Ultrafast laser inscribed $Yb:KGd(WO_4)_2$ and $Yb:KY(WO_4)_2$ channel waveguide lasers

F.M. Bain,[1,*] A.A. Lagatsky,[1] R.R. Thomson,[2] N.D. Psaila,[2] N.V. Kuleshov,[3] A.K. Kar,[2] W. Sibbett,[1] and C.T.A. Brown[1]

[1]*J. F. Allen Physics Research Laboratories, School of Physics and Astronomy, St Andrews, Fife, Scotland KY16 9SS, UK*

[2]*School of Engineering and Physical Science, David Brewster Building, Heriot-Watt University, Edinburgh, Scotland EH14 4AS, UK*

[3]*Research Institute for Optical Materials and Technologies, Belarusian National Technical University, 65 Nezavisimosti Avenue, 220013, Minsk, Belarus*

**fmb9@st-andrews.ac.uk*

Abstract: We demonstrate laser action in diode-pumped microchip monolithic cavity channel waveguides of $Yb:KGd(WO_4)_2$ and $Yb:KY(WO_4)_2$ that were fabricated by ultrafast laser writing. The maximum output power achieved was 18.6 mW with a threshold of approximately 100 mW from an $Yb:KGd(WO_4)_2$ waveguide laser operating at 1023 nm. The propagation losses for this waveguide structure were measured to be 1.9 $dBcm^{-1}$.

OCIS codes: (140.3390) Lasers material processing; (140.3480) Lasers, diode-pumped; (140.3580) Lasers, solid state; (140.3615) Lasers, ytterbium; (230.7380) Waveguides, channeled.

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1. Introduction

Ultrafast laser inscription of waveguides is proving to be a practical technique for flexible writing in a wide variety of transparent dielectric media [1,2]. Such techniques can be used to create direct refractive index increases within the written volume [1] or refractive index increases due to material strain close to the written volume within which the index is lowered [3,4]. The mechanisms responsible for the refractive index changes are not as yet fully understood but it is agreed that these depend strongly on material type and writing parameters such as pulse energy, scan speed, wavelength, focusing geometry, repetition rate, pulse duration and polarization. Previously, lasing from channel waveguides fabricated by this technique has been observed in phosphate and oxyfluoride glasses co-doped with Er, Yb ions at around 1.5 μm [5–7], in crystalline LiF at 707 nm [8] and Nd:YAG around 1 μm [9–11].

Recent progress in development of novel rare-earth doped crystalline media has resulted in a range of efficient gain media that are suitable for further developments towards waveguide-based laser modules. Amongst them, the Yb-doped monoclinic potassium double tungstates, notably Yb:$KGd(WO_4)_2$ (Yb:KGdW) and Yb:$KY(WO_4)_2$ (Yb:KYW) [12,13] show particular promise for use as compact diode-pumped ultrashort pulse lasers [14]. The main disadvantage of these materials, as with any quasi-three-level laser system, is that the lower lasing level is thermally populated and thus high pump intensities with a good overlap between pump and lasing modes are required for low-threshold and efficient operation. These requirements can be satisfied readily in waveguide-based laser configurations. As previously reported, efficient lasing has been demonstrated in planar waveguides of Yb:KYW [15,16] and for Lu, Gd co-doped Yb:KYW grown by liquid phase epitaxy (LPE) [17,18]. Channel waveguides have been demonstrated in Yb:KYW by strip loading an LPE grown planar waveguide layer where laser performance was reported with a threshold of 82 mW of absorbed pump power and a maximum output power of 14 mW at 1025 nm [19]. Using an ultrashort pulse laser writing technique channel waveguides were fabricated successfully in Yb:KYW demonstrating propagation losses in the range of 2-2.5 $dBcm^{-1}$ at 1 μm [20] and in KGdW with 1.8 $dBcm^{-1}$ losses at 1600 nm [21].

Here we report, for the first time to our knowledge, the lasing of channel waveguides in Yb-doped KYW and KGdW crystals using an ultrashort pulse laser writing technique and assemblies involving diode-pumped monolithic configurations.

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2. Laser writing conditions

The samples used for writing experiments were crystalline Yb^{3+}(5 at%):KGdW and Yb^{3+}(5 at%):KYW substrates having dimensions of 2(*b*) × 10(*a*) × 10(*c*) mm^3 and 1(*b*) × 10(*a*) × 10(*c*) mm^3 respectively. Writing was performed parallel to the crystallographic *c* axis using an Yb:fibre laser operating at 1064 nm with a pulse duration of 1.3 ps at a 500 kHz repetition rate. The samples were translated perpendicularly to the laser beam at a constant velocity of 6 mms^{-1} using automated high precision xyz stages. The laser beam was focused at a depth of 430 μm into the Yb:KGdW crystal and 360 μm into the Yb:KYW crystal using a × 20 microscope objective with a 0.4 numerical aperture. Pairs of modified tracks were written because this technique had previously been employed to improve confinement and guiding in the central unmodified region [20].

