High-peak-power optically-pumped AlGaInAs eye-safe laser with a silicon wafer as an output coupler: comparison between the stack cavity and the separate cavity

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Abstract: An intrinsic silicon wafer is exploited as an output coupler to develop a high-peak-power optically-pumped AlGaInAs laser at 1.52 μm. The gain chip is sandwiched with the diamond heat spreader and the silicon wafer to a stack cavity. It is experimentally confirmed that not only the output stability but also the conversion efficiency are considerably enhanced in comparison with the separate cavity in which the silicon wafer is separated from other components. The average output power obtained with the stack cavity was 2.02 W under 11.5 W average pump power, corresponding to an overall optical-to-optical efficiency of 17.5%; the slope efficiency was 18.6%. The laser operated at 100 kHz repetition rate and the pulse peak power was 0.4 kW.

OCIS codes: (140.7270) Vertical emitting lasers; (140.3380) Laser materials; (140.6810) Thermal effects.

References and links

1. Y. T. Chang, K. W. Su, H. L. Chang, and Y. F. Chen, "Compact efficient Q-switched eye-safe laser at 1525 nm with a double-end diffusion-bonded Nd:YVO_4 crystal as a self-Raman medium," Opt. Express **17**(6), 4330–4335 (2009).
2. Y. F. Chen, "Efficient 1521-nm Nd:GdVO4 Raman laser," Opt. Lett. **29**(22), 2632–2634 (2004).
3. H. T. Huang, J. L. He, X. L. Dong, C. H. Zuo, B. T. Zhang, G. Qiu, and Z. K. Liu, "High-repetition-rate eye-safe intracavity KTA OPO driven by a diode-end-pumped Q-switched Nd:YVO_4 laser," Appl. Phys. B **90**(1), 43–45 (2008).
4. R. D. Stultz, V. Leyva, and K. Spariosu, "Short pulse, high-repetition rate, passively Q-switched Er:yttrium-aluminum-garnet laser at 1.6 microns," Appl. Phys. Lett. **87**(24), 241118 (2005).
5. Y. F. Chen, "Stimulated Raman scattering in a potassium titanyl phosphate crystal: simultaneous self-sum frequency mixing and self-frequency doubling," Opt. Lett. **30**(4), 400–402 (2005).
6. S. H. Ding, X. Y. Zhang, Q. P. Wang, F. F. Su, P. Jia, S. T. Li, S. Z. Fan, J. Chang, S. S. Zhang, and Z. J. Liu, "Theoretical and experimental study on the self-Raman laser with Nd:YVO_4 crystal," IEEE J. Quantum Electron. **42**(9), 927–933 (2006).
7. Y. F. Chen and L. Y. Tsai, "Comparison between shared and coupled resonators for passively Q-switched Nd:$GdVO_4$ intracavity optical parametric oscillators," Appl. Phys. B **82**(3), 403–406 (2006).
8. H. T. Huang, J. L. He, X. L. Dong, C. H. Zuo, B. T. Zhang, G. Qiu, and Z. K. Liu, "High-repetition-rate eye-safe intracavity KTA OPO driven by a diode-end-pumped Q-switched Nd:YVO_4 laser," Appl. Phys. B **90**(1), 43–45 (2008).
9. I. Sokólska, E. Heumann, S. Kück, and T. Łukasiewicz, "Laser oscillation of Er^{3+}:YVO_4 and Er^{3+}, Yb^{3+}:YVO_4 crystals in the spectral range around 1.6 μm," Appl. Phys. B **71**(6), 893–896 (2000).
10. M. Wang, L. Zhu, J. Zhou, W. Chen, and D. Fan, "Perfomance of an actively Q-switched Er^{3+}:Yb^{3+}:YVO_4 laser," Laser Phys. Lett. **10**(8), 085806 (2013).
11. A. Fuerbach, M. Jeanty, M. Yu. Sharonov, A. Bykov, V. Petricevic, and M. Lenzner, "Direct diode-pumped laser operation of Cr^{3+}- doped $LiInGeO_4$ crystals," Opt. Express **15**(24), 16097–16101 (2007).
12. J. Y. Huang, W. Z. Zhuang, W. C. Huang, K. W. Su, C. Hu, K. F. Huang, and Y. F. Chen, "Comparative studies for Cr^{4+}:YAG crystal and AlGaInAs semiconductor used as a saturable absorber in Q-switched Yb-doped fiber lasers," Opt. Express **17**(23), 20800–20805 (2009).

