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Low-threshold miniature Ce:LiCAF lasers

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Abstract

We present a miniature Ce:LiCAF laser with extremely low threshold used as a tunable wavelength converter for an inexpensive $Nd:YVO_4$ microchip laser. Untuned, the laser operates with a threshold of 200 nJ and an absolute efficiency of 31%. Using an intra-cavity prism, continuous tuning from 283 to 314 nm is observed. These sources are well suited for applications in biological and chemical detection.

OCIS: 140.0140; 140.3580; 140.3600; 140.3610

There are many applications that require small-scale source of tunable UV radiation, such as flow cytometry, and remote detection of chemical and biological agents. The family of cerium-doped laser crystals [1] offer an attractive all-solid-state route; these crystals can be tuned directly in the UV, avoiding tunable non-linear conversion steps that are required for alternative sources based on tunable visible or IR lasers. The two most-used cerium-doped crystals are $Ce^{3+}:LiLuF_4$ (Ce:LiLuF) and $Ce^{3+}:LiCaAlF_6$ (Ce:LiCAF), which are tunable from 305–330 nm to 282–315 nm, respectively. Importantly, Ce:LiCAF can be pumped at around 266 nm, and so can utilize frequency-quadrupled Nd-based pump lasers [2]. Ce:LiLuF, on the other hand, is pumped at around 250 or 289 nm; common pump sources are frequency-doubled copper vapor lasers [3] or KrF lasers [4], although a clear route for compact systems is to use Ce:LiCAF or Ce:LiSAF as a pump source [5].

Cerium-doped LiCAF operates as a simple four level laser system; the upper laser level has a lifetime of 25 ns, and so the laser typically operates in gain-switched mode with Q-switched pump sources. High absolute efficiency operation of up to 42% [2] is aided by the small quantum defect (0.92 for 290 nm operation using a 266 nm pump wavelength), high emission cross-section ($9.6\times 10^{-18}\ cm^2$) and low excited state absorption cross-section ($3.6\times 10^{-18}\ cm^2$) [6].

In this paper, we present the performance of an extremely low threshold Ce:LiCAF laser. Our goal was to scale down the threshold in order to make use of low-energy passively Q-switched microchip lasers as a route to produce a relatively inexpensive, small, and robust tunable UV source. Pumped by CW IR lasers diodes, short-cavity monolithic microchip lasers use an intra-cavity saturable absorber and frequency-doubling crystal to generate sub-nanosecond pulses at 532 nm. Microchip lasers are extremely well suited for pumping Ce:LiCAF lasers. The peak power at 532 nm can be high enough (10s of kW) for efficient doubling to the required 266 nm wavelength even for pulse energies of only a few microjoules. The short pump pulse combined with a short Ce:LiCAF laser cavity ensures low threshold and high efficiency operation by reducing the build-up time and so minimizing the loss from fluorescence decay of the upper laser level.

The experimental set-up is shown in Fig. 1. The pump laser pulse is derived from a *Pulselas* laser manufactured by Alphalas GmbH. This is a passively Q-switched frequency-doubled $Nd:YVO_4$ laser, delivering 40 μJ pulses at 532 nm, with a repetition rate of 1 kHz. The output

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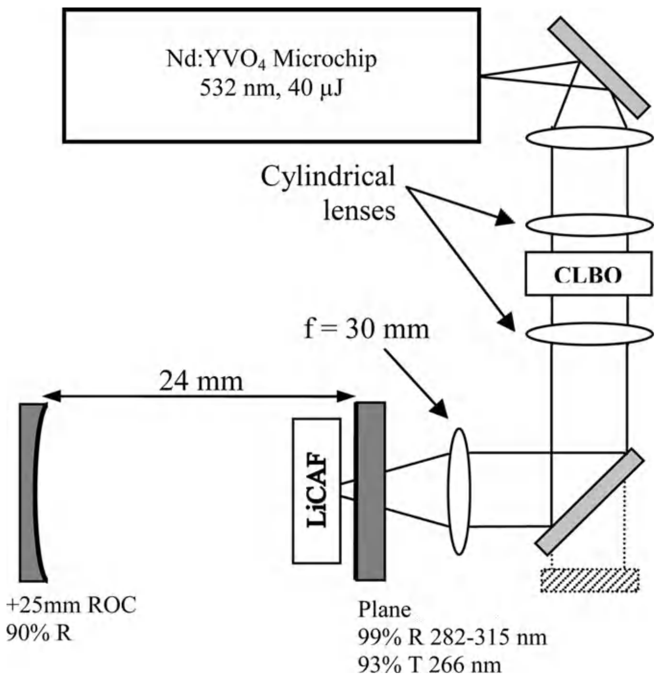

Fig. 1. Experimental set-up, showing collimation of the 532 nm output of the microchip laser, doubling to 266 nm using a CLBO crystal, and focusing into the Ce:LiCAF crystal contained in a near-hemispherical cavity.

beam is collimated, and cylindrically focused into a 5-mm long CLBO crystal (maintained at 150 °C), generating 12 µJ pulses at 266 nm. The pulse lengths of the 532 and 266 nm pulses are 750 and 550 ps, respectively.

