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Citation for published version:

MacDonald, JR, Beecher, SJ, Berry, PA, Schepler, KL & Kar, AK 2013, 'Compact mid-infrared Cr:ZnSe channel waveguide laser', *Applied Physics Letters*, vol. 102, no. 16, 161110.
<https://doi.org/10.1063/1.4803058>

Digital Object Identifier (DOI):

[10.1063/1.4803058](https://doi.org/10.1063/1.4803058)

Link:

[Link to publication record in Heriot-Watt Research Portal](#)

Document Version:

Publisher's PDF, also known as Version of record

Published In:

Applied Physics Letters

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Citation: [Applied Physics Letters](#) **102**, 161110 (2013); doi: 10.1063/1.4803058

View online: <http://dx.doi.org/10.1063/1.4803058>

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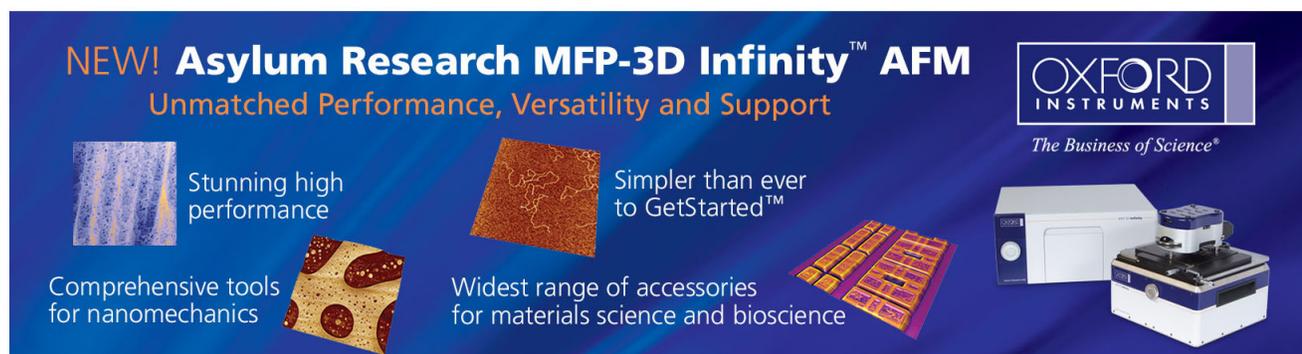
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Compact mid-infrared Cr:ZnSe channel waveguide laser

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(Received 18 January 2013; accepted 13 April 2013; published online 24 April 2013)

We demonstrate a mid-infrared channel waveguide laser in Cr:ZnSe operating at 2573 nm. The compact cavity has a total footprint of less than 3 cm² and produces a maximum power output of 18.5 mW. The depressed index cladding structures guide across the entire emission band of Cr:ZnSe, from 1.9 μm to 3.4 μm, indicating the viability of the device for integrated and robust continuously tunable mid-infrared sources. © 2013 AIP Publishing LLC [<http://dx.doi.org/10.1063/1.4803058>]

Laser sources in the mid-infrared region (2–5 μm) are of great interest for a broad range of medical, commercial, scientific, and military applications due to the location of many organic and inorganic molecular absorption lines in this region. In particular, technologies such as molecular spectroscopy, laser surgery, chemical sensing, non-invasive imaging, and military applications are driving research into high power, tunable, compact, and robust mid-infrared laser sources.^{1–3} Cr²⁺ doped II-VI semiconductors have been shown to possess many of the required properties for these applications, including large emission cross-sections, room temperature operation, and broad gain bandwidth.^{4–6} Indeed, Cr:ZnSe has been dubbed the Ti:Sapphire of the mid infrared having demonstrated wide continuous tunability from 1973 to 3349 nm,⁷ narrow linewidth,⁸ high power continuous wave operation² of 14 W, and pulsed operation of 18.5 W.⁹ Further increases in output power have been limited by the severe problem of thermal-lensing due to the high thermo-optic coefficient ($\frac{dn}{dT}$) of ZnSe ($70 \times 10^{-6} \text{ K}^{-1}$).⁵ This property leads to self-focusing in the laser gain material, often causing cavity instability or optical damage. As a result, crystal geometry, cavity design, and heat removal techniques have all been investigated to tackle thermal issues. One example is the master oscillator power amplifier (MOPA) configuration,² which allowed for the increase in the maximum achievable continuous wave output power to 14 W. Despite improvements to the design, thermal problems ultimately remain the limiting factor in accessing greater output powers. A desirable approach would be to utilise a guided-wave geometry thereby potentially reducing the effects of thermal-lensing.¹⁰ Williams *et al.*¹¹ have demonstrated lasing in a planar waveguide structure but with unreported power; Sparks *et al.* have demonstrated ZnSe fiber structures with low losses,¹² but to date have not published results with the Cr doping.

