Efficient mid-infrared Cr:ZnSe channel waveguide laser operating at 2486 nm

John R. Macdonald,[1,*] Stephen J. Beecher,[1] Patrick A. Berry,[2] Graeme Brown,[1] Kenneth L. Schepler,[2] and Ajoy K. Kar[1]

[1]*Institute of Photonics and Quantum Sciences, Heriot-Watt University, Edinburgh EH14 4AS, UK*

[2]*Air Force Research Laboratory, Wright Patterson Air Force Base, Ohio 45433, USA*

**Corresponding author: jrm7@hw.ac.uk*

Received April 10, 2013; revised May 21, 2013; accepted May 21, 2013; posted May 23, 2013 (Doc. ID 188537); published June 19, 2013

We report a Cr:ZnSe channel waveguide laser operating at 2486 nm. A maximum power output of 285 mW is achieved and slope efficiencies as high as 45% are demonstrated. Ultrafast laser inscription is used to fabricate the depressed cladding waveguide in a polycrystalline Cr:ZnSe sample. Waveguide structures are proposed as a compact and robust solution to the thermal lensing problem that has so far limited power scaling of transition metal doped II-VI lasers.

OCIS codes: (160.6990) Transition-metal-doped materials; (230.7380) Waveguides, channeled; (140.5680) Rare earth and transition metal solid-state lasers.

http://dx.doi.org/10.1364/OL.38.002194

Laser sources in the mid-IR region (2–5 μm) are of great interest to a wide range of disciplines due to the overlapping atmospheric transmission windows and the location of many organic and inorganic molecular absorption lines. Technologies such as remote sensing, laser surgery, noninvasive imaging, and communications are some examples of the diverse applications driving research into compact, tunable and high power sources.

Transition metal ions doped into II-VI semiconductors have shown many desirable qualities as laser gain media including large absorption and emission bandwidth, large emission cross sections, no excited state absorption, and room temperature operation [1–4]. Arguably the most promising of these materials is Cr:ZnSe, which to date has demonstrated high CW and pulsed output powers of 14 W and 18.5 W, respectively [2,5], wide continuous tunability of 1973–3339 nm [6], narrow linewidth operation [7], and sub-100-fs pulse durations [8]. However, despite these achievements, the power scaling of these sources has long been impeded by the high thermo-optic coefficient (dn/dT) of the materials, $70 \times 10^{-6}\ K^{-1}$ and $46 \times 10^{-6}\ K^{-1}$ for Cr:ZnSe and Cr:ZnS, respectively [4]. Under high pump irradiances, thermal lensing occurs in the gain media, causing cavity instability leading to decreasing laser power and even optical damage. These thermal issues can be reduced by appropriate choices in pump wavelength, crystal geometry, heat removal techniques, and master oscillator power amplifier (MOPA) configurations. These techniques have successfully pushed maximum CW output powers to above 10 W; however instability remains a problem, with thermal lensing currently the limiting factor [5].

An attractive solution to this problem would be to utilize a waveguide geometry that can offer a significant reduction to difficulties caused by thermal lensing in the gain medium [9]. Planar waveguides have been developed in Cr:ZnSe [10], with unreported laser output power. Channel waveguides provide the potential for lower thresholds and maintaining high gain over longer propagation distances by providing full two-dimensional transverse beam confinement. ZnSe optical fibers demonstrating low propagation losses have been manufactured [11]; however, transition metal doped ZnSe fiber has not yet been reported. Ultrafast laser inscription has been reported as a viable method for waveguide fabrication in ZnSe substrates [12], and the technology was used in the fabrication of the first Cr:ZnSe channel waveguide laser. These initial structures reported an output power of 18.5 mW for a pump power of ∼1200 mW utilizing a double depressed cladding structure [13]. This Letter details a significant improvement in waveguide fabrication resulting in more than a 15× improvement in laser efficiency using an alternative waveguide design.

Okhrimchuk *et al.* reported that exacting a subsurface material modification in ZnSe with a femtosecond laser is challenging [14]. We solved this problem by using the reduced peak power of picosecond pulses, limiting the effect of nonlinear processes that distort the pulse propagation prior to absorption, such as Kerr-induced self focussing and filamentation [12]. In this work, shorter pulses with higher peak powers are used in combination with multiple translations of the sample through the laser focus to create a high aspect ratio modified region. These tall elements with a lower refractive index than the pristene material create a thick cladding around an unmodified core region.

