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# Stable CW low noise operation of a diode-pumped monolithic laser at 355 nm beyond 30 mW

Nicolas Aubert, Thierry Georges, Corinne Chauzat, Raymond Le Bras  
Oxxius SA, 4 rue Louis de Broglie, F-22300 Lannion, France  
Patrice Féron, ENSSAT, BP447, 6 rue de Kerampont, 22300 Lannion, France

## ABSTRACT

Low noise CW UV lasers are needed for applications in bioinstrumentation (cell sorting, cytometry ...) and semiconductors (wafer inspection, micromachining ...). We have recently demonstrated that such laser sources can be obtained with diode pumped solid state (DPSS) architectures. One key to success was the quasi-monolithic structure of the laser. The advantages of quasi-monolithic DPSS lasers for UV generation are simplicity of design, compactness, efficiency and thus low power requirements and limited heating.

In this paper, we present for the first time a long term characterization of the diode pumped CW 355 nm laser. The interplay between pump absorption, cavity length, 1064 mode size, walk-off angle, acceptance angle has been optimized. In our experiments, the temperature of each element of the laser was controlled and UV power, noise and spectra were monitored versus these temperatures. At 2.5 W pump power, low noise UV power beyond 30 mW was measured on most samples built. At a reduced pump power of 1.65 W, all lasers were operating at 10 to 15 mW and could be maintained at 10 mW over days. The noise level remained below the 1% rms level. More long-term measurements will be presented at the conference.

## KEYWORDS

Intra-cavity tripling, UV laser, diode pumping, microchip assembly

## 1. INTRODUCTION

Many applications such confocal microscopy, flow cytometry, cell sorting, CD mastering, semiconductor inspection and reprographics require a low noise CW source with a wavelength in the vicinity of 355 nm. Argon lasers have a strong emission at 351 nm, they have been in the market over the last 40 years but they are bulky, require 10-50 kW of electrical power and water cooling. High repetition rate diode pumped mode-locked YAG lasers can produce quasi-CW 1064 nm emissions that can be easily tripled in frequency. They can replace Argon lasers although they remain quite bulky because of cavity lengths of the order of 1 m, the electrical power consumption is close to 1 kW and they are quite expensive (ref. 1).

Diode-pumped, intracavity frequency tripled Nd lasers are a good candidate for a compact low cost CW UV source (ref. 2), provided that the main issues such as birefringence interference (ref. 3) and green noise (ref. 4-5) are solved. We have recently demonstrated low noise mW-range 355 nm sources with less than 3W pumping (ref. 6-7). In this paper, we present further improvement of such lasers and a detailed stability analysis.

## 2. EXPERIMENTAL RESULTS

### 2.1 Description of the laser

The laser cavity consists of three parts, namely the amplifying crystal, an optional Brewster plate and the nonlinear crystal group (Figure 1). The 1064 nm amplifying crystal is a 1mm long 1.1% Nd doped YVO<sub>4</sub> crystal. The input facet of the crystal is coated with HR at 1064 nm (>99.8%). The Brewster plate is a 1 mm wide fused silica plate. The nonlinear group is made of 4 elements that are optically contacted. The first crystal is a 5mm long KTP cut for a 35°C type II SHG phase matching. The third element is a 4 mm long LBO crystal cut for type I THG. The LBO crystal is sandwiched between two fused silica plates. The output plate is HR coated at 1064 nm (R=99.86%) and the transmission at 532 nm and 355 nm are 0.15% and 95% respectively. The middle plate is HR coated at 355 nm (98%) in order to prevent the UV emission from penetrating the KTP crystal. Optical contacting of SH and THG crystals together with the output coupler prevents birefringence interference issues. In order to reduce the internal losses of the laser, we have carefully selected the non linear crystals and we have optimized the optical contacting between these crystals.

The total cavity length is about 20 mm. In absence of the Brewster plate, the cavity length is reduced and the amplifying crystal can be optically contacted to the nonlinear crystal group. The addition of polarizing elements (Nd:YVO<sub>4</sub> gain and Brewster plate) and 45° oriented birefringent crystals results in a birefringent (or Lyot) filter. This important feature will be discussed in the next section. The whole nonlinear group is temperature controlled by a TEC. This allows a tuning of the peak wavelength of the filter, which can be achieved over a 1-2K temperature range. This has no impact on the nonlinear frequency conversion because of the large phase-matching temperature acceptance of the two nonlinear crystals (56 K for KTP and more than 10 K for LBO crystals).

