Mid-Infrared Depressed Cladding Waveguides in Chromium Doped II-VI Semiconductors

Adam Lancaster[1], John R. Macdonald[2], Stephen J. Beecher[3], Sean A. McDaniel[4], Gary Cook[5] , Patrick A. Berry[5], Kenneth L. Schepler[6] and Ajoy K. Kar[1*]

[1]Institute of Photonics and Quantum Sciences, Heriot-Watt University, Edinburgh EH14 4AS, UK
[2]Optoscribe, 5 Bain Square, Kirkton Campus, Livingstion, EH54 7DQ, UK
[3]Optoelectronics Research Centre, Southampton University, Southampton SO17 1BJ, UK
[4]Leidos Inc, 3745 Pentagon Blvd, Beavercreek, OH 45431, USA
[5]Air Force Research Laboratory, Sensors Directorate, Wright Patterson Air Force Base, OH 45433, USA
[6]CREOL, The College of Optics & Photonics, University of Central Florida, 4000 Central Florida Blvd., Orlando, Fl, 32816, USA
**a.k.kar@hw.ac.uk*

Laser sources in the mid-infrared region (2-5µm) are of great interest to application in communications, remote sensing and IR countermeasures. Transition metal doped II-VI semiconductors possess many desirable laser medium qualities such as large emission bandwidths, no excited state absorption and room temperature operation[1-3]. Of these materials chromium doped ZnSe has come to the fore with tens of watts output power and tuneable laser operation form 1973-3349 nm demonstrated in Cr:ZnSe [4, 5]. Power scaling of these sources to beyond 20 W has been hampered by the high thermo-optic coefficient of the host material, 70×10^{-6} K^{-1} for ZnSe [7]. Consequently, at high pump irradiances, thermal lensing occurs in the gain medium leading to cavity instability and even optical damage. Waveguide geometry provides an attractive solution to the problem of thermal lensing, bringing the prospect of compact, robust, vibration insensitive geometry well suited to applications outside of the laboratory.

Ultra-fast laser inscription (ULI) is used to fabricate the waveguides in the ZnSe and ZnS. ULI focuses femtosecond pulses inside a transparent material to induce a change in refractive index at the beams focus via non liner absorption processes. The waveguides used in this work take advantage of a negative refractive index change and hence ULI is used to inscribe the cladding of the waveguide. The sample is translated thought the focus of the laser multiple times to form a annular waveguide, the end facet of a waveguide is shown in Figure 1.

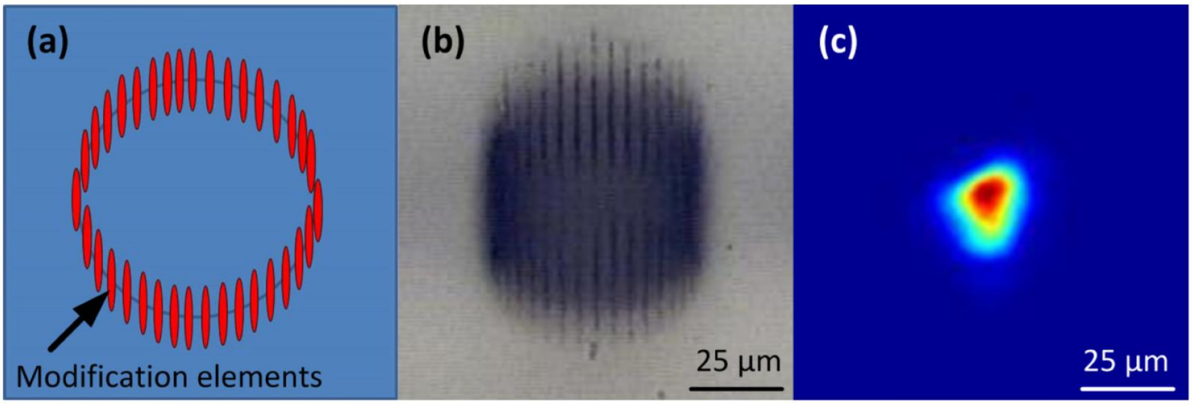

Figure 1. (a) Schematic diagram of annular depressed cladding waveguide structure in Cr:ZnS. (b) optical micrograph of 60 µm diameter waveguide end facet composed of 40 modification elements. (c) associated laser output mode at 2.33 µm imaged at waveguide end facet. Image taken using the 60%R output coupler cavity [6].

A laser cavity is formed by placing an input coupler and output coupler at end facets of the sample. The pump laser beam is focused into the sampler using an objective lens and the output of the laser is collimated using a second lens. The experimental setup used for the Cr:ZnSe laser is shown in Figure 2. This laser achieved a slope efficiency of 45% and a maximum output power of 285 mW which was only limited by the available pump power of 1200 mW [8]. A tuneable waveguide has been demonstrated with a range of 2077-2770 nm and line widths as low as 53 pm [9].

