties of the SELG glass are significantly more attractive than those of typical phosphate glasses. However, to be of practical interest, the spectroscopic parameters need to be similar to the usual phosphates so that efficient laser action can be obtained.

6 Spectroscopic peculiarities

We have not noticed any differences between the Yb-Er doped SELG glass and the Yb-Er phosphate glasses in the bottleneck parameters; thus, the $^4I_{11/2}$ and the $^4I_{13/2}$ lifetimes of the Er^{3+} ion in the SELG are 2.5 ± 0.5 μs and 8.5 ms, respectively – which are quite typical parameters for phosphate glasses. The $^4I_{11/2}$ – level lifetime of the Er^{3+}–

Parameter	Kigre Inc. QX/Er	Investigated glass (SELG)
Thermal expansion α (20–40 °C), ($\times 10^{-7}$ K^{-1})	82	72
Refractive index n @1.54 μm	1.521	1.53
dn/dT (20–40 °C), ($\times 10^{-7}$K^{-1})	0	27
Thermooptical parameter $W = \mathrm{d}n/\mathrm{d}T + \alpha(n-1)$, ($\times 10^{-7}$ K^{-1})	41	66
Density, (g / cm^3)	2.90	2.83
Thermal conductivity (W/m K)	0.85	0.83 ± 0.04
Hardness, (kg f / mm^2)	435	702 ± 30
Weight loss in water (10^{-5} g/cm^2 hour) at 100 °C	5.2	0.2–1[1]
Deformation temperature (°C)	485	755
Thermal shock resistance[2] (°C):		
1. Without ion exchange strengthening	100–110	165–175
2. With ion exchange strengthening	200–210	285–315

[1] Weight loss tests give quite different results depending upon the duration of the sample treatment. During the first 24–36 h of treatment practically no visible corrosion or loss of weight can be registered. Further treatment results in visible stains and accelerating weight loss.
[2] The thermal chock resistance is measured by dropping heated samples into a bucket of water at room temperature. The figures in the table indicate the temperature shock at which the heated samples fractured

TABLE 1 Measured properties of the SELG glass compared with the measured parameters of the QX/Er glass from Kigre Inc

Type of rods tested	Damaging pump power, W
Phosphate Yb-Er glass (without strengthening)	430 ± 25
SELG (without strengthening)	1700 ± 200
Strengthened SELG	2300 ± 500

TABLE 2 Test of optical damage from flashlamp pumping

system was measured for a Yb-free sample (Yb was substituted by Y). The sample was excited at 0.53 μm from a pulsed laser, and the luminescence at 0.98 μm was observed with a photo-multiplier tube through an appropriate spectral filter. The $^4I_{13/2}$ lifetime was measured in a Yb-Er-doped sample with the help of excitation from a pulsed 0.975 μm LD, and the 1.5 μm luminescence was detected with a Ge photodiode. Both samples were well dehydrated (the absorption coefficient $\alpha < 1.5\,\mathrm{cm}^{-1}$ at 3.33 μm).

The absorption spectrum of the OH^- group in the glass does not differ from that of a typical phosphate glass (see Fig. 2). Nevertheless, when investigating the luminescent lifetime, τ_0 of the $^4F_{5/2}$-level of the Yb ions, in Er-free samples with different OH^- concentration, we observed an unpleasant peculiarity of the SELG glass – an unusually high Yb–OH^- energy transfer rate. Figure 3 shows the relationship between the absorption coefficient at 3.33 μm and the Yb–OH^- energy transfer rate – W_{OH} in the SELG glass and in the above-mentioned concentrated ($4 \times 10^{21}\,\mathrm{cm}^{-3}$ Yb^{3+}) laser glass. It can be clearly seen that W_{OH} is directly proportional to the absorption coefficient, and the proportionality coefficient for the SELG glass is a factor of two larger. In comparison with ordinary Yb-Er phosphate laser glasses (with Yb content of $\sim 2 \times 10^{21}\,\mathrm{cm}^{-3}$, i.e. about the same as in the SELG) the Yb $\rightarrow$ OH^- energy transfer rate in the SELG is about one order of magnitude larger. The reason for this behavior is not clear, and should be a theme for future investigation. At this point, we speculate that this is due to the close distance between the rare-earth ions and the OH^- groups in the SELG glass.