#252143 Received 16 Oct 2015; revised 13 Nov 2015; accepted 13 Nov 2015; published 17 Nov 2015

13. S. C. Huang, H. L. Chang, K. W. Su, A. Li, S. C. Liu, Y. F. Chen, and K. F. Huang, "AlGaInAs/InP eye-safe laser pumped by a Q-switched Nd:$GdVO_4$ laser," Appl. Phys. B **94**(3), 483–487 (2009).
14. H. L. Chang, S. C. Huang, Y.-F. Chen, K. W. Su, Y. F. Chen, and K. F. Huang, "Efficient high-peak-power AlGaInAs eye-safe wavelength disk laser with optical in-well pumping," Opt. Express **17**(14), 11409–11414 (2009).
15. P. Millar, R. B. Birch, A. J. Kemp, and D. Burns, "Synthetic diamond for intracavity thermal management in compact solid-state lasers," IEEE J. Quantum Electron. **44**(8), 709–717 (2008).
16. A. J. Maclean, R. B. Birch, P. W. Roth, A. J. Kemp, and D. Burns, "Limits on efficiency and power scaling in semiconductor disk lasers with diamond heatspreaders," J. Opt. Soc. Am. B **26**(12), 2228–2236 (2009).
17. F. van Loon, A. J. Kemp, A. J. Maclean, S. Calvez, J.-M. Hopkins, J. E. Hastie, M. D. Dawson, and D. Burns, "Intracavity diamond heatspreaders in lasers: the effects of birefringence," Opt. Express **14**(20), 9250–9260 (2006).
18. C.-P. Wen, P.-H. Tuan, H.-C. Liang, K.-F. Huang, and Y.-F. Chen, "Compact high-peak-power end-pumped AlGaInAs eye-safe laser with a heat-spreader diamond coated as a cavity mirror," IEEE J. Sel. Top. Quantum Electron. **21**(1), 148–152 (2015).
19. J. Jin, J. W. Kim, C.-S. Kang, J.-A. Kim, and T. B. Eom, "Thickness and refractive index measurement of a silicon wafer based on an optical comb," Opt. Express **18**(17), 18339–18346 (2010).
20. H. J. Eichler, B. Liu, M. Kayser, and S. I. Khomenko, "Er:YAG-laser at 2.94 μm Q-switched by a FTIR-shutter with silicon output coupler and polarizer," Opt. Mater. **5**(4), 259–265 (1996).

1. Introduction

High-peak-power lasers in the eye-safe wavelength region near 1.5-1.6 μm have been developed by several ways [1–12] including the stimulated Raman scattering, the optical parametric oscillators pumped by Nd-doped lasers, and the solid-state lasers (SSLs) directly using Er^{3+} -doped or Cr^{4+} -doped as the gain media. In addition to SSLs, optically-pumped InP-based semiconductor lasers are identified to be another promising technology for developing high-peak-power eye-safe laser sources. However, the low refractive index contrast in the eye-safe region usually causes a hindrance on the fabrication of distributed-Bragg-reflectors (DBRs) on the InP substrate [13]. To resolve the lack of good DBRs, a transparent Fe-doped InP substrate was exploited to deposit the gain medium of the periodically multiple quantum wells (QWs) and an external high reflection (HR) dielectric mirror was used to form the cavity [13,14]. With this approach, the direct end-pumping instead of the oblique pumping scheme can be employed, leading to a supplementary advantage. In optically-pumped semiconductor lasers (OPSLs), a diamond heat spreader is often required to contact the surface of the gain chip for the efficient heat removal [15–17]. Recently, a more compact cavity for the InP-based OPSLs has been demonstrated by depositing the dielectric HR coating on the uncontacted surface of the diamond heat spreader to eliminate the requirement of the external HR mirror [18]. Nevertheless, since an external output coupler (OC) is usually needed to form a complete cavity, the critical alignment and the sensitivity to vibration still exist for InP-based OPSLs.