Aside from potential benefits for thermal issues, the waveguide geometry offers a compact and environmentally robust solution for laser technology and its implementation outside of the laboratory. Moreover, the integrated nature of a waveguide cavity would avoid intracavity absorption of the laser emission due to water vapour, which is a significant problem in producing modelocked Cr:ZnSe laser sources.¹³

Ultrafast laser inscription technology offers an attractive solution to these problems by allowing the fabrication of channel waveguides inside bulk Cr:ZnSe crystals. Laser inscription fabricates sub-surface channel waveguides via nonlinear absorption effects that lead to ionisation of electrons and a subsequent energy transfer into the material lattice.¹⁴ This energy transfer can result in localized structural modifications, including but not limited to a localized change in refractive index. Careful control of this refractive index modification can allow the direct inscription of waveguides inside the bulk material by translating the material substrate through the laser focus. Furthermore, this inscription technique can be used to create waveguides of arbitrary cross-section by fabricating the desired structure with multiple, successive translations of the material substrate through the laser focus.¹⁵

The substrate used for this study was a polycrystalline Cr:ZnSe substrate measuring $6.8 \times 7.5 \times 2.8$ mm and containing $6 \times 10^{18} \text{ cm}^{-3}$ Cr ions obtained commercially from IPG Photonics Corporation. In order to achieve low loss guiding of mid-infrared light it was necessary to develop a double depressed cladding structure in the bulk Cr:ZnSe. In this case, laser inscription was used to induce a localised reduction in the refractive index of the bulk material.^{16,17} The structures fabricated consisted of an outer cladding region, an inner cladding region, and a core region comprised of unmodified Cr:ZnSe as shown in Figure 1. The inner cladding was subject to low inscription irradiances (pulse energies $< 0.5 \mu\text{J}$) in order to avoid micro-cracking in the substrate, which would lead to greater scattering losses in

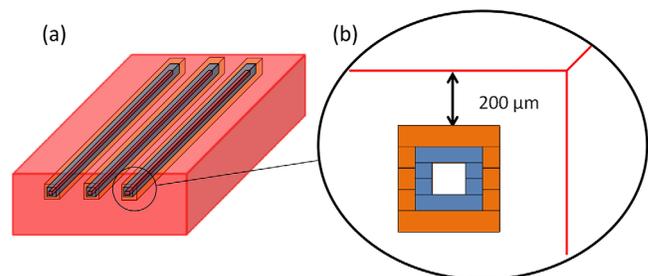


FIG. 1. Waveguide design. (a) Bulk Cr²⁺:ZnSe crystal with buried channel waveguides. (b) Detailed view of the double depressed cladding waveguide cross-section. Red regions represent a region subject to higher irradiances than orange regions. White coloured core is a non-irradiated Cr:ZnSe region now surrounded by reduced index cladding.

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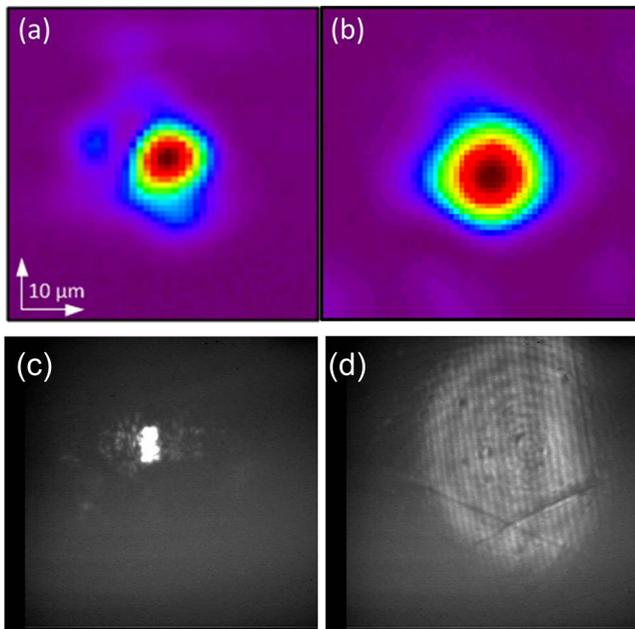