Waveguides were inscribed using 750 fs pulses at 100 kHz repetition rate from a Yb:fiber MOPA system (IMRA μJewel D400) with a range of pulse energies from 1–2.1 μJ investigated. These pulses were focused into a $8.5 \times 6.5 \times 2.1$ mm polycrystalline Cr:ZnSe sample, doped to $8.5 \times 10^{18}\ cm^{-3}$ with Cr ions, using a 0.6 NA objective. The sample was translated through the beam at velocities ranging from 0.5–27 $mm \bullet s^{-1}$. The structure design was similar to that first demonstrated in Nd:YAG by Okhrimchuk *et al.* [15], and consisted of multiple elements forming a circular cross section as shown in Fig. 1. Because of the high threshold for modification, each element was formed by multiple passes of the substrate through the laser focus. In addition to the parameters detailed above, the diameter, number of elements in each waveguide, and the number of translations of the sample through

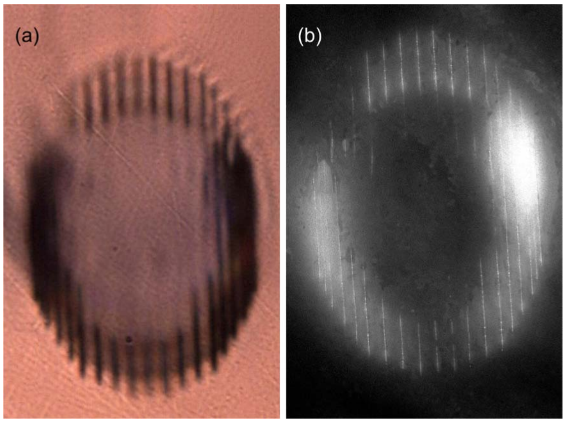

Fig. 1. (a) Optical micrograph of waveguide end facet taken in transmission mode under white light illumination. (b) Dark field image of the waveguide end facet. Field of view for both images is 100×150 μm.

the focus to create each element were investigated. Structures with diameters of 40, 60, 80, 120, 160, and 200 μm were fabricated with a range of component elements numbering from 40 to 120 and number of sample translations per element between 1 and 51. After inscription, the sample end facets were ground back and polished to remove any surface damage and waveguide tapering due to the inscription beam transitioning on and off the sample during fabrication leaving waveguides of 6.0 mm length.

The Cr:ZnSe sample with multiple inscribed waveguides was inserted into a cavity formed of a planar dielectric pump input mirror (T > 98% 1928 nm, R > 99% 2450 nm) and planar output coupler positioned at opposite ends of a waveguide. Both mirrors had pitch, yaw, and Z axis (defined as the axis of light propagating through the waveguide) translation control. The gain medium was pumped with a 1928 nm Tm:fiber laser (AdValue Photonics) capable of providing 1.35 W of randomly polarized output after an optical isolator and variable reflectivity power control. The optical isolator utilized with the pump source prevented back reflections from the waveguide end facet reaching the Tm:fiber pump laser. The angular alignment of the mirrors was optimized under full pump power and the mirrors were brought into close proximity to the waveguide end facets. In order to remove residual pump from the laser output, two longpass filters (Spectragon LP2000) were placed before the power meter and spectrometer. The transmission of this filter combination at 1928 nm was $<1 \times 10^{-4}$% and 84.5% at 2486 nm. The waveguide laser operation was investigated for 80%, 70%, and 60% reflectivity output couplers.

