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Letter
All-solid-state injection-seeded tunable ultraviolet laser

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Abstract. We report what we believe is the first injection-seeded tunable ultraviolet (UV) laser based on a directly pumped UV-active medium, which combines the usually mutually exclusive properties of narrow bandwidth and high conversion efficiency.

1. Introduction

For a variety of applications, pulsed tunable ultraviolet (UV) laser sources with high pumping-to-tunable-output efficiency, narrow output radiation bandwidth, low beam divergence and, for most applications, a very low ‘background emission’ level are needed. Given recent developments, one of the most promising approaches for devising a tunable UV laser would be an all-solid-state system based on Ce-activated laser media such as Ce : LiCAF/LiSAF [1, 2] or Ce^{3+} : $LiLuF_4$ (Ce : LLF) [3, 4] crystals directly pumped in the UV.

However, there are well known difficulties with devising high-spectral-brightness tunable laser sources. Typically, as the pumping power increases, any simple single-stage tunable laser (in particular, the optical layouts used in [1–3]) will suffer an unacceptably high level of emitted ‘background’ radiation. This is due to the amplified spontaneous emission (ASE) pertinent to any high-gain laser medium, a problem known since dye laser development in the 1970s [5]. In addition, the output radiation bandwidth narrowing by reinforcement of the intracavity spectral selection is usually accomplished at a significant sacrifice of conversion efficiency but, even then, increasing the output power normally tends to increase the output spectral bandwidth.

A solution to these problems is a two-stage laser layout with low-power injection seeding [5, 6] which can provide high power and high conversion efficiency while keeping the output radiation bandwidth narrow. Injection seeding combined with the selectivity introduced in the power stage of the laser significantly reduces ASE contribution in the tunable output of the entire system [6].

Here we report what we believe is the first injection-seeded tunable UV laser based on a directly pumped UV-active medium.

2. Approach

To implement the above laser, a Ce : LiCAF crystal pumped by a quadrupled Nd-doped yttrium aluminium garnet laser (Nd-YAG) [1, 2, 4] was chosen as an active medium for this investigation to simplify all pumping arrangements. Also from the simplicity standpoint, we used an injection-seeded laser layout first described in [6] where the narrow-band low-power seeding radiation is injected into a ring cavity with a single low-selective dispersive element. We also planned to take advantage of the substantial overall ASE suppression offered by the injection-seeded dispersive ring cavity layout tested in [6].

One more choice of importance was the seeding source. It is quite common for injection-seeded laser systems that the injection seeder (based typically on a traditional 'Hansch-type' frequency-narrowing layout [7]) consumes a significant amount of the available pumping energy (very often up to 50% at moderate levels of per pulse pumping energy) solely to generate a low-pulse-energy narrow-bandwidth seed pulse. Therefore, our main emphasis was placed on development of an injection seeder with low-threshold (while also tunable and narrow-band) operation. That allowed us to use the same pumping source for the seeder and the dispersive ring laser. Just a minor fraction of pumping energy would be needed for efficient output spectrum formation in this case.

In principle, dynamic distributed-feedback (DFB) tunable operation is normally easily attainable using pulsed laser-pumped high-gain active media. A pump-induced frequency-selective Bragg grating technique was developed for dye lasers starting in the early 1970s (for example [8]). Direct UV pumping has been used to demonstrate a dynamic DFB lasing in Ce : LiCAF [9]. Narrow-band tunable UV operation [9] was obtained even though a weak-coupling second-order Bragg grating was used. For the injection seeding in this work, we used a mirrorless low-threshold tunable narrow-band pump-induced dynamic *first-order* DFB grating, an approach extensively studied earlier for dye lasers (for example [8, 10]). This stage turned out to be a key element for our entire tunable narrow-band high-conversion-efficiency (high-spectral-brightness) UV laser system.

3. Experimental details

Figure 1 shows the experimental layout of our tunable UV laser. It consists of firstly a narrow-band tunable dynamic DFB seeder and secondly a low-selectivity ring-cavity regenerative laser amplifier. Ce : LiCAF rods are used as active media in both a laser–seeder (C_1) and in a regenerative amplifier (C_2). A Ce : LiCAF single-crystal boule (with 2.7 at.% Ce^{3+} doping plus 1% Na added in the melt to increase the single-site Ce-acceptability level) was grown using the Bridgman-Stockbarger technique. The boule was cut to form two cylindrical active rods C_1 and C_2, each of diameter 6 mm and length 11 mm, with a flat polished window on the side. Ce : LiCAF rod polished ends were tilted in a roof-like way at about 10° to prevent any uncontrolled lasing due to Fresnel feedback. Both C_1 and C_2 rods were oriented with their optical axes normal to the plane of propagation in figure 1.

