# Continuous-wave and Q-switched operation of a compact, diode-pumped Yb$^{3+}$:KY(WO$_4$)$_2$ planar waveguide laser

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**Abstract:** A diode-pumped LPE-grown Yb:KYW planar waveguide laser is demonstrated in a microchip monolithic cavity configuration. Output powers as high as 148mW and thresholds as low as 40mW were demonstrated during continuous-wave operation. Pulses of 170ns duration with maximum pulse energy of 44nJ at a 722kHz repetition rate were generated when Q-switched using a semiconductor saturable absorber mirror.

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# 1. Introduction

The trivalent ytterbium ion, Yb$^{3+}$, has been identified as a suitable dopant for creating efficient diode-pumped, solid-state lasers operating around 1µm due to a range of advantageous spectroscopic properties. These lasers are characterized by a simple two-level electronic structure, reducing detrimental processes such as losses from excited-state absorption, upconversion, and concentration quenching. This is combined with a very low quantum defect that implies reduced heat generation and high laser efficiency. Furthermore, most of the Yb-doped materials possess a strong absorption peak around 980nm that makes them highly suitable for diode pumping using commercially available InGaAs diode lasers [1].

In the past, many different Yb$^{3+}$-doped crystals have been evaluated for their suitability as efficient laser gain media [2-8] and a wide variation in some key laser parameters has been observed. The potassium double tungstates, notably KY(WO$_4$)$_2$ (KYW) and KGd(WO$_4$)$_2$ (KGW), doped with trivalent ytterbium, have been identified as particularly promising gain media due partly to their large absorption and emission cross-sections together with the ability to be doped heavily with Yb$^{3+}$ (in the case of KYW [9]). Efficient and low threshold diode-pumped laser systems based on these crystal hosts operating around the 1µm spectral region have been demonstrated [4, 10]. The Yb-doped tungstates have additionally shown themselves to be suitable for efficient pulsed operation in regimes involving either Q-switching [11] or mode locking [12]. Their relatively broad emission spectra can support the generation of sub-100fs pulses [13] and high emission cross sections lead to stable mode locking. When considering Q-switching, the relatively long upper-state lifetimes compared, for instance, to neodymium as a dopant can be especially advantageous [11]. The double tungstates also possess a high Raman gain coefficient that can be suitable for the simultaneous generation of additional laser wavelengths due to self-frequency Raman conversion of the fundamental wavelength during high peak power pulsed operation [11, 14]. A major disadvantage of Yb$^{3+}$-doped lasers is that the final laser level is thermally populated (due to the quasi three-level energy manifold) and high efficiency in such systems can only be achieved at room temperature when there is an extremely good overlap of the pump and laser modes at high pump intensities. These requirements can be satisfied readily by using waveguide geometries for the laser resonator. Apart from the highly efficient and low threshold operation achievable with waveguide configurations, such laser devices are characterized by a simple monolithic

laser structure that can be incorporated into practical integrated devices. Additionally, the double tungstates are particularly attractive for such applications due to their high refractive indices of ~2 [15].

A well-developed technique for producing high-quality crystalline planar waveguides with low propagation losses is liquid-phase epitaxy (LPE) [16]. Recently, low-loss Yb:KYW planar waveguides have been demonstrated using the LPE technique [17]. As a result of the similar ionic radii of $Yb^{3+}$ and $Y^{3+}$, it was possible to obtain crack-free layers with doping concentrations as high as 15 at. % [18]. Due to KYbW being isostructural with KYW, the refractive index of Yb:KYW increases linearly with Yb doping concentration. By varying the latter, the desired refractive index can be obtained for an optimized guiding effect. Furthermore, it has been shown that by doping with additional rare-earth ions it is possible to produce crack-free Yb:YKW layers with even higher doping levels or to create larger modifications of refractive index [19]. Lasing was recently reported using a LPE-grown Yb:KYW layer as a gain medium, pumped by a Ti:sapphire laser, with an output power of up to 290mW, lasing thresholds around 80mW and slope efficiencies as high as 80.4%, in a z-fold cavity configuration. By moving to a more compact simple two-mirror cavity the maximum output power was reduced to 121mW [17].

In this paper we describe, for the first time to our knowledge, a diode-pumped LPE-grown Yb:KYW planar waveguide laser in a microchip monolithic cavity arrangement. By replacing one end mirror with an output-coupling SESAM we also demonstrated Q-switched operation with maximum average output powers of over 30mW and pulse durations as short as 170ns.

