Monolithic thermally bonded Er\(^{3+}\), Yb\(^{3+}\):glass/Co\(^{2+}\):MgAl\(_2\)O\(_4\) microchip lasers

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**Abstract**

The highest ever reported 10 kW peak power in monolithic thermally bonded Er\(^{3+}\), Yb\(^{3+}\):glass/Co\(^{2+}\):MgAl\(_2\)O\(_4\) microchip laser was achieved. To show the superiority of monolithic microchip lasers over those with external mirrors the laser generation characteristics of the same samples in both cases were compared. © 2015 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

**Introduction**

Microchip lasers generating at 1.5 μm wavelength find many applications in telecommunication as well as in the army [1,2]. The radiation at this wavelength is considered to be “eye-safe” and its transmission in the atmosphere and in optical fibres is very high. For this reason many different glass as well as crystalline active media doped with erbium and ytterbium ions have been developed for the last two decades [3–19]. Crystals are characterized by good mechanical and thermal properties but because of up-conversion processes their operation efficiency is limited. This limitation does not apply to glasses (to obtain efficient up-conversion luminescence the medium should possess relatively low phonon energy which is not characteristics of glasses [20]) and although they have worse thermal and mechanical parameters they became preferable active media for “eye-safe” microchip lasers [5,7,8,11]. From the point of view of most applications pulse generation is especially desirable and it can be easily achieved by the use of a semiconductor saturable absorber mirror (SESAM) [21] or a saturable absorber crystal [8]. Even though SESAMs enable to generate pulses with relatively high peak power (up to 10.6 kW) [22] they cannot withstand high energies because of their relatively low damage threshold (10–100 mJ/cm\(^2\)) [22]. This situation effectively limits the pulse energy that can be generated by such lasers. In case of saturable absorber crystals the damage threshold is 2–3 orders of magnitude higher (several J/cm\(^2\)) [23] which makes them preferable for high energy microchip laser applications. The most efficient type of saturable absorber at 1.5 μm is Co\(^{2+}\):MgAl\(_2\)O\(_4\) crystal (MALO) which can be rigidly joined [8] or thermally bonded [24] with the active media. The peak power generated in both cases using external mirrors reached 2.2 kW and 7.68 kW. However it can be further increase by depositing thin layers of input and output mirrors directly on the thermally bonded sample making one monolithic microchip laser.

In this paper we present the highest ever reported peak power (over 10 kW) of monolithic thermally bonded Er\(^{3+}\), Yb\(^{3+}\):glass/Co\(^{2+}\):MgAl\(_2\)O\(_4\) microchip laser. The generation parameters of thermally bonded samples using external mirrors were compared with the generation parameters of monolithic microchip lasers made of the same samples.

**Experimental setup and results**

Four samples of the phosphate glass doped with Er\(^{3+}\) and Yb\(^{3+}\) ions 1.9 mm long were thermally bonded with four samples of MALO saturable absorber 0.29 mm long with small signal transmission equal to 97.5%. The thermally bonded samples were characterized by 4 × 4 mm\(^2\) cross section and the length 2.19 mm. Both sides of them were polished to make them plane parallel. The active media and MALO crystals used to prepare the samples were described in more details in paper [24].

During the first experiment external plane mirrors were used. Input mirror was characterized by high transmission at 975 nm and high reflection at 1535 nm while output mirror was partially transmitting (T = 3.5%) at 1535 nm. The samples were in direct contact with the mirrors so the length of the resonator was equal...
together with straight line approximation are presented in Fig. 2. The generation characteristics showing the average output power versus the pump power incident on the active medium; SA, saturable absorber; GB, generated beam.

Fig. 2. Characteristics of the average output power versus the pump power incident on the active medium.

The monolithic microchip lasers show similar differences of generation parameters which can be explained in the same way as for the samples with separate mirrors. The best results were achieved for the second microchip reaching the output peak power of 10.18 kW. One can see that the results for monolithic microchip lasers are much better than for the same samples with separate mirrors. The peak power is almost two times higher while the threshold was significantly decreased. The main reason for better behaviour of the monolithic microchip lasers compared to that with external mirrors are lower losses in the cavity caused by reflections at the boundaries between different media (in case of monolithic samples there are no air gaps in the cavity). Moreover MALO works as an additional heat sink due to high thermal conductivity (13.8 J K\(^{-1}\) cm\(^{-1}\) s\(^{-1}\)) [8]. Additionally, monolithic setup ensures stability with respect to mechanical vibration and thermal deformation of the resonator and the alignment of the laser is much easier achievable. Comparing the results in Table 1 with that in Table 2 one can see that for monolithic microchip lasers the differences between the microchips (especially in case of the threshold and pulse repetition rate) are much lower. It shows that, from technological point of view, microchip lasers are more easily reproducible than lasers with separate mirrors.

In Figs. 5, 6 and 7 the pulse shape, pulse train (for 675.68 Hz repetition rate) and spectrum generated by the second monolithic

![Diagram](image_url)

Table 1

<table>
<thead>
<tr>
<th>Sample</th>
<th>(P_p) [kW]</th>
<th>(\tau_p) [ns]</th>
<th>(E_p) [J]</th>
<th>(\sigma) [%]</th>
<th>(P_h) [mW]</th>
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<td>3.44</td>
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One can see that there are some differences between generation parameters of the investigated samples. The second sample seems to be the best one with the highest peak power reaching 7.61 kW and the highest slope efficiency equal to 7.92%. The pulse width for all samples was around 3.5 ns. The lower peak power relates to lower threshold and higher repetition rate. Such situation may suggest that the differences may be caused by small variances of the length of the saturable absorber. The change of the length of the saturable absorber by 10% results in the change of the small signal transmission by 0.25% (the absorption coefficient of MALO was 0.873 cm\(^{-1}\)). Such difference is relatively big in case of microchip lasers and may result in big changes of the output peak power. The differences may also be caused by some inhomogeneity in the glass and in MALO or in the joints between them. Using laser beam analyser the \(M^2\) parameter for sample 2 was measured to be \(M^2 = 3.28\) and \(M^2 = 3.03\).

During the second experiment the input and output mirrors were directly deposited on the samples making monolithic microchip lasers. The characteristics of these mirrors were the same as in case of the first experiment (high transmitting input mirror at 975 nm and high reflecting at 1535 nm and the output mirror partially transmitting (\(T = 3.5\%\)) at 1535 nm). The length of the resonator was also equal to 2.19 mm. The stability of the resonator in this case is again achieved by thermal expansion of the glass sample. To pump the sample the same fibre coupled laser diode was used operating in the same quasi-cw regime. The setup used in this experiment is presented in Fig. 3. The generation characteristics showing the average output power in function of the pump power and the repetition rate is presented in Fig. 4. The generation parameters are shown in Table 2.

Table 2

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microchip laser are presented, respectively. Using laser beam analyser the $M^2$ parameter for this microchip was measured to be $M^2_x = 2.77$ and $M^2_y = 2.27$. The far-field distribution of the beam intensity is presented in Fig. 8. The blue square frame around the intensity distribution of the beam is caused by the aperture of the laser beam analyser and should not be taken into consideration.

3. Summary

In conclusion we have demonstrated the monolithic thermally bonded $\text{Er}^{3+}$, $\text{Yb}^{3+}$:glass/Co$^{2+}$:MgAl$_2$O$_4$ microchip lasers, that generated the highest 10.18 kW peak power ever reported for such type of lasers. The advantage of monolithic microchip lasers over those with external mirrors was shown.
Acknowledgements

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References