FIG. 2. Pump and signal waveguide modes. (a) Image of the 1928 nm waveguide mode. (b) Image of the 3392 nm waveguide mode, showing wavelengths beyond the emission band of $\text{Cr}^{2+}:\text{ZnSe}$ are also guided by the structure. The field of view for both (a) and (b) is $60\ \mu\text{m}$ horizontal, $50\ \mu\text{m}$ vertical. (c) Image of the 2500 nm waveguide mode. (d) Image of the 2500 nm light propagating through unmodified material under the same optical alignment as (c).

the waveguide. An outer cladding region was fabricated farther from the waveguide core with higher irradiances to reduce losses due to tunnelling (see Figure 1(b)).

Waveguide inscription in a ZnSe substrate is complicated by the large nonlinear component of the refractive index (n_2) of ZnSe, $2.8 \times 10^{-14}\ \text{cm}^2\ \text{W}^{-1}$ at 1060 nm, greater than $100\times$ that of fused silica.¹⁸ This becomes highly significant when tightly focusing femtosecond pulses inside the material, as the peak irradiances generated are typically $>1\ \text{TW}\ \text{cm}^{-2}$. In order to avoid detrimental nonlinear effects such as filamentation and self-focusing of the inscription beam, it is necessary to use pulse durations on the order of picoseconds rather than the more commonly used femtosecond pulse inscription.¹⁹ This reduces the peak irradiance generated inside the substrate and therefore avoids detrimental nonlinear effects. The

waveguide inscription was performed using a fiber master oscillator power amplifier (Fiber MOPA) source. The laser (IMRA $\mu\text{Jewel D400}$) utilizes chirped pulse amplification and by limiting the recompression of the pulse after amplification, a longer chirped pulse can be used for waveguide inscription. The central wavelength of the inscription laser was 1047 nm, and pulse energies of $0.35\text{--}1\ \mu\text{J}$ were used to fabricate a range of waveguides at a depth of $200\ \mu\text{m}$ below the surface of the bulk $\text{Cr}:\text{ZnSe}$. The inscription beam was focused with a 0.6NA aspheric lens, and the sample was translated through the focus with Aerotech XYZ air-bearing stages at a velocity of $0.5\ \text{mm}\ \text{s}^{-1}$. A succession of individual scans was used to construct the desired structure cross-section. The pitch between each individual scan was $0.4\ \mu\text{m}$ in the horizontal axis, and the vertical offset between each block of modification was 9 and $12\ \mu\text{m}$ for the inner and outer cladding, respectively. These distances correspond to the physical distance that the air-bearing stages were translated. The final structure was measured $72 \times 110\ \mu\text{m}$ in cross-section.

The guiding characteristics of the waveguide were assessed at the two extremes of the emission band, 1928 and 3390 nm. For 1928 nm a single mode AdValue Photonics thulium fiber laser was coupled into the waveguide with an anti-reflection (AR) coated ZnSe objective. The output facet was imaged with another AR coated ZnSe objective onto a Flir SC7000 camera, the intensity distribution of the waveguide mode is shown in Figure 2(a). For the long wavelength edge of the emission band a helium neon laser operating at 3390 nm was coupled into the waveguide using the ZnSe objective and imaged in the same manner, and the intensity distribution of the waveguide mode is presented in Figure 2(b). To demonstrate the guiding properties of the structure Figure 2(c) shows 2500 nm light from a $\text{Cr}:\text{ZnSe}$ laser coupled into the waveguide, and Figure 2(d) shows the light propagating through unmodified material under the same focusing conditions.

To measure propagation losses of the structure a 2300 nm narrow linewidth, single emitter laser diode from m2k-laser was coupled into the waveguide. By changing the temperature of the waveguide the optical length of the etalon formed by Fresnel reflections from the front and back facet is changed. By measuring the visibility of this fringe set the