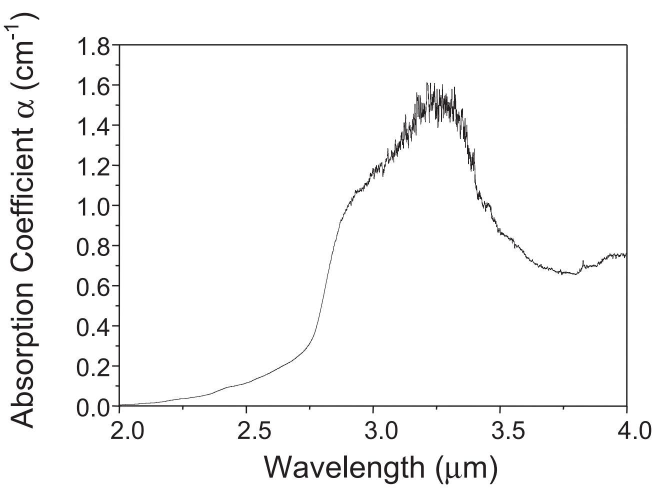

FIGURE 2 Mid-IR absorption spectrum in a well-dehydrated SELG glass sample due to OH^- groups

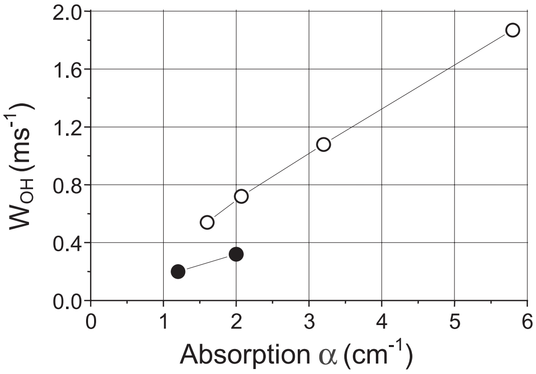

FIGURE 3 The dependencies of $Yb^{3+} \rightarrow OH^-$ energy transfer rates, $W_{OH} = 1/\tau_{Yb} - 1/\tau_0$, in SELG (*open circles*) and in the above-mentioned concentrated laser glass ($4 \times 10^{21}\,\mathrm{cm}^{-3}$ Yb^{3+}, *solid circles*) versus the absorption coefficient α at 3.33 μm. τ_{Yb} is the experimentally measured lifetime of the Yb^{3+} $^4F_{5/2}$-level in Yb-doped SELG glass and τ_0 is the radiation lifetime, $\tau_0 \approx 1.2$ ms

The Yb-Er energy transfer rate, W_{Er}, in the SELG glass was estimated by the formula $W_{Er} = 1/\tau_{Yb} - 1/\tau_0 - W_{OH}$, where τ_{Yb} is the measured lifetime (102 μs) of the $^4F_{5/2}$-level at low excitation level. The sample contained $1.7 \times 10^{21}\,\mathrm{cm}^{-3}$ Yb^{3+} and $2.3 \times 10^{19}\,\mathrm{cm}^{-3}$ Er^{3+}. This Er^{3+} concentration is typically used for flashlamp-pumped lasers. The OH^- absorption coefficient, α, of the sample was $1.4\,\mathrm{cm}^{-1}$ at 3.33 μm (see Fig. 3). The resulting value of $W_{Er} = 8500\,\mathrm{s}^{-1}$ for the glass with the above-mentioned Er concentration is one of the highest observed for phosphate glasses [11]. However, it is not quite high enough for efficient lasing due to competition with the Yb $\rightarrow$ OH^- energy transfer. The resulting Yb $\rightarrow$ Er energy transfer quantum yield (at low excitation level), $\eta = 1 - \tau_{Yb} \cdot (1/\tau_0 + W_{OH}) = 0.87$, is noticeably lower than what is needed for efficient Yb-Er laser glass ($\eta > 0.95$). This high value of η is demanded because the Yb $\rightarrow$ Er energy transfer rate decreases significantly during laser action, i.e. at the erbium excitation level of > 0.5 (for example, see [12]). The demand for a quantum yield of $\eta \geq 0.95$ (at a fixed Er concentration of about $2.3 \times 10^{19}\,\mathrm{cm}^{-3}$) restricts the allow-

Glass tested	Sample mountings	Absorbed damaging CW $Ti{:}Al_2O_3$ laser power	Comments
Concentrated ($4 \times 10^{21}\,\mathrm{cm}^{-3}$ Yb^{3+})	Freely suspended	500 mW	Glass sample fractures
laser glass for LD pumping	Copper heat-sink mounted	740 mW	Glass surface melts and deforms
SELG ($2 \times 10^{21}\,\mathrm{cm}^{-3}$ Yb^{3+})	Freely suspended	> 1400 mW	No damage at full power of pump lasers
	Copper heat sink mounted	> 1400 mW	

TABLE 3 Optical damage test with CW $Ti{:}Al_2O_3$ laser pumping at the absorption peak (975 nm)

able OH^- concentration in the glass corresponding to an absorption coefficient of about 0.2–0.3 cm^{-1} at a wavelength of 3.33 μm. This low dehydration level is still technologically difficult to obtain for the SELG glass. Fortunately, the typical Er concentration in diode-pumped microchip lasers lies within the $(5-15)\times10^{19}$ cm^{-3} range [1]. In this case, the Yb-Er energy transfer rate increases proportionally to the Er concentration, and becomes efficient enough even at the now accessible glass dehydration level.