Laser output was observed for multiple structures, but the highest output power was obtained from an 80 μm diameter waveguide consisting of 80 elements with each element made up of nine translations of the sample through the laser focus, shown in Fig. 1. The input–output characteristics and slope efficiency of the laser were studied using each output coupler. The maximum slope efficiency, corrected for signal transmission through the pump blocking filter, of 45% was obtained using a 60% reflectivity output coupler and the maximum output power of 285 mW was recorded for 1.11 W of pump, giving a 26% optical-to-optical efficiency with no sign of roll-off in the laser efficiency. Slope efficiencies of 32% and 22% were obtained with the 70% and 80% reflectivity output couplers, respectively. Figure 2(a) shows the laser output power as a function of pump power for the 60%, 70%, and 80% reflectivity output couplers and continuous wave pumping. The maximum incident pump of 1.11 W was calculated by subtracting the Fresnel reflection from the uncoated front facet of the Cr:ZnSe, which contributes a 17.7% loss to the pump input. Since there will be some additional loss due to mode mismatch between the pump input and the waveguide mode, the efficiency calculated here can be assumed

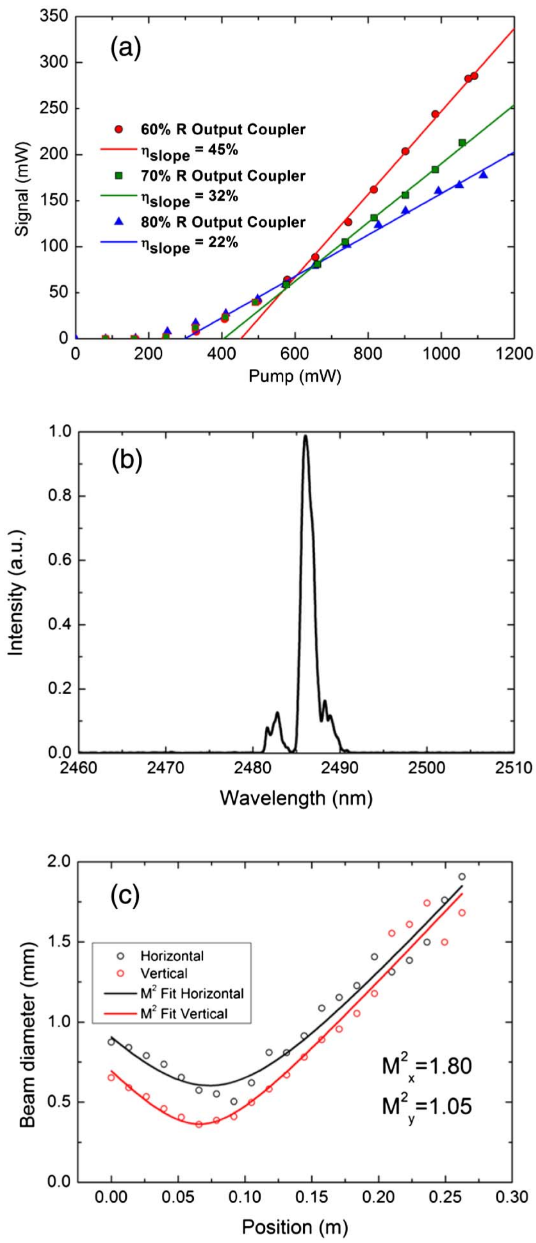

Fig. 2. (a) Laser output dependence on pump power for the waveguide laser using an output coupler with reflectivity of 60%, 70%, and 80%. (b) Optical spectrum of the laser for 1.1 W of pump power. (c) M^2 beam quality for 1.1 W of pump power.

to be a lower bound value. For this maximum output power, the laser spectrum and beam quality were measured. Figure 2(b) presents the optical spectrum showing a peak output at 2486 nm and spectral width of 1.6 nm (FWHM). Figure 2(c) shows the beam quality of the laser. A $M^2 = 1.05$ was measured in the axis parallel to the inscription laser propagation direction and $M^2 = 1.80$ was measured in the axis orthogonal to the inscription laser propagation direction.

To measure cavity round trip losses, a Findlay–Clay type analysis was carried out [16]. Because of the cavity design, it was important to consider thermal expansion of the gain medium under incident pump. Any excessive expansion of the gain medium would change the coupling conditions between the cavity mirrors and waveguide end facets. To avoid the need for realignment of the cavity, a chopper was placed in the pump beam path for these laser threshold measurements. The chopper operated at a 50% duty cycle and this allowed cavity alignment to be optimized at the low average incident pump power of 200 mW (400 mW peak power). Threshold measurements could then be taken with minimal thermal effects. The average threshold powers were observed to be 125, 155, and 200 mW (250, 310, and 400 mW peak) with the 80%, 70%, and 60% reflectivity output couplers, respectively. Using these values and assuming all parasitic cavity losses are due to waveguide propagation loss, this is calculated to be $0.7\ \mathrm{dB} \bullet \mathrm{cm}^{-1}$, which is a significant reduction from the value of $3.5\ \mathrm{dB} \bullet \mathrm{cm}^{-1}$ previously demonstrated [13].