In this work, we employ an intrinsic silicon wafer as an OC to develop a high-peak-power AlGaInAs laser at 1.52 μm. The coated diamond heat spreaders and the gain chip are pressed together with the silicon wafer to form a plane-parallel stack cavity. Compared with the performance of a separate cavity, where the silicon wafer is separated from all other components, the stack cavity is confirmed to enhance the cavity stability as well as the conversion efficiency. Furthermore, the bandwidth of the lasing spectrum obtained with the stack cavity is nearly two times narrower than that obtained with the separate cavity. With a pump width of 50-ns at a repetition rate of 100 kHz, the average output power is approximately 2.02 W under an average pump power of 11.5 W. The maximum output peak power is found to be up to 0.4 kW.

2. Device fabrication and experimental setup

Figure 1(a) and Fig. 1(b) show the experimental configuration of the AlGaInAs eye-safe laser pumped by a 1.06 μm Yb-doped pulsed fiber laser module (SPI redENERGY G3). The pump source was operated to output a 100 kHz pulse train with a pulse width of 50 ns. The diameter of the pump spot size was controlled to be approximately 800 ± 30 μm for optimizing the power scale up and the spatial overlap between the pump and lasing beams. A Fe-doped InP substrate with high transmission at the pump and lasing wavelength was exploited to fabricate the gain structure by metal-organic chemical-vapor deposition. The gain structure comprised 30 groups of triple AlGaInAs QWs that were spaced at half-wavelength intervals by AlGaInAs barrier layers to locate the QWs at the anti-nodes of the cavity longitudinal modes. To prevent the surface oxidation and recombination, a window layer of InP was deposited on the gain structure. Instead of the barrier pumping, the in-well pumping method was utilized to obtain a better carrier confinement for improving the quantum efficiency. The single-pass absorption of the gain chip was measured to be approximately 80% for the low-level pump power.

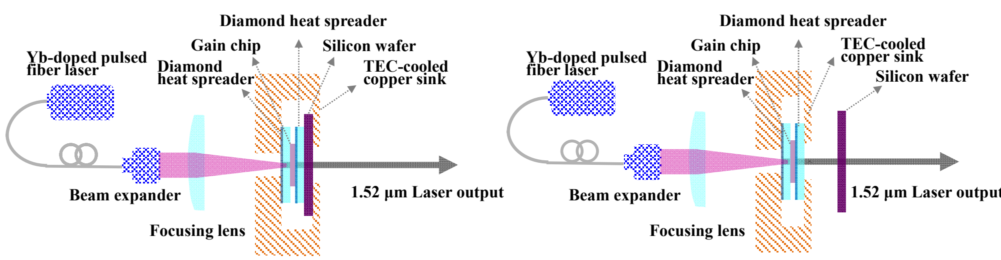

Fig. 1. Experimental configurations of the AlGaInAs eye-safe laser operated in (a) a stack cavity and (b) a separate cavity.

