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Laser generation in newly developed PAL77 and PAL80 glasses doped with Er\(^{3+}\) and Yb\(^{3+}\) ions

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Abstract

Laser generation in newly developed glasses PAL77 and PAL80 doped with erbium and ytterbium ions is presented. The slope efficiency of 19.94% and threshold of 229.7 mW were achieved. The results were compared with the results for the best types of glasses such as Concentrated, SELG and EAT14. It was shown that the investigated glasses can be successfully used as active media for lasers generating at 1.5\(\mu\)m wavelength.

Keywords: erbium glass, 1.5\(\mu\)m wavelength, microchip laser

(Some figures may appear in colour only in the online journal)

1. Introduction

For the last two decades a huge amount of effort has been invested in research to develop highly efficient glass [1–12] and crystalline [13–29] active media for laser generation at 1.5\(\mu\)m wavelength. Such lasers are attractive not only for telecommunication but also for medical and military applications [30]. The active ion used for generation at this wavelength is erbium, which is usually co-doped with ytterbium that can be pumped by commercially available laser diodes generating at 975 nm wavelength. There are many types of crystals and glasses that can be used as host materials for erbium and ytterbium and are characterized by good generation results [4, 7, 11, 12, 21–23]. Crystals have very good thermal and mechanical properties however their operation efficiency is limited by up-conversion processes. Glasses, on the other hand, with worse thermal and mechanical properties, are characterized by relatively high efficiencies which makes them preferable active media for generation at 1.5\(\mu\)m wavelength. Glasses are also easy to manufacture which in turn is crucial for mass production of microchip lasers.

One can find many types of glasses that can be used as active media for microchip lasers. However, on account of good generation parameters and commercial availability, four of them seem to be the most promising. The most common one is QX/Er glass manufactured by Kigre company [12].
Table 1. Mechanical parameters of PAL77 and PAL80 glasses.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>PAL77 (%)</th>
<th>PAL80 (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha_T$—thermal expansion coefficient (20–300°C)·10^{-2}K^{-1}</td>
<td>71.8</td>
<td>77.9</td>
</tr>
<tr>
<td>$\rho$—density (g·cm^{-3})</td>
<td>2.87</td>
<td>2.87</td>
</tr>
<tr>
<td>$\kappa$—thermal conductivity (W·m^{-1}·K^{-1})</td>
<td>0.745</td>
<td>0.745</td>
</tr>
</tbody>
</table>

Table 2. Spectroscopic parameters of PAL77 and PAL80 glasses.

<table>
<thead>
<tr>
<th>Glass</th>
<th>$l$ (mm)</th>
<th>$N_{Er}$·10^{21} (cm^{-3})</th>
<th>$N_{Yb}$·10^{19} (cm^{-3})</th>
<th>$\alpha_0$ (cm^{-1})</th>
<th>$\sigma_{abs}$·10^{-20} cm^{2}</th>
</tr>
</thead>
<tbody>
<tr>
<td>PAL77</td>
<td>1.9</td>
<td>1.73</td>
<td>8.9</td>
<td>19.4</td>
<td>1.12</td>
</tr>
<tr>
<td>PAL80</td>
<td>1.9</td>
<td>1.72</td>
<td>9.1</td>
<td>18.9</td>
<td>1.10</td>
</tr>
</tbody>
</table>

Figure 1. Absorption coefficient spectra of the investigated glasses.

The transmission spectra of the glasses were measured using spectrometer Lambda 900. Taking into account multiple reflections inside the samples the absorption coefficient spectra were calculated and are shown in figure 1.

The highest absorption coefficient for both glasses is at 975 nm wavelength. Moreover the higher value is for PAL77 which is due to a slightly higher concentration of ytterbium. The spectroscopic parameters such as concentrations of erbium $N_{Er}$ and ytterbium $N_{Yb}$, absorption coefficient at 975 nm wavelength $\alpha_0$, and the length of the investigated samples are presented in table 2. The absorption cross section can be calculated as a ratio of the absorption coefficient to the concentration of the ytterbium ions. Thus, the absorption cross sections at 975 nm $\sigma_{abs}$ amount to 1.12·10^{-20} and 1.10·10^{-20} cm^{2} for PAL77 and PAL80, respectively. The different values of $\sigma_{abs}$ for PAL77 and PAL80 are caused by different concentrations of erbium and ytterbium ions which is explained in paper [31].

Four samples of each glass were examined to make the generated results more reliable. To achieve efficient laser generation, appropriate coatings were deposited on the samples. Dichroic input mirrors (anti-reflection (AR) coatings at 975 nm and high reflection (HR) coatings at 1535 nm) were deposited on one side of the samples and AR coatings at 1535 nm on the other side. The glass samples used for the generation experiments were flat and parallel round plates of 6 mm diameter. Generation investigations were carried out for four output plain-parallel couplers with different reflections $R$ (98.70, 98.15, 97.64, and 96.49%) at 1535 nm. To pump the samples, a fiber coupled laser diode with fiber core diameter 100 µm was used. The laser diode operated at 975 nm wavelength at room temperature (25°C). To avoid damage of the glass by heat a quasi CW regime with a period equal to 20 ms and duty cycle of 50% was applied. The experimental setup is presented in figure 2.