The Ce:LiCAF crystal used in these experiments (grown by VLOC Inc.) was co-doped with sodium in order to reduce charge imbalance caused by the replacement of Ca^{2+} ions with Ce^{3+} ions in the host crystal lattice. This co-doping results in higher crystal yields, and reduced scattering losses in the crystal [7]. The crystal was grown with 3.5 at.% Ce in the melt. Ce:LiCAF is a uni-axial crystal, and for optimum performance was aligned with the pump polarization parallel to the crystal *c*-axis (which was contained in the plane of the end face of the crystal); this alignment minimizes undesired excited-state absorption [6]. With a thickness of 2.2 mm, the plane-parallel crystal exhibited a single pass absorption of 88% at 266 nm. The cerium crystal was placed in a near-hemispherical cavity comprising a plane dichroic mirror (transmitting 93% at 266 nm, reflecting more than 99% at 285–340 nm) and a curved mirror with a radius-of-curvature of 25 mm (transmitting 10%). The cavity length was 24 mm, and the cerium crystal was placed adjacent to the plane mirror. The 266 nm pump beam was focused through the dichroic plane mirror to a 13 µm spot (radius for $1/e^2$ intensity, measured by magnifying onto a CCD camera) at the center of the cerium crystal. The cavity length was then adjusted to optimize the slope efficiency of the laser output.

Fig. 2 shows the output characteristic for this untuned cavity (solid line). The stated pump pulse energy was that measured after the final focusing lens. The laser output

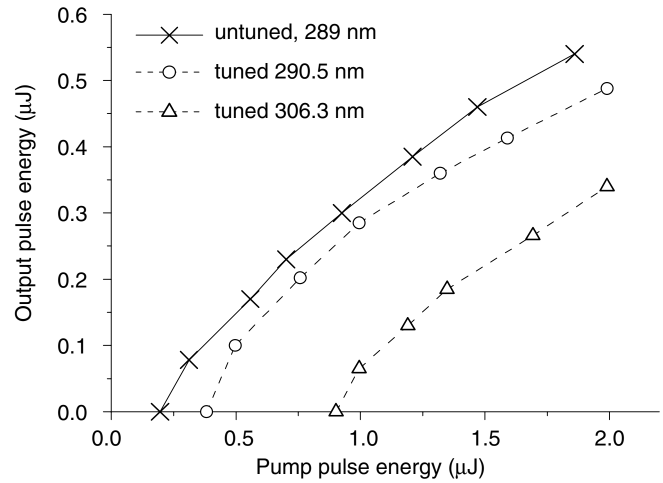

Fig. 2. Output characteristics of the Ce:LiCAF laser for both untuned (solid line) and prism-tuned (dotted lines) configurations.

was found to be π-polarized, with a threshold of 200 nJ. Measurements were restricted to pump energies under 2 µJ: owing to the small pump spot size at the dichroic plane mirror, damage occurred for higher pump energies. The output of the laser was a TEM_{00} mode, with a measured M^2 value of 1.12. The spectral width of the output was 4 nm, centered at 289 nm.

The shape of the output characteristic curve is typical for gain-switched lasers. The curve is very steep just above threshold; this is associated with a rapid decrease in the build-up time of the Ce:LiCAF laser pulse as the pump energy is increased, permitting earlier extraction of the inversion and reducing losses to fluorescence. The slope of the curve in this region is much higher than the genuine slope efficiency that would be measured well above threshold. The steepening effect becomes insignificant once the build-up time has been reduced to much less than the upper laser level lifetime (25 ns for Ce:LiCAF). Fig. 3 shows the temporal profile of the pump pulse and output pulse for a pump pulse energy of 1.9 µJ. The 550 ps pump pulse is well separated from the 1.7 ns output pulse, which builds up about 2 ns after the pump pulse. For pump pulse energies greater than approximately 1.25 µJ, saturation of the

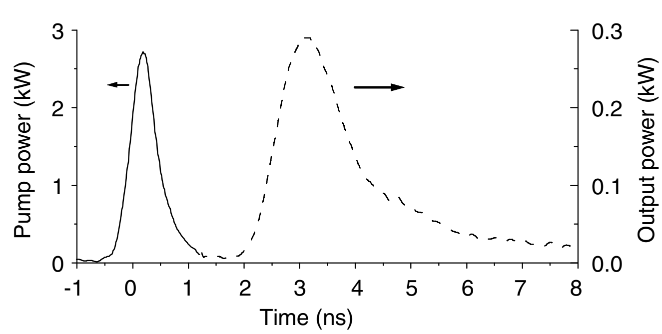

Fig. 3. Temporal profile of the 1.9 µJ, 266 nm pump pulse (solid line), and the 550 nJ, 289 nm pulse emitted from the Ce:LiCAF laser (dashed line). The pump pulse duration is 550 ps, and the 289 nm pulse duration is 1.7 ns.