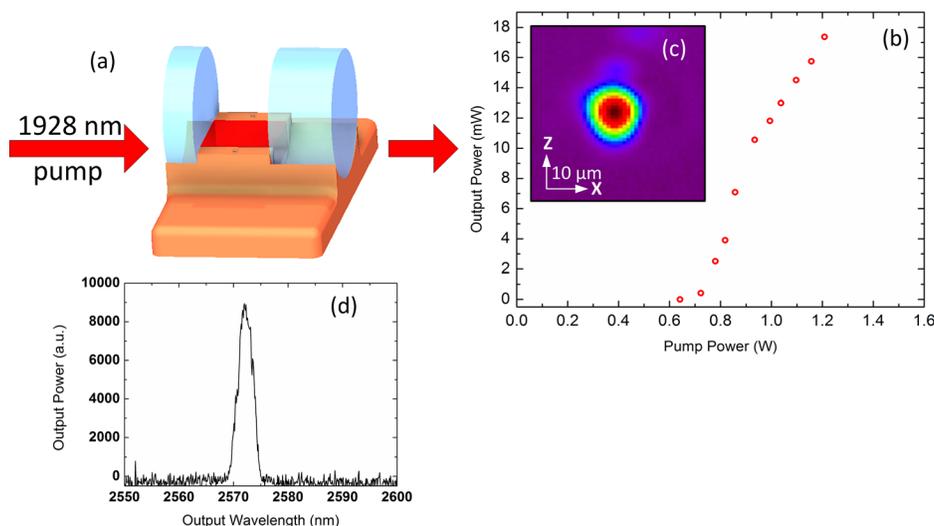


FIG. 3. Waveguide laser characterisation studies. (a) Waveguide laser cavity assembly with butt-coupled dichroic mirror and output coupler mirror. (b) Laser output power against input pump power. (c) Near field image of the laser output mode at 2573 nm. (d) Laser output power spectral density.

fineness of the etalon can be calculated, yielding an upper limit for propagation losses of 3.5 dB cm^{-1} at 2300 nm.

To test the waveguide as a laser gain element a simple laser cavity was constructed by butt-coupling a dichroic mirror on the input side of the waveguide and an output coupler mirror on the opposite side with optical coupling compound between all facets. The dichroic mirror was anti-reflection coated for the pump wavelength and highly reflective for 2050–2430 nm. The output coupler was 80% reflective for a wavelength range of 1700–2700 nm. The waveguide was pumped at 1928 nm by the thulium fiber laser, and continuous wave lasing was observed with a threshold of 700 mW. The laser spectrum was measured using a 300 mm monochromator (Gilden Photonics) and showed lasing at 2573 nm. The mode profile was measured by imaging the waveguide facet onto the Flir SC7000. These data are displayed in Figure 3.

After threshold an initial slope efficiency of 5% was observed with a secondary slope efficiency seen for pump powers over 900 mW. The origin of this change in slope is unclear at present, but the secondary slope shows no sign of deviation or roll off at higher pump powers over 1 W and maintains a slope efficiency of 2.5% despite the high pump irradiance of 490 kW cm^{-2} . This observation is a key indicator that the waveguide structures are suitable for high power applications that require operation at high pump irradiances. The output showed a single mode, near-symmetric 2-D Gaussian distribution with a slight asymmetry, as indicated in Figure 3(b). The mode field diameter was measured as $16.6 \mu\text{m}$ in the horizontal axis and $19.9 \mu\text{m}$ in the vertical axis. The maximum output power achieved was 18.5 mW for a pump power of 1.2 W. We believe the low efficiency of this initial demonstration to be due to the high propagation losses in the laser cavity. A substantial reduction in the propagation losses could be achieved through further optimization of the waveguide fabrication parameters, reducing micro-cracking in waveguide outer cladding.

The development of a Cr:ZnSe channel waveguide laser marks a major turning point in the realization of compact and robust mid-infrared laser sources. The small cavity length of 6 mm is comparable to other compact Cr:ZnSe laser cavities of 2.5 mm (Ref. 20) and 10 mm (Ref. 21), and the environmental stability offered by waveguide laser geometry will allow this technology to be exploited in real life applications. The integrated cavity design offers a solution to the problem of operating on water absorption peaks for laser surgery and for the modelocking of Cr:ZnSe lasers. Furthermore, through optimization of waveguide losses,

adaptation of the guided-wave geometry could be utilized to significantly reduce the problem of thermal lensing from the challenge of reaching higher powers with Cr:ZnSe lasers. The combination of these attributes provides the means to develop mid-infrared sources with the desired qualities for a host of applications.

This work was supported by the European Office of Aerospace Research and Development (EOARD) (Grant No. FA8655-11-1-3001) and the Engineering and Physical Sciences Research Council (EPSRC) (Grant No. EP/G030227/1). J.R.M. and S.J.B. thank Graeme Brown for helpful discussions. K.L.S. and P.A.B. thank Sean McDaniel and Jason Schmidt for experimental assistance.

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