Two commercial single-crystal CVD diamonds (ElementSix Inc.) were utilized as heat spreaders to contact the both surfaces of the gain chip, respectively. One surface of the first CVD diamond was coated to simultaneously act as a heat-spreader and rear mirror with high-transmission (T > 95%) at 1.06 μm and high-reflection (R > 99.8%) at 1.52 μm at the pumped facet. The other surface of the first diamond was uncoated to remain flatness for capillary bonding to the epitaxial side of the gain chip. The total transmittance at 1.06 μm of this coated diamond was measured to be approximately 80%. One surface of the second CVD diamond was coated to be highly reflective of R > 99.8% at 1.06 μm to reflect the residual pump light for the secondary pass absorption; the other surface was uncoated. The coated surface of the second CVD diamond was used to contact with the substrate side of the gain chip. On the other hand, an intrinsic silicon wafer was employed for capillary bonding with the uncoated surface of the second CVD diamond to form an effective output coupler. The use of the silicon wafer was mainly due to its optical properties that reveal an extremely low absorption and a high refractive index at the wavelengths longer than 1100 nm [19,20]. The reflectivity of the silicon wafer only was approximately 48% in the range of 1150-1600 nm. The combined reflectivity of the second CVD diamond and silicon wafer was measured to be approximately 70% that was rather close to the optimal value of the present laser cavity, according to the previous investigation [18]. The thicknesses of the coated CVD diamonds, the gain chip and the silicon wafer were 500, 300, and 600 μm, respectively. The overall structure assembled by the first CVD diamond, the gain chip, the second CVD diamond, and the silicon wafer displayed a configuration of the stack cavity. The whole package of the stacked components was tightly pressed into a copper heat sink with a 2-mm-diameter aperture, where indium foils were employed to be the contact interface. The copper heat sink was cooled by a thermal-electric cooler at 8 °C. To make a comparison, a separate cavity was constructed by separating the silicon wafer from all other components with a distance of 10 mm, as shown in Fig. 1(b).

3. Experimental results

Figure 2 shows experimental results of average output powers versus the input absorbed powers for the stack and separate cavities. The threshold pump powers for both cases are nearly the same to be approximately 0.7 W. It can be seen that the slope efficiency and optical conversion efficiency for the stack cavity is significantly superior to that for the separate

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cavity. The increase of the efficiency for the stack cavity is primarily attributed to a lower intra-cavity loss which is estimated approximately 0.05 as well as a higher heat spreading. The input-output characteristics of the separate cavity displayed a thermally induced rollover phenomenon for the pump power greater than 10 W. In contrast, the average output power of the stack cavity could be scaled up. At an absorbed pump power of 11.5 W, the maximum average output power for the stack cavity was found to up to 2.0 W. The laser beam factor M^2 were both nearly the same and approximately 1.5 in stack and separate cavity.

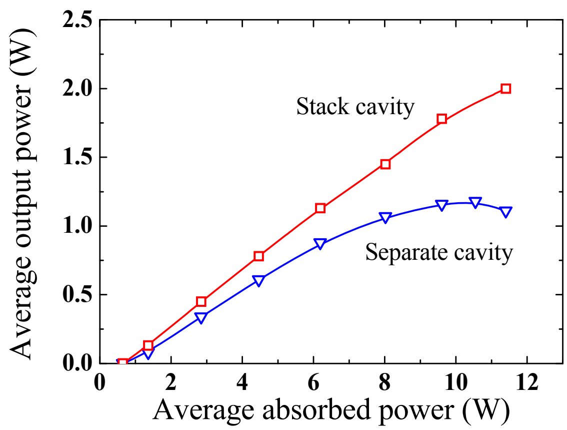

Fig. 2. Output performance of the optically-pumped AlGaInAs laser operated in stack and separate cavities at a 100 kHz repetition rate.