In the case of the Yb:KGdW crystal, 168 different structures were written with variations of key parameters such as pulse energy, polarization and scan separation. The incident pulse energy on the sample ranged from 296 nJ to 558 nJ in steps of approximately 20 nJ. The inscribing beam polarization was set to either be linear along the *a* or *c* axes, or circular. The scan separation between the two pairs of tracks for each structure was varied between 10 μm and 35 μm in 5 μm steps. Similar parameters were used for the 176 structures written in the Yb:KYW crystal where the pulse energy range was 252-578 nJ in steps of approximately 20 nJ and the scan separation was varied between 20 μm and 35 μm in steps of 5 μm. Circular polarization was used for all the structures written in Yb:KYW. After inscription, the crystal end facets were repolished and the length of the written structures was 9 mm for both Yb-doped KYW and KGdW samples.

3. Guiding and laser emission results

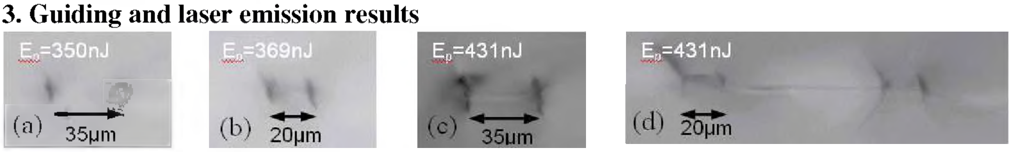

Fig. 1. Representative microscope images of Yb:KGdW waveguide end facets written at different pulse energies and scan separations. In (b,c) cracking between the two written regions of a single structure can be observed, as is cracking between adjacent sets of structures in (d).

In the case of Yb:KGdW the threshold for crystal structure modification, when two tracks were evident when viewed under a microscope, was around 350 nJ pulse energy using a circularly polarized laser writing beam (Fig. 1(a)). With scan separations of 20 μm and pulse energies of around 370 nJ additional cracking between the two pairs of modified regions became apparent (Fig. 1(b)), and at pulse energies greater than 430 nJ cracking occurred not only between pairs of tracks with 35 μm separation (Fig. 1(c)) but continuous cracking was observed between adjacent structures along the width of the crystal (Fig. 1(d)). In the case of Yb:KYW structural modification occurred at energies greater than 340 nJ, and no cracking between written structures was apparent even at the highest writing energies of 578 nJ (Fig. 2).

Fig. 2. Microscope image of Yb:KYW waveguide end facets.

A single-mode fibre-coupled InGaAs laser diode operating at 980 nm and producing up to 470 mW output power (sufficient to saturate the absorption of the crystal) was used to identify guiding regions and for lasing assessments in a simple monolithic cavity configuration (Fig. 3). A Faraday isolator was inserted into the pump laser beam to prevent back reflection effects and a half-wave plate was used to investigate different pump polarizations. A × 30 (f = 6.2

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mm) objective and a × 10 (f = 15.4 mm) objective were used to collimate and couple the pump laser beam into the waveguide structures. This gave a $1/e^2$ beam diameter of approximately 18 μm. For each structure investigated the exact positions of the objectives were adjusted to achieve optimal coupling of the pump. A thin fused silica substrate coated for high transmission at 980 nm and high reflection at 1010-1100 nm was used as the input high-reflector mirror. Output couplers with transmissions of 1%, 3% and 5% were placed at the second facet to assess laser performance. The output from the crystal was collimated and a dichroic beam splitter was used to separate the laser output from any residual pump.

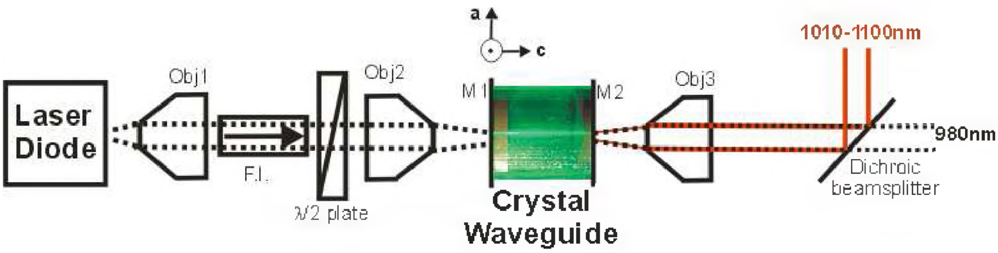

Fig. 3. Laser cavity experimental setup. Obj1 - × 30 objective; Obj2, Obj3 - × 10 objective; F.I. - Faraday isolator; M1 - high reflecting mirror at 1010-1100 nm with high transmission at 980 nm; M2 - 1%, 3% or 5% output coupler.