7 Flashlamp pumped laser experiments

As will be understood from the above statements, no extreme laser performance can be anticipated from the SELG glass under flashlamp pumping due to the strong competition between the Yb→OH and Yb→Er energy transfer at the low ($\sim2\times10^{19}$ cm^{-3}) erbium concentration, which is typical for flashlamp-pumped erbium glasses. Laser rods, with dimensions of ∅ 6.3 × 67 mm, were made of the ‘old’ Yb-Er phosphate glass and the SELG glass. We used a flashlamp cavity cooled with ordinary distilled water that absorbs a significant amount of the pump energy in the Yb^{3+}absorption band. Nevertheless, the lasing properties of the SELG glass and the ‘old’ Yb-Er phosphate glass were compared in the same flashlamp cavity. The Yb^{3+} and Er^{3+} ion concentration was approximately the same in both glasses. Figure 4 represents the input-output energy dependencies for both glasses in the case of single-pulse operation. It can be seen that the efficiency of the new SELG glass is sufficiently lower than that of the ‘old’ one. However, it was still possible to extract a higher output power from the SELG rod as it had a higher damage threshold. Thus, an average output power of 6.65 W was obtained with the SELG glass, while the ‘old’ phosphate glass already fractured at 2.6 W. In this way, despite a poorer efficiency, the SELG glass demonstrated an average power per cm of rod length not far from that of the Kigre Inc. QX-Er glass (20 W from a 15.2 cm long rod [13]).

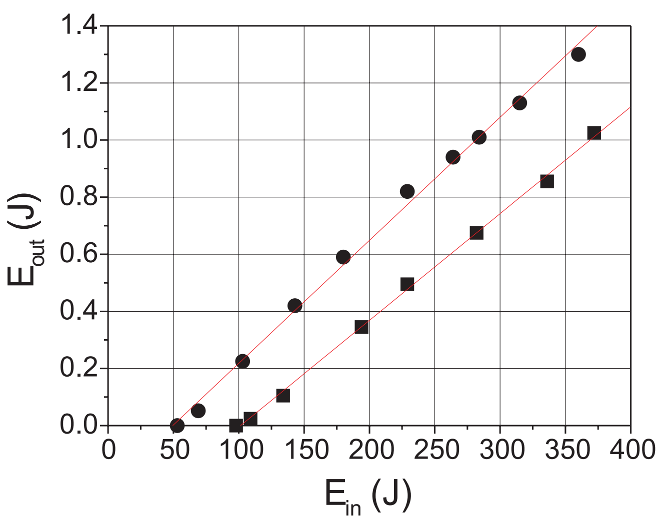

FIGURE 4 Laser output energy, E_{out}, versus flashlamp pump energy, E_{in}, for the SELG glass (*squares*) and for the ‘old’ phosphate glass (*circles*) under flashlamp pumping, both with concentrations of 2.3×10^{19} cm^{-3} Er^{3+}, $\sim2\times10^{21}$ cm^{-3} Yb^{3+}. The size of the rods was ∅ 6.3 × 67 mm

8 Laser pumped experiments

The synthesized batch of SELG glass for diode (and Ti:Al_2O_3) laser pumping contained a Er^{3+}concentration of 10^{20} cm^{-3}. Its dehydration level corresponded to an absorption coefficient of 1.38 cm^{-1} at 3.33 μm. The measured Yb^{3+} luminescent lifetime, τ_{Yb}, in this glass is 24 μs. From this the Yb-Er energy-transfer quantum yield, η, at a low excitation level can be estimated to be about 97%, which should be quite enough for efficient lasing.

The glass chip employed in the laser pumping experiments was a flat and parallel round plate of size ∅ 8 × 1 mm. It was rigidly joined to a divalent cobalt-doped flat-parallel Co^{2+}:$MgAl_2O_4$-plate of size ∅ 8 × 0.7 mm plate with a small-signal single-pass absorption of 1.5% at 1.54 μm. The outer facet of the glass chip had a 99.9% reflecting optical coating at 1.54 μm and that of the front side of spinel plate was 96%. Both of the optical coatings were transmitting > 90% at the pump wavelength. The tight joint with the Co^{2+}:$MgAl_2O_4$ plate was required for the following purposes:

- Passive Q-switching of the mini-laser cavity [14].
- Additional heat sink due to the high thermal conductivity of the Co^{2+}:$MgAl_2O_4$ plate (13.8 J/K cm s).
- Avoiding separate alignment of the Co^{2+}:$MgAl_2O_4$ plate and the laser glass chip.
- Ensuring stability with respect to mechanical vibrations.
- Diminishing of thermal deformations. The thermal expansion of Co^{2+}:$MgAl_2O_4$ ($\sim60\times10^{-7}$ K^{-1}) is very close to that of the SELG glass (see Table 1).