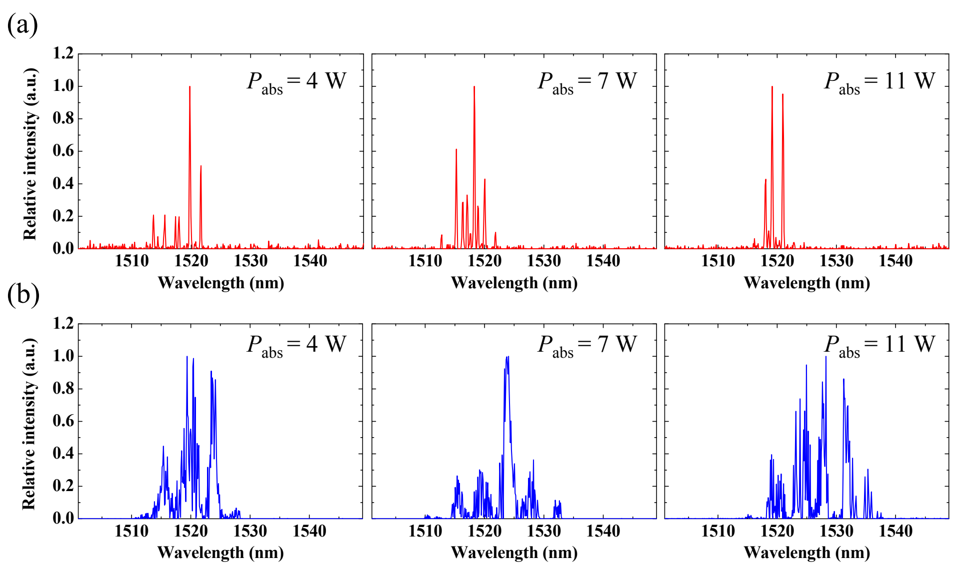

Fig. 3. The lasing spectrum of (a) stack cavity and (b) separate cavity obtained at three average absorbed powers.

The lasing spectra were measured by an optical spectrum analyzer (Advantest Q8381A) with a diffractive monochromator to allow high-speed measurement of pulsed light with a resolution of 0.1 nm. Figures 3(a) and 3(b) show the lasing spectra obtained under several absorbed pump powers for the stack and separate cavities, respectively. It can be seen that the bandwidths of the lasing spectra for the stack cavity are considerably narrower than those for

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the separate cavity. Note that since there are several optical interfaces inside the cavity, there exist the fine structures in the lasing spectra resulted from the intra-cavity etalon effect. As the absorbed pump power increases, the lasing spectra for both the stack and separated cavity can be roughly categorized into 3-5 main groups. As shown in Fig. 3, the combined etalon effects of the stack cavity can lead to the average spectral width for each group to be only 0.1-0.2 nm, close to the resolution of the spectrum analyzer. Figure 4 shows the thermally induced red shift of the central wavelengths of lasing spectra with respect to the absorbed pump powers under both cavity configurations. It can be seen that the central wavelength for the stack cavity only shifts from 1518 nm to 1519 nm, whereas the central wavelength shift for the separate cavity changes from 1518 nm to 1527 nm. The experimental result validates that the heat removal ability for the stack cavity is far better than that for the separate cavity.

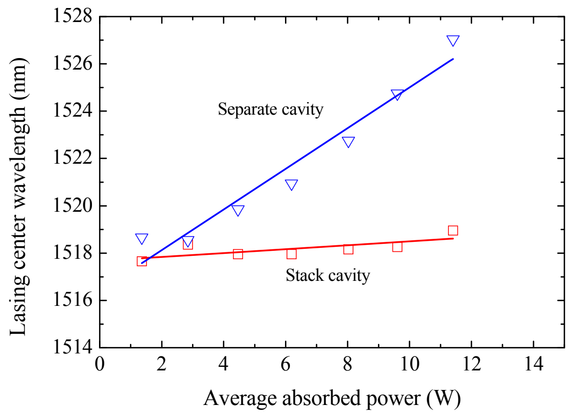

Fig. 4. The relationship between the central wavelength redshifts and the absorbed pump power for the eye-safe laser operated under the stack cavity and the separate cavity.