## 2. Experimental setup

For the planar waveguide laser experiments single-crystalline layers of Yb(3 at. %):KYW with a thickness of 14µm were grown on both the top and bottom (010) surface of a 4mm-long plane-plane undoped KYW crystal. At this doping level there is a refractive index difference of ~$1\times10^{-3}$ with respect to the undoped substrate [17] thereby creating a planar waveguide that could support 2 transverse modes along the $N_n$ axis at the lasing wavelength around 1µm. A schematic of the laser set-up is shown in Fig. 1 where the pump source was a 980nm fibre-coupled InGaAs single-mode laser diode that produced up to 480mW of output power. A half-wave plate was used to ensure the light was polarised along the $N_m$ axis of the crystal and a Faraday isolator was inserted to prevent back reflections from the laser cavity. A range of microscope objectives and lenses with focal lengths ranging from 8mm to 25mm were used to end-fire couple the pump into the waveguide. The best laser performance was obtained with the 15.4mm focal length objective at incident pump beam diameter of 1.5mm, which provided a pump spot diameter of 18µm, but it should be noted that similar results were also obtained with the 11mm and 20mm focal length lenses for which the spot sizes were 14µm and 24µm respectively. A thin fused silica substrate, which was coated for high transmission at 980nm and high reflection at 1020-1100nm, was held in place to the surface of the crystal by the surface tension of a thin layer of fluorinated liquid (n=1.303) [20]. An output coupler was similarly located at the other facet of the crystal to create a simple monolithic plane-plane cavity. The output couplers with transmissions of 1%, 3% and 5% in the range 1020nm-1100nm were used to assess continuous-wave laser performance of Yb:KYW planar waveguide laser. A dichroic beamsplitter was used to separate the residual pump and laser output beams. An upper limit on the absorbed pump power was calculated by comparing the throughput power when launched into the doped region to that of the bulk undoped region in a similar way to that described by Pelenc et al. [21]. Interestingly no active cooling of the sample has been used during these evaluations of the laser performance.
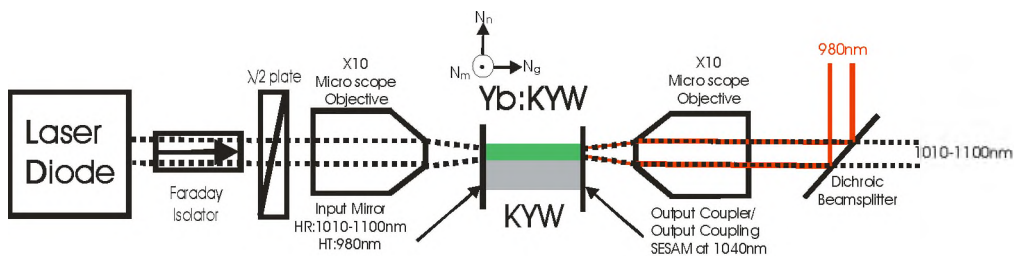
Fig. 1 Schematic of the laser setup (side view)

To achieve Q-switching the output-coupling mirror was replaced by a SESAM. Two different commercially available output-coupling SESAMs (Batop GmbH, Germany) were used. One had a modulation depth of 0.6%, non-saturable losses of 0.4% and transmission of 1.5% of intracavity radiation; while the other was characterized by a modulation depth of 1.8%, non-saturable losses of 1.2% and transmission of 0.4%. Both SESAMs had saturation fluences around $90\mu J/cm^2$ and were designed to operate around a centre wavelength of 1040nm.

## 3. Experimental results

### 3.1 Continuous-wave planar waveguide laser operation

With the 1% output-coupled Yb:KYW planar waveguide laser demonstrated a lasing threshold at 40mW of absorbed pump power. A maximum output power of up to 90mW was produced for around 325mW of absorbed pump power, with a slope efficiency of 34% at the 1044nm lasing wavelength. With the 3% output coupler in place, the threshold increased to around 70mW, while the output power reached 126mW. A slope efficiency of 51% was measured at the laser wavelength of 1041nm. A maximum output power of 148mW (340mW absorbed pump power) from this Yb:KYW planar laser was produced at 1039nm using the 5% output coupler, and the corresponding slope efficiency was measured to be 62% (Fig. 2 (a)). The blue shift in output wavelength as the output-coupling is increased is typical of quasi-three-level lasers, and can be attributed to the pump-dependence of the gain profiles at threshold conditions [10, 22]. By plotting the inverse of the slope efficiency against the inverse of the output coupling, the round-trip intracavity losses were calculated to be as low as 1.15% (Fig. 2 (b)). Assigning these losses entirely to propagation loss, an upper limit for the propagation loss in the Yb:KYW planar waveguide was found to be $0.06dBcm^{-1}$.
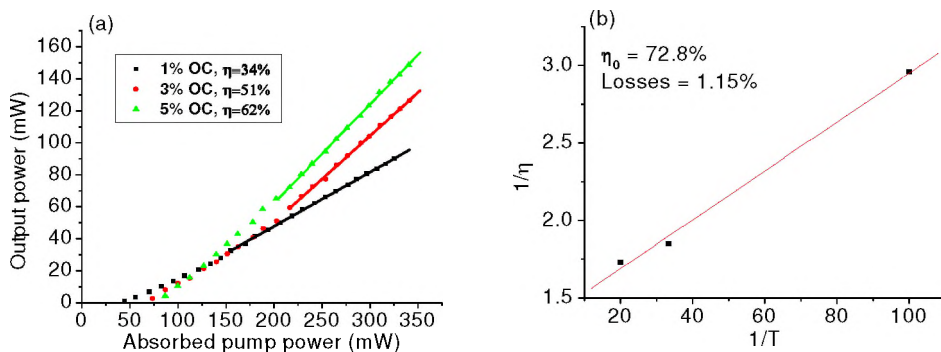