Yb:KGdW waveguides

In the case of Yb:KGdW, when the pump beam was polarized along the axis *a*, well confined guiding was observed in structures where additional cracking occurred between the two parallel tracks both above and below the cracked region as shown in Fig. 4(a,b). In the structures where no additional modification happened between the two lines guiding still occurred in approximately the same regions but was not so well confined (Fig. 4(c)).

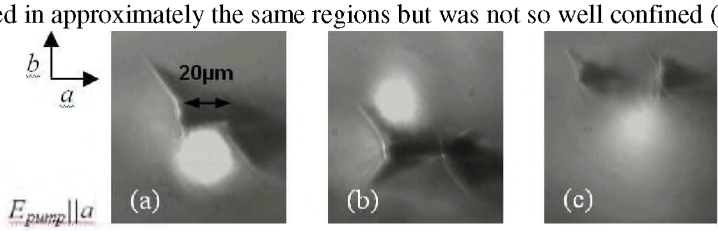

Fig. 4. Microscope images of Yb:KGdW waveguide end facets with guiding modes for $E_{pump}||a$. (a) and (b) show guiding above and below cracked regions. (c) shows poor guiding below the modified regions when no cracking occurred.

The best laser performance was achieved for the guiding region illustrated in Fig. 4(a) (written with pulse energy of 408 nJ and scan separation of 20 μm) and optimal coupling was observed for a pump spot size of 18 μm. With the 1% output coupler the maximum output power was 9 mW and the lasing threshold was at 111 mW of incident power. A maximum output power of 18.6 mW was recorded with 5% output coupling and this and other related results are shown in Fig. 5(a). The lasing wavelengths were around 1023 nm for all output couplings and the laser output polarization was along the *a* axis. The $1/e^2$ diameter of this guided mode was found to be 27 μm (*a*-axis direction) by 30 μm (*b*-axis direction). The image of the beam in the far-field is shown in Fig. 5 (inset) showing a near-Gaussian profile with the M^2 measured to be 1.5 and 1.2 in the *a* and *b* axes respectively. From these divergence measurements, the average refractive index step was estimated to a first order approximation to be 0.8×10^{-3} and 1×10^{-3} in the *a* and *b* axes at 1020 nm.

The propagation losses of the waveguide structure were determined by transversally exciting the waveguide structure and then recording the luminescence from the output facet of the waveguide with an optical spectrum analyzer as a function of distance between excitation spot and waveguide output (luminescence decay method) [22]. By fitting an exponential

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decay to the measurements taken at 1060 nm, which is well away from the ytterbium absorption, the propagation losses of the waveguide were determined to be 2.1 dBcm^{-1}. Using an alternative and simpler transmission method at 1064 nm and assuming perfect coupling efficiency, the propagation losses were determined to be 1.9 dBcm^{-1}, in reasonable agreement with the luminescence measurements.

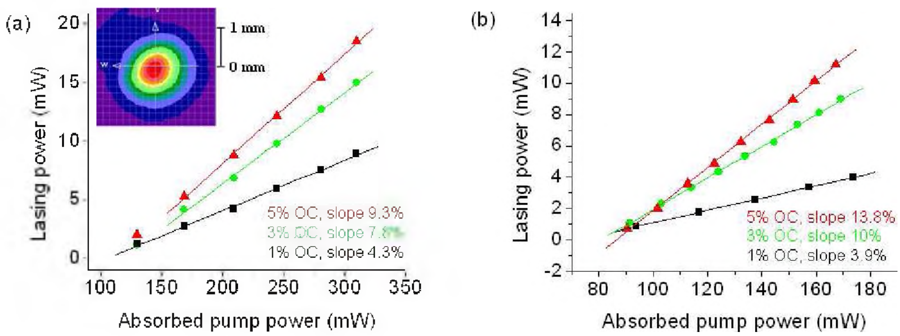

Fig. 5. Yb:KGdW lasing power as a function of pump power for 1%, 3% and 5% output couplers for (a) *E*||*a* polarization and (b) *E*||*b* polarization. Inset: Far-field beam profile.

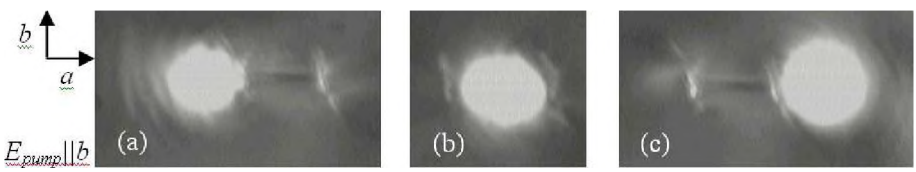

Fig. 6. Microscope images of Yb:KGdW end facets with guiding modes (a) to the left, (b) in the central region, and (c) to the right for *E*||*b*. The images relate to structures written with a pulse energy of 369 nJ. (a) and (c) are for a scan separation of 20 µm, whereas (b) is for a scan separation of 25 µm where no cracking occurred between the two written tracks.