In contrast with [9], where a *second-order* pump-induced Bragg grating was used as a mechanism for Ce : LiCAF laser wavelength selection, we took advantage of a high-coupling *first-order* pump-induced Bragg grating to minimize the seeder threshold. We used a layout similar to [8] to cause two segments of the pump beam to interfere by internally reflecting part of the beam from the back surface of prism

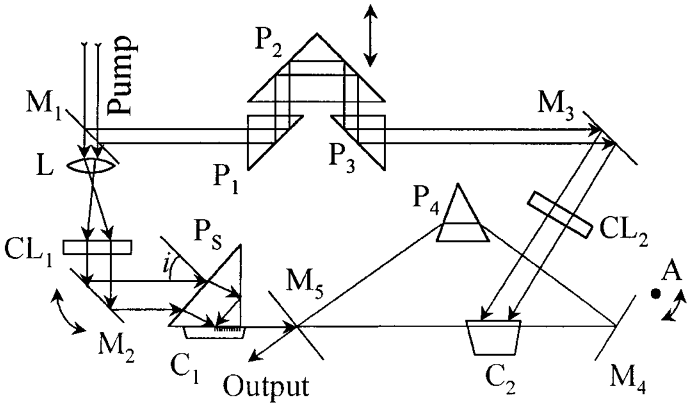

Figure 1. Experimental set-up of the tunable UV Ce : LiCAF injection seeded laser. Comprehensive description for all optical components and beam paths is given in the summary.

P_s. Quadrupled radiation of a *Q*-switched Nd : YAG laser (maximum pulsed energy, 40 mJ; pulse duration, about 10 ns; pulse repetition rate, 10 Hz) was used for pumping both the prism DFB Ce : LiCAF seed laser and the ring-cavity regenerative laser amplifier. Mirror M_1 was used to split the pumping energy between the seeder and the ring laser. Mirror M_1 reflection can be chosen depending on the total pumping energy, so that just the minimum pumping energy is applied to the seeder to provide the required tunability. For our pumping energy of 40 mJ, we used a mirror M_1 which had about 1 : 10 'transmission-to-reflection' ratio at 266 nm.

To simplify our optical arrangement further, a Ce : LiCAF prism DFB injection seeder was made as a combination of a fused-silica pump-beam-splitting isoceles right-angled prism P_s and a Ce : LiCAF laser rod, attached (using an index matching fluid) to one of the sides which formed the right angle in the prism. A portion of the pumping beam transmitted through the mirror M_1 passed through the spherocylindrical telescopic system (spherical lens L and cylindrical lens CL_1) to form a line-shaped pumped area on the rod C_1 side window after bouncing from the auxiliary high-reflection mirror M_2. To obtain the necessary seeder wavelength tunability, the interference angle between the direct-pumping and prism-reflected pumping portions of the pump line in the active rod side window plane was changed by rotation of mirror M_2. In fact, this rotation changes the incidence angle of the pump beam at the hypotenuse face of the prism (see figure 1) and so the DFB laser oscillation wavelength λ_{osc} changes as derived from [10]

$$\lambda_{\mathrm{osc}} = \frac{1.41 n_{\mathrm{cr}} \lambda_{\mathrm{p}}}{(n_{\mathrm{pr}}^2 - \sin^2 i)^{1/2}} + \sin i,$$

where n_{pr} is the prism material refraction index, n_{cr} is the laser crystal refraction index (both at the pumping wavelength λ_{p}), and i is the pump beam incidence angle at the hypotenuse edge of the prism (see figure 1).

To induce a grating with the best possible visibility (which also lowers the seeder–laser pumping threshold) the pump laser polarization was chosen to be vertical, that is perpendicular to the plane of the optical layout shown in figure 1.

This is also consistent with the active rod optical axis position in terms of minimizing the excited-state absorption for pumping radiation [2]. Neither diffraction gratings nor adjustable auxiliary feedback mirror-like elements (as in [9]) were used for our set-up.

The ring laser resonator had a perimeter of about 1 m and was formed by a totally reflecting (in the spectral range from about 280 to 305 nm) mirror M_4, mirror M_5 ($R = 25\%$) and a UV-grade fluorite (CaF_2) equilateral dispersive prism P_4 also closing the ring. The ring laser rod C_2 was pumped with the portion of the vertically polarized pump beam reflected from mirror M_1. The pump beam passed through the optical delay line (prisms P_1–P_3) was reflected by mirror M_3 and was focused by a 0.5 m cylindrical lens (CL_2) to form a line-shaped pumped area on the side window of the active rod C_2. Ring laser transverse pumping was arranged tilted so that the effective length of the line-shaped pumping area 1 mm wide was elongated by a factor of 1.75 with respect to the initial pump beam diameter of about 6 mm to use the whole laser rod length efficiently. That, in turn, reduced the intrinsic ring resonator ASE level by a factor of nearly two owing to the smaller solid angle of the elongated gain region. The ring laser was tuned by rotating the mirror M_4 about the off-set axis A. Injection seeding as well as output coupling of the ring laser were accomplished through the mirror M_5.