In conclusion, we have demonstrated a Cr:ZnSe channel waveguide laser with a factor of 9 improvement in slope efficiency compared to previously demonstrated devices, raising the current best performance to 45%. A 15× improvement in maximum output power from 18.5 to 285 mW was achieved and this value was limited only by the available pump power of 1.11 W. Operating with the maximum available pump power, the system displayed an optical conversion efficiency of 26%. A low threshold of 250 mW was observed using an 80% reflectivity output coupler. Such low laser thresholds will allow the construction of compact and robust, diode pumped Cr:ZnSe lasers for real world applications. The device performance detailed in this Letter paves the way to utilizing Cr:ZnSe channel waveguides to power scale current chromium laser technology.

This work was supported by the European Office of Aerospace Research and Development (EOARD) grant number FA8655-11-1-3001 and the Engineering and Physical Sciences Research Council (EPSRC) grant number EP/G030227/1. J. R. M and S. J. B thank Mark Stewart for assistance on the design and manufacturing of optomechanical apparatus.

References

1. L. D. DeLoach, R. H. Page, G. D. Wilke, S. A. Payne, and W. F. Krupke, IEEE J. Quantum Electron. **32**, 885 (1996).
2. T. J. Carrig, G. J. Wagner, W. J. Alford, and A. Zakel, Proc. SPIE **5460**, 74 2004).
3. R. H. Page, K. I. Schaffers, L. D. DeLoach, G. D. Wilke, F. D. Patel, J. B. Tassano, Jr., S. A. Payne, W. F. Krupke, K. T. Chen, and A. Burger, IEEE J. Quantum Electron. **33**, 609 (1997).
4. I. T. Sorokina, Opt. Mater. **26**, 395 (2004).
5. P. A. Berry and K. L. Schepler, Opt. Express **18**, 15062 (2010).
6. E. Sorokin, I. T. Sorokina, M. S. Mirov, V. V. Fedorov, I. S. Moskalev, and S. B. Mirov, in *Advanced Solid-State Photonics* OSA Technical Digest Series (CD) (Optical Society of America, 2010), AMC2.
7. G. J. Wagner, B. G. Tiemann, W. J. Alford, and T. J. Carrig, in *Advanced Solid-State Photonics* OSA Technical Digest (Optical Society of America, 2004), WB12.
8. M. N. Cizmeciyan, H. Cankaya, A. Kurt, and A. Sennaroglu, Appl. Phys. B **106**, 887 (2012).
9. J. Nilsson and D. N. Payne, Science **332**, 921 (2011).
10. J. E. Williams, V. V. Fedorov, D. V. Martyshkin, I. S. Moskalev, R. P. Camata, and S. B. Mirov, Opt. Express **18**, 25999 (2010).
11. J. R. Sparks, R. He, N. Healy, M. Krishnamurthi, A. C. Peacock, P. J. A. Sazio, V. Gopalan, and J. V. Badding, Adv. Mater. **23**, 1647 (2011).
12. J. R. Macdonald, R. R. Thomson, S. J. Beecher, N. D. Psaila, H. T. Bookey, and A. K. Kar, Opt. Lett. **35**, 4036 (2010).
13. J. R. Macdonald, S. J. Beecher, P. A. Berry, K. L. Schepler, and A. K. Kar, Appl. Phys. Lett. **102**, 161110 (2013).
14. A. G. Okhrimchuk, V. K. Mezentsev, H. Schmitz, M. Dubov, and I. Bennion, Laser Phys. **19**, 1415 (2009).
15. A. G. Okhrimchuk, A. V. Shestakov, I. Khrushchev, and J. Mitchell, Opt. Lett. **30**, 2248 (2005).
16. D. Findlay and R. A. Clay, Phys. Lett. **20**, 277 (1966).