3. Results and calculations

The slope efficiency $\eta$ and threshold $P_{th}$ of the investigated glasses for different output couplers are presented in table 3.

The symbol $n_g$ means that the generation was not achieved in the pump power range of up to 500 mW. The pump power was limited to this value so as to avoid damaging the active media. The characteristics of the average output power versus the average pump power incident on the active medium for the best sample of PAL80 are presented in figure 3.

The best generation results achieved for PAL77-1 and PAL80-4, and the best generation results of the other types of glasses presented in [11], are shown in table 4. It can be seen that the generation parameters are comparable, apart from the slope efficiency of PAL77 which is much lower. Better generation results for PAL80 may suggest that the addition of Sb$_2$O$_3$ improved the quality of the glass. Even though there are some differences in the slope efficiencies and thresholds, all glasses can be considered as potential active media for lasers generation at 1.5 µm. Slope efficiencies around 10% don’t eliminate...
the glass from application to microchip lasers, and such glass can also be thermally bonded with MALO saturable absorber making up monolithic microchip lasers.

All of the investigated samples generated several longitudinal modes around 1535 and 1545 nm wavelengths. The number of modes depended on the pump power and the reflection of the output coupler. For higher pump power, as well as for lower reflection of the output coupler, more modes were generated around 1545 nm wavelength. This phenomenon was caused by the changes in the relation between the gain and the resonator losses which is explained in [32]. The shift of modes from 1535 to 1545 nm wavelength versus pump power for PAL88-4 and for the output coupler with $R = 98.70\%$ are shown in figure 4.

![Experimental setup.](image)

**Figure 2.** Experimental setup.

**Table 3.** Slope efficiency $\eta$ and threshold $P_{th}$ of the investigated samples for different output couplers.

<table>
<thead>
<tr>
<th>$R$ [%]</th>
<th>Sample</th>
<th>$\eta$</th>
<th>$P_{th}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>98.70</td>
<td>PAL77-1</td>
<td>98.70</td>
<td>98.15</td>
</tr>
<tr>
<td>98.15</td>
<td>PAL77-2</td>
<td>8.88</td>
<td>10.16</td>
</tr>
<tr>
<td>97.64</td>
<td>PAL77-3</td>
<td>8.22</td>
<td>9.89</td>
</tr>
<tr>
<td>96.49</td>
<td>PAL77-4</td>
<td>7.94</td>
<td>8.08</td>
</tr>
<tr>
<td>96.70</td>
<td>PAL80-1</td>
<td>8.49</td>
<td>8.55</td>
</tr>
<tr>
<td>96.04</td>
<td>PAL80-2</td>
<td>8.48</td>
<td>9.06</td>
</tr>
<tr>
<td>96.49</td>
<td>PAL80-3</td>
<td>11.2</td>
<td>11.1</td>
</tr>
<tr>
<td>96.49</td>
<td>PAL80-4</td>
<td>14.05</td>
<td>16.44</td>
</tr>
</tbody>
</table>

![Output power versus pump power for PAL80-4 sample.](image)

**Figure 3.** Output power versus pump power for PAL80-4 sample.

**Table 4.** Comparison of the slope efficiency $\eta$ and the threshold $P_{th}$ for different glasses.

<table>
<thead>
<tr>
<th>Sample</th>
<th>$\eta$</th>
<th>$P_{th}$</th>
<th>$R$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concentrated</td>
<td>20.53</td>
<td>161.2</td>
<td>98.70</td>
</tr>
<tr>
<td>SELG</td>
<td>22.04</td>
<td>198.1</td>
<td>98.15</td>
</tr>
<tr>
<td>EAT14</td>
<td>22.85</td>
<td>165.3</td>
<td>97.64</td>
</tr>
<tr>
<td>PAL77-1</td>
<td>11.1</td>
<td>205.9</td>
<td>96.49</td>
</tr>
<tr>
<td>PAL80-4</td>
<td>19.94</td>
<td>229.7</td>
<td>96.49</td>
</tr>
</tbody>
</table>

The distribution of the beam intensity in the far-field region for PAL88-4 and PAL77-1 was measured. The measurement was carried out for the output coupler with $R = 98.70\%$ and for the pump power equal to 375 mW. The results are shown in...
J Młyniczak and N Belghachem

4. Summary

CW laser generation in newly developed erbium and ytterbium doped glasses was presented. The results show that the newly developed glasses, although not as efficient as the best types of glasses, are effective active media that can be used for laser generation at 1.5 μm wavelength. The glasses may also be used as the active media in q-switched lasers, and moreover they can be thermally bonded with MALO in order to make up a monolithic microchip laser. Investigations of pulse laser generation in separated as well as in thermally bonded samples will be done during the next stages of the ongoing project.

Acknowledgment

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References