In a non-seeded lasing standing-wave regime (the injection seeding beam is blocked out) the dispersive ring laser generated two counter-propagating beams with slope efficiencies of 12% each at the maximum of the tuning curve around 288.5 nm (figure 2, curve a). The output radiation spectral bandwidth was about 0.8 nm. With the injection beam present, almost complete suppression of the 'reverse' (with respect to the injection seeding beam direction) beam was observed; no measurable power in the reverse direction was detected with the same power meter settings as for the direct beam. The slope efficiency for the single output

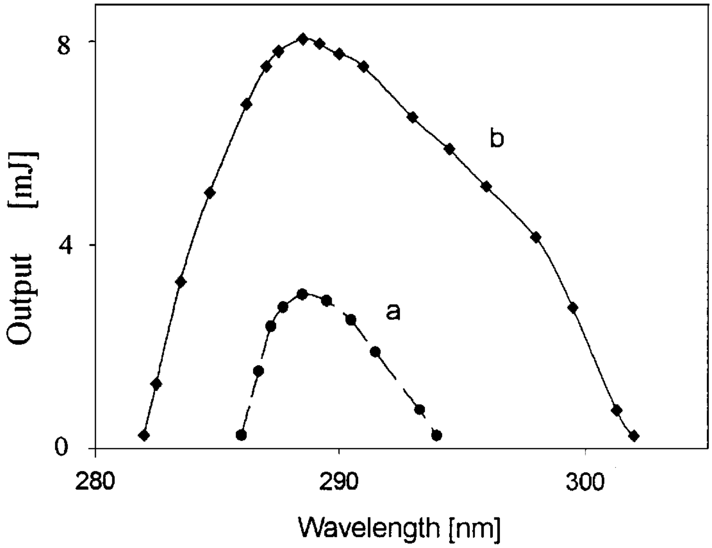

Figure 2. Tuning curves for the ring laser only (the injection seeding beam is blocked out) (curve a) and the injection-seeded ring-cavity tunable UV Ce : LiCAF laser at the total pumping energy of 40 mJ at 266 nm (curve b).

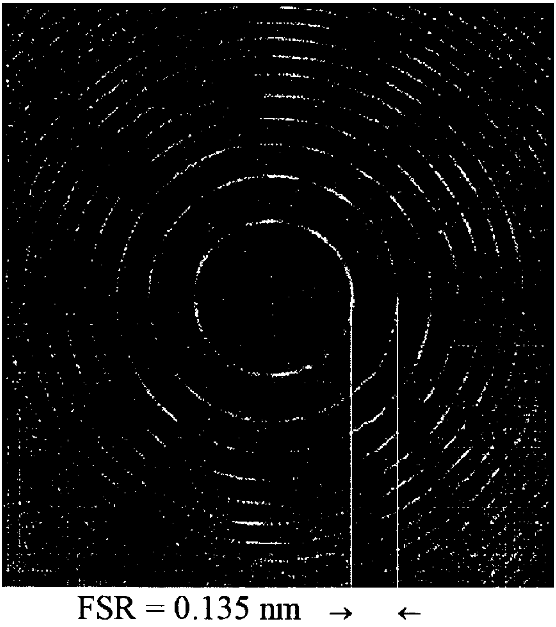

Figure 3. Ce : LiCAF injection-seeded laser output Fabry-Pérot interferogram. The output spectral bandwidth was measured using the Fabry-Pérot interferometer with a FSR of 0.135 nm and was found to be 0.015 nm (about a ninth of the FSR).

beam increased to 32%. This increased slope efficiency (more than the combined slope efficiency of 24% for the two unseeded beams) can be partially explained by the switch from the standing-wave to the running-wave regime as seeded lasing begins [6]. In addition, injection seeding with a level essentially exceeding the spontaneous noise level in the ring cavity reduced the characteristic lasing rise time, which, in turn, diminished ASE losses and, thus provided an additional (overproportional) increase in conversion efficiency. The optical delay time between the injection and regenerative amplifier pumping pulses was optimized to 2–3 ns by minimizing the ASE level and maximizing the overall conversion efficiency. Tunability characteristics for the whole system are shown in figure 2, curve b. As can be seen from figure 2, injection seeding provided significant tunability extension and more than a two-fold increase in conversion efficiency. The output radiation spectral bandwidth for the whole injection-seeded Ce : LiCAF laser was defined by the linewidth of the DFB injection seeder only.

A Fabry–Pérot interferogram obtained using a Fabry–Pérot interferometer with a free spectral range (FSR) of 0.135 nm and a video camera with a UV-sensitive vidicon tube is shown in figure 3. The output radiation spectral bandwidth, as determined from these measurements, was found to be 0.015 nm (about a ninth of the FSR). The narrow-band output obtained in the vicinity of the tuning curve maximum was 8 mJ. The ASE 'background' level was estimated to be less than 0.1%. This makes our tunable laser very promising for a variety of applications such as selective laser-induced fluorescence relating to the characterization of the free radicals of combustion and atmospheric significance in the near-UV region.

4. Conclusions

We report the operation of an injection-seeded tunable UV laser based on a directly pumped UV-active medium. Our device consists of a narrow-band tunable dynamic DFB Ce : LiCAF seeder and low-selectivity ring-cavity regenerative Ce : LiCAF laser amplifier. This device successfully combines the usually mutually exclusive properties of narrow bandwidth (0.015 nm) and high conversion efficiency (32% slope) important for a variety of applications.

Acknowledgments

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