Lasing tests were done both with laser-diode and Ti:Al_2O_3 CW laser pumping. The pumping took place through the Co^{2+}:$MgAl_2O_4$ plate. In the case of the fiber-coupled diode pumping scheme, the radiation from a single 0.975 μm laser-diode was focused into the laser glass chip. The pumped area was circular with a diameter of 80 μm and about 80% of the incident pump power (up to 1.2 W) were absorbed in the laser glass. The laser emitted a stable train of Q-switched pulses, each having a duration of 5 ± 1 ns (FWHM). The pulse repetition rate ranged from 1–25 kHz depending on the pump power. The estimated peak output power reached 1.6 kW for the low repetition rates and 1.2 kW at high repetition rates without any traces of optical damage. The highest average output power obtained was an impressive 150 mW. The mean output power versus incident pump power is plotted in Fig. 5 (solid squares). The absolute optical-to-optical efficiency (with respect to the incident pump power) reached 15% in the diode-pumped case.

The applied pump power in the later case was obviously far below the damage level. To more carefully evaluate the average output power possibilities of such a micro-chip laser, we have tested its performance using CW Ti:Al_2O_3 laser pumping at 0.975 μm. In the case of low power (< 550 mW), the Ti:Al_2O_3 laser operated in the TEM_{00} mode, and the pump spot in the laser glass was round with a diameter of ∼ 80 μm. At high pump power (> 730 mW), the Ti:Al_2O_3 laser was operating in multi-mode and the pump spot diameter increased to ∼ 110 μm. The pump-power range between 550–730 mW corresponded to unstable lasing mode-structure, which resulted in an unstable and lowered output power of the Yb-Er:glass laser. In all of the cases, the Yb-Er

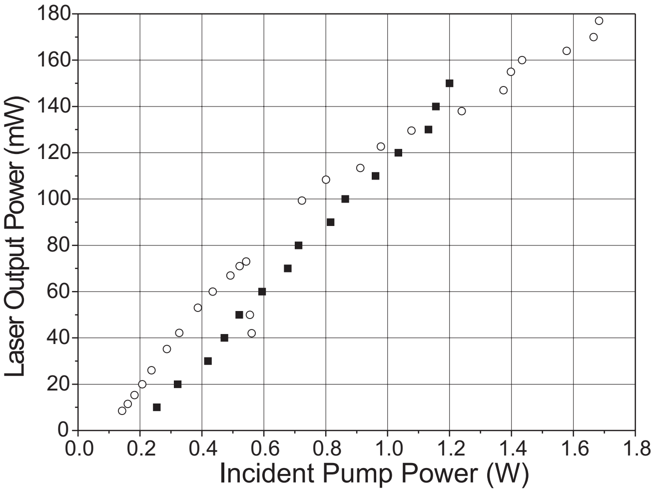

FIGURE 5 Input-output characteristics of the monolithic, passively Q-switched microchip laser under CW laser-diode pumping (*solid squares*) and $Ti:Al_2O_3$ laser pumping (*open circles*)

SELG microchip laser operated in the TEM_{00} mode and with several $(3-10)$ longitudinal modes. The input-output power performance in the case of $Ti:Al_2O_3$ laser-pumping is shown in Fig. 5 (curve 2). The output pulse duration was 5 ns (FWHM). At full pump power of the $Ti:Al_2O_3$ laser (1.7 W) the Yb-Er SELG glass chip emitted up to 180 mW of average power in the Q-switched mode and at a 70 kHz pulse repetition rate, still with no traces of optical or thermal damage.

9 Conclusion

A new, strong Yb-Er glass for high average-power lasers at 1.54 μm was developed. The glass is sufficiently stronger than the commercially available Yb-Er laser glasses, and is especially suitable for diode pumped high-average power microchip lasers. A microchip laser fabricated of the new glass, used under $Ti:Al_2O_3$ laser pumping, resulted in the highest reported average output power of 180 mW in passively Q-switched operation and with an excellent optical efficiency of 15% in the case of laser-diode pumping. The average output power was only limited by the available pump power, and not by the thermal damage of the laser glass.

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