Fig. 2. (a) Output power as a function of absorbed pump power for three different output couplers. (b) Inverse of the slope efficiency plotted against inverse of the output coupling.

Two identical lenses were used to form an image of the end facet cavity mode profile, which was viewed using a beam profiler and the cavity mode was determined to be elliptical with diameters of 14µm and 80µm along the $N_n$ and $N_m$ axis, respectively. The corresponding

$M^2$ values were found to be around 1.2 and in excess of 10. The poor beam quality along the $N_m$ axis is typical behavior for such planar waveguide devices. Based on the obtained near field laser output profiles the refractive index difference between Yb:KYW epitaxial layer and KYW substrate was calculated to be $6.8 \times 10^{-4}$, that is in a good agreement with initial assumptions.

### 3.2 Yb:KYW planar waveguide Q-switched laser

By using a SESAM with an initial absorption of around 1% and an output coupling of 1.5% at 1040nm stable Q-switching of the Yb:KYW planar waveguide laser was realized at a threshold level of around 100mW of absorbed pump power. The maximum average output power of 33mW was generated at a pulse repetition frequency of 722kHz (Fig. 3 (a)). The pulse durations were observed to decrease with increasing pump power, reaching an asymptotic minimum value of around 170ns (Fig. 3 (b)). The maximum pulse energy was calculated to be 44nJ (Fig. 3 (b)) and the corresponding peak power was 250mW. The spectral bandwidth of these pulses was around 0.1nm, at a central lasing wavelength of 1040nm. The pulse fluence incident on this SESAM was calculated to be around 13.5μJ/cm$^2$ during laser experiments. Using a SESAM with a transmission of 0.5%, stable Q-switching was also achieved, but the average output power was only 5.5mW as a result of low output coupling. Pulse durations around 170ns were produced at a maximum repetition rate of 630kHz.
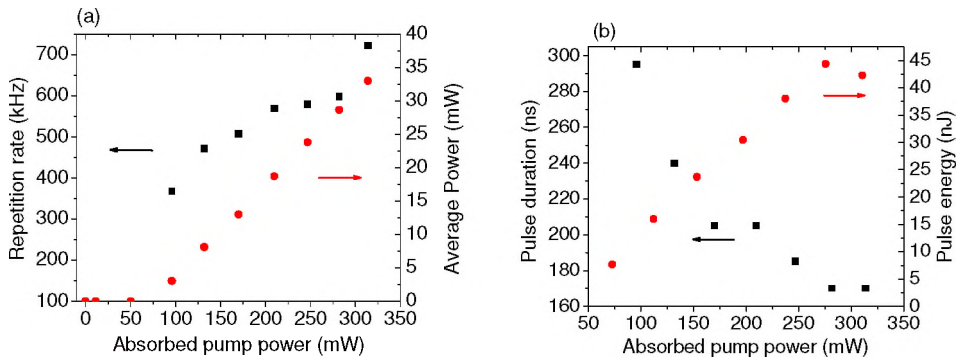


Fig. 3. Results for the Q-switched laser using a 1.5% output-coupling SESAM showing (a) repetition rate and average output power and (b) pulse duration and pulse energy as a function of absorbed pump power.

## 4. Conclusion

In conclusion, a diode-pumped LPE-grown Yb:KYW planar waveguide laser has been demonstrated. An output power of 148mW was achieved with a corresponding slope efficiency of 62% during continuous-wave operation. The lasing threshold was measured to be as low as 40mW of absorbed pump power with an output coupling of 1%. Propagation loss of the Yb:KYW LPE layer was estimated to be low at 0.06dBcm$^{-1}$. Q-switched Yb:KYW waveguide laser operation was also demonstrated in a monolithic cavity configuration, with pulse durations of around 170ns, pulse energies up to 44nJ and a repetition rate of 722kHz.

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