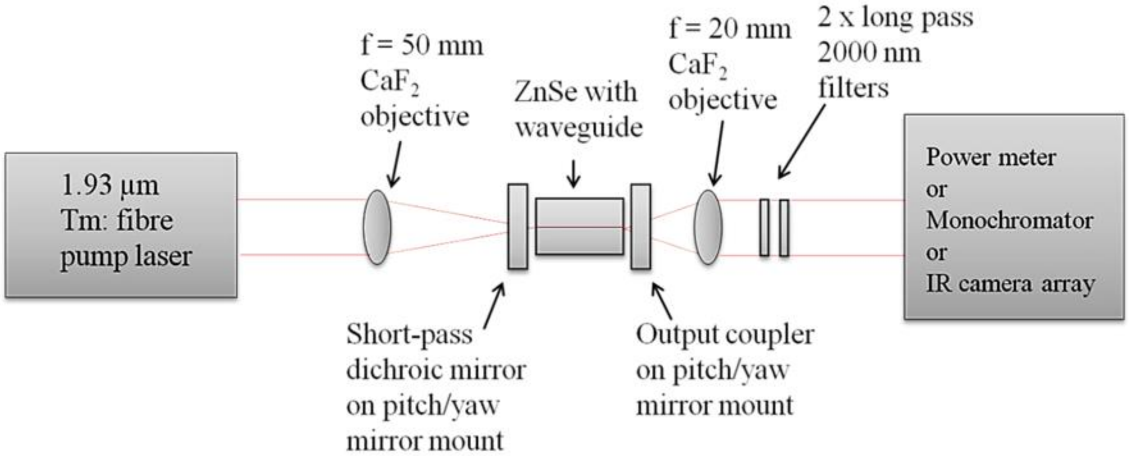

Figure 2. Schematic of Cr:ZnSe circular depressed cladding waveguide laser setup.

A 38 W thulium fibre laser at 1908 nm was used as the pump source for the high power testing. An output power of 1.7 W was achieved with 9.3 W of incident pump power [10]. Higher pump intensity where not investigated for fear of ablating the end facet of the waveguide. Thus larger diameter waveguides with lower losses are needed to facilitate higher pump powers. Gain-switch operation was investigated which exhibited an output pulse energies of up to 12 µJ with the narrow linewith of 1 nm. Another solution for power scaling is to utilise Cr:ZnS with its lower thermo-optic coefficient (46 K^{-1}) and higher thermal conductivity[11]. Initial work has demonstrated 101 mw of CW laser power 2333 nm using 1.5 W of pump power [6]. Future work will be to develop lower loss waveguides and bring them closer to the samples surface allowing for more effective cooling.

References:

1. DeLoach, L.D., R.H. Page, and G.D. Wilke, *Transition metal-doped zinc chalcogenides: spectroscopy and laser demonstration of a new class of gain media.* IEEE Journal of Quantum Electronics, 1996. **32**: p. 885-895.
2. McKay, J., K.L. Schepler, and G.C. Catella, *Efficient grating-tuned mid-infrared* Cr^{2+}*:CdSe laser.* Optics Letters, 1999. **24**(22): p. 1575-1577.
3. Page, R.H., et al., Cr^{2+}*-doped zinc chalcogenides as efficient, widely tunable mid-infrared lasers.* Quantum Electronics, IEEE Journal of, 1997. **33**(4): p. 609-619.
4. Berry, P.A. and K.L. Schepler, *High-power, widely-tunable* Cr^{2+}*:ZnSe master oscillator power amplifier systems.* Optics Express, 2010. **18**(14): p. 15062-15072.
5. Sorokin, E., et al. *Ultrabroad Continuous-Wave Tuning of Ceramic Cr:ZnSe and Cr:ZnS Lasers*. in *Lasers, Sources and Related Photonic Devices*. 2010. San Diego, California: Optical Society of America.
6. Macdonald, J.R., et al., *Compact Cr:ZnS channel waveguide laser operating at 2333 nm.* Optics Express, 2014. **22**(6): p. 7052-7057.
7. Sorokina, I.T., Cr^{2+}*-doped II–VI materials for lasers and nonlinear optics.* Optical Materials, 2004. **26**(4): p. 395-412.
8. Macdonald, J.R., et al., *Efficient mid-infrared Cr:ZnSe channel waveguide laser operating at 2486 nm.* Optics Letters, 2013. **38**(13): p. 2194-2196.

9. Macdonald, J.R., et al. *Widely Tunable Cr:ZnSe Channel Waveguide Laser*. in *Advanced Solid-State Lasers Congress*. 2013. Paris: Optical Society of America.
10. Berry, P.A., et al., *Fabrication and power scaling of a 1.7 W Cr:ZnSe waveguide laser.* Optical Materials Express, 2013. **3**(9): p. 1250-1258.
11. Mirov, S.B., et al., *Recent Progress in Transition-Metal-Doped II-VI Mid-IR Lasers.* Selected Topics in Quantum Electronics, IEEE Journal of, 2007. **13**(3): p. 810-822.