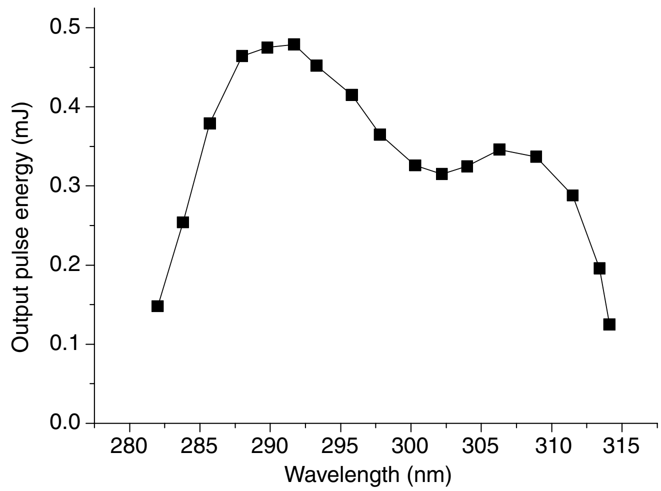

Fig. 4. Output power of the prism-tuned Ce:LiCAF laser across its 283–314 nm tuning range, for a pump pulse energy of 2 μJ.

pump absorption becomes significant, and the slope of the curve rolls off; for a pump energy of 1.9 μJ, the pump absorption is decreased from 88% to 83.5%. Owing to these build-up time and saturation effects, estimation of the slope efficiency is difficult; however the laser runs with an absolute efficiency of between 31% and 33% for an output energy ranging between 175 and 460 nJ, and 29% for the maximum output energy of 550 nJ.

In order to access the full wavelength range of Ce:LiCAF, a UV-grade fused silica Brewster prism was added to the cavity close to the output coupler. Fig. 4 shows the tuning curve obtained by rotating the output coupler, for a pump pulse energy of 2 μJ. It is clear that this pump energy is easily sufficient for achieving continuous tuning across the full range of Ce:LiCAF from 283 to 314 nm. Also shown in Fig. 2 are the output characteristics for this tuned laser when tuned to the peaks at 290.5 and 306.3 nm. The pump energy thresholds were 380 and 900 nJ, respectively, with maximum absolute efficiencies of 24% and 17%, respectively. We note that this is particularly efficient operation at the long-wavelength emission peak compared to previously reported efficiencies of 13% [2] and 7% [8], resulting in a more uniform tuning curve. The cause of this improvement is not currently clear; we note however that the present laser is very distinct from those previously published, having a shorter cavity length (24 mm), shorter pump pulse duration (550 ps), shorter laser crystal (2.2 mm), and a plane–plane crystal rather than a Brewster cut crystal.

The present results were obtained using a microchip pump laser capable of generating 12 μJ pulses at 266 nm (40 μJ at 532 nm). This laser is at the upper end of the range of pulse energies available from commercially offered microchip lasers. However, the goal of this research is to develop miniature lasers that can be pumped with less expensive smaller-scale microchip lasers, by reducing the threshold while maintaining high efficiency and broad tunability. We have shown that a 266 nm pump energy of only 2 μJ is sufficient to access the full tuning range of Ce:LiCAF for the present arrangement.

The lowest threshold that may be achieved with a given laser material is largely determined by the doping levels that can be achieved. The maximum doping level determines the shortest length of crystal that exhibits reasonable absorption of the pump light. Using this shortest crystal, the threshold may minimized by decreasing the size of the focused pump beam, until a limit is reached when the Rayleigh range of the pump beam is comparable to the crystal length.

In the present case, a 2.2-mm long crystal grown with 3.5 at.% Ce in the melt results in 88% pump absorption. This level of cerium doping is the most achievable at present: residual charge imbalance not perfectly corrected by sodium codoping, along with strain associated with the size mismatch between the Ce and the substituted Ca lattice sites, leads to poor quality crystals for higher levels of Ce doping [7]. The experiments presented here, with a pump spot size of 13 μm corresponding to a Rayleigh range of 2 mm, therefore closely approach the limit of low threshold scaling that can be readily achieved with this material.

In summary, the Ce:LiCAF laser presented here is a compact add-on that may be used with relatively inexpensive microchip lasers, converting the fixed-wavelength 266 nm output into a versatile widely tunable source providing access to the UV region of particular interest to chemists and biologists.

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