With the pump beam polarization along the crystallographic axis *b*, guiding occurred in the regions between the two tracks, as expected, with additional guiding to the left and right of the two tracks, as illustrated in Fig. 6(a-c). In this case the best laser performance was achieved in the structure depicted in Fig. 6(c) which was written at 369 nJ pulse energy with a 20 µm scan separation. The laser performance in this configuration is illustrated in Fig. 5(b) and showed a minimum threshold of 74 mW and a maximum slope efficiency of 13.8% for 1% and 5% output couplers respectively. The maximum measured output power was 11 mW at a wavelength of 1036 nm. The lasing polarization was along the *b* axis. Other structures depicted in Fig. 6(a,b) were characterized with higher propagation losses of >4 dBcm^{-1} from which no lasing could be obtained.

Yb:KYW waveguides

The profiles of the guiding regions in the Yb:KYW crystal at *E*||*a* pump polarization conditions are depicted in Fig. 7 indicating a multimode propagation. Measured losses for these structures were around 5 dBcm^{-1} and no lasing was observed.

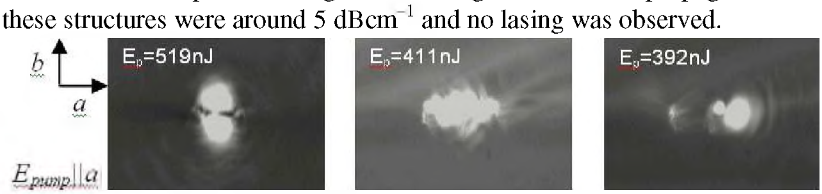

Fig. 7. Representative examples of “poor” guiding in Yb:KYW structures for *E*||*a* polarization written at various pulse energies.

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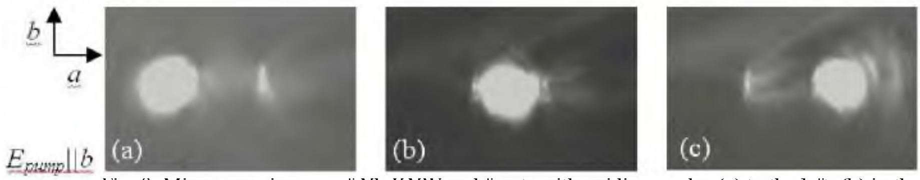

Fig. 8. Microscope images of Yb:KYW end facets with guiding modes (a) to the left, (b) in the central region, and (c) to the right, for *E*||*b* pump polarization. All structures were written with a pulse energy of 392 nJ and a scan separation of 20 μm.

When the guided light was polarized along the crystallographic *b* axis the picture was similar to the *b* axis case for the Yb:KGdW crystal, with guiding to the left, right and in the central region of the tracks as illustrated in Fig. 8(a-c). Lasing was achieved in several waveguides written at pulse energies between 355 nJ and 453 nJ with thresholds >70 mW and output powers <10 mW at 1037 nm. The minimum propagation losses were measured to be 3.7 $dBcm^{-1}$ in the central region for the structure written with 411 nJ pulses and a scan separation of 20 μm, although best lasing performance was found in a side guiding region for this structure where the propagation losses were 3.9 $dBcm^{-1}$. The optimized lasing results for each crystal and polarization are summarized in Table 1.

Table 1. Summary of optimized lasing results for each crystal. The scan separation is 20 μm in each case for guiding in a side region. The maximum output power was achieved using a 5% output coupler but, as expected, the lowest threshold was reached with an 1% output coupler.

Material	Polarization	Writing energy (nJ)	Maximum laser output power (mW)	Minimum threshold (mW)	Propagation loss ($dBcm^{-1}$)
Yb:KGdW	*E*||*a*	408	18.6	111	1.9
Yb:KGdW	*E*||*b*	369	11.2	74	2.9
Yb:KYW	*E*||*b*	411	8.2	77	3.9

4. Conclusion

In conclusion, we have demonstrated lasing from Yb:KGdW and Yb:KYW channel waveguides fabricated by ultrashort pulse laser writing. Guiding occurred in regions surrounding the irradiated focal volume, and lasing was achieved in a diode-pumped compact monolithic cavity arrangement. The results show that the best channel waveguide structure was formed in the Yb:KGdW crystal for which a maximum output power of 18.6 mW was obtained with an M^2 of 1.5 and 1.2 along the *a* and *b* axes.

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