The temporal behaviors for the laser outputs under both cavity configurations were further recorded by a LeCroy digital oscilloscope (Wave pro 7100, 10 G samples/s, 1 GHz bandwidth). Figures 5(a) and 5(b) shows experimental results of the pulse trains measured at a pump power of 10 W for the stack and separate cavities, respectively, where there are two different time scales, one with time span of 200 μs for demonstrating the pulse train and the other with time span of 500 ns for demonstrating the single pulse shape. It is clear that the peak-to-peak fluctuation in the stack cavity is conspicuously better than that in the separate cavity and estimated as 3% and 10% respectively. On the other hand, the difference of the single pulse shape between the pump and lasing pulses is relatively small for the stack cavity and rather significant for the separate cavity. Figure 6(a) and 6(b) indicate the small pulse width variation and the corresponding pulse peak power operated at 100 kHz rate under stack cavity. The maximum peak power is found to be 0.43 kW at an absorbed pump power of 11.5 W. The superiority of the stack cavity is believed to mainly come from the better heat removal.

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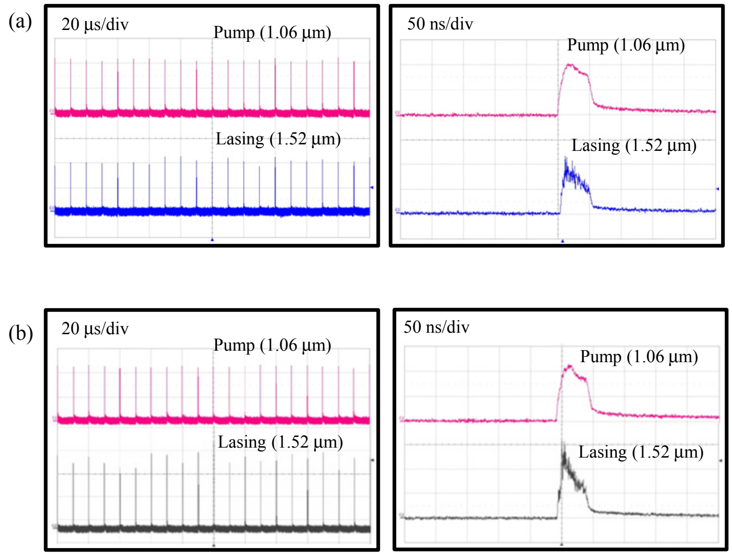

Fig. 5. Typical pump and output pulse trains and the single pulse profiles under 10-W absorbed power for (a) the stack cavity and (b) the separate cavity.

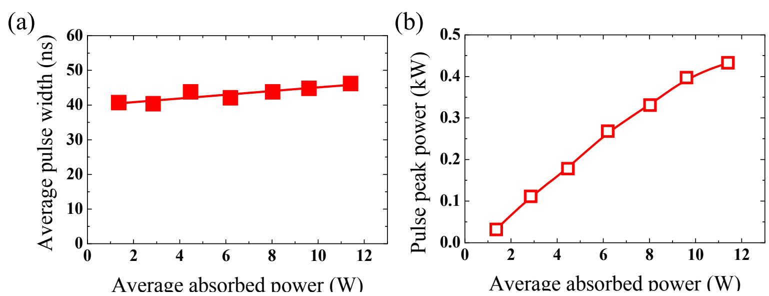

Fig. 6. The variation of (a) pulse width and (b) pulse peak power operated under stack cavity at a repetition rate of 100 kHz.

4. Conclusion

In summary, a high-peak-power AlGaInAs laser at 1.52 μm exploiting an intrinsic silicon wafer as an OC has been demonstrated. With the gain chip sandwiched between two coated diamond heat spreaders and then tightly contacted to a silicon wafer, a plane-parallel stack cavity with 2-mm-long cavity length has been fulfilled. The output performances for the stack cavity have been compared to a separate cavity with a similar configuration but removing the silicon wafer from all other components. The optical conversion efficiency and the cavity stability has been verified to be greater improved under the stack cavity design due to a better heat removal. The bandwidths of the lasing spectra for the stack cavity have been measured to be approximately two times narrower than those for the separate cavity. With a pump pulse width of 50 ns at a repetition rate of 100 kHz, the average output power and the output peak power under an absorbed pump power of 11.5 W have been found to be up to 2.02 W and 0.4 kW, respectively. These experimental results can provide a promising concept of stack cavity design in the development of microchip lasers.

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