The laser is pumped by a 3W 1\*100 μm 808 nm diode beam launched into the amplifying medium by a GRIN lens. The diode wavelength is temperature controlled with a separate TEC. Heat removal in the Nd:YVO<sub>4</sub> crystal is achieved with a third TEC.

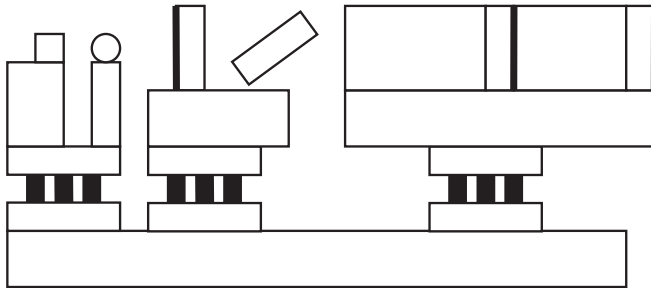


Figure 1 : Description of the laser

The use of type II frequency-doubling in intra-cavity frequency tripled lasers is usually not recommended because of birefringence interference (ref. 3): when a birefringent element is introduced out-of-axis in the cavity, the polarization state strongly depends on the exact wavelength. Any attempt to tune the wavelength results in a modification of the balance of the power between the different polarization axes of the doubling crystal and thus results in a modification of the frequency conversion efficiency. The design of figure 1 solves this problem and provides a solution for single frequency operation. The axis of the type II frequency doubling crystal and of the

frequency tripling crystal are aligned at  $\theta = 45^\circ$  of the Brewster axis. If the polarization of the Nd:YVO<sub>4</sub> is aligned to the Brewster polarization, the whole cavity acts as a birefringent (Lyot) filter. The wavelength with 100% transmission is linearly polarized in the Brewster plate and splits equally over the two polarization axes of the frequency doubling crystal (maximum frequency doubling efficiency) (Figure 2). If the laser cavity is not too long, the axial modes are well separated and the filtering effect can be efficient enough to select a single frequency. Any change in the laser cavity will modify the selected mode but not the split between the polarizations and will keep maximum frequency conversion efficiency.

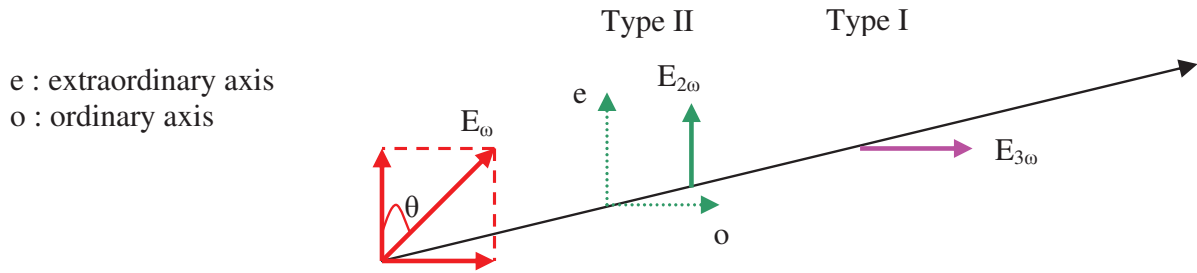


Figure 2: Directions of the wave polarization and the birefringent crystal axis. The angle  $\theta$  is formed between the polarized fundamental wave and the extraordinary ray of the KTP

If the laser cavity is not too long, the axial modes are well separated and the filtering effect can be efficient enough to select a single frequency. Any change in the laser cavity will modify the selected mode but not the split between the polarizations and will offer maximal frequency-conversion efficiency.

## 2.2 1064 nm operation

The GRIN lens provides moderate focusing of the pump beam to about 80  $\mu\text{m}$  diameter. At pumping levels ranging between 1.5 W and 2 W, the signal mode diameter is of the order of 80  $\mu\text{m}$  and the overlap with the pump is good. Most of the following experiments were performed at this pumping level. We could improve the overlap between pump and signal at higher pump levels by introducing 2 focusing lenses, but decided to keep the single lens to maximize the stability of the laser.

Thanks to a careful optimization of the laser cavity loss (good quality of the crystals and of the optical contacts, good parallelism of all interfaces), we were able to increase the intracavity power at 1064 nm from 45 W (ref. 7) up to 60-80 W with a 1.6 W pumping power. This eventually results in higher UV power.

Infrared emission is strongly affected by nonlinear conversion efficiency. SHG emission is recirculated using HR reflectors at 532 nm (green). The amount of green power is thus strongly sensitive to phases in the amplifying medium and thus to the exact infrared wavelength and to the amplifier temperature. Any pump power change induces a change in the thermal load of the amplifier and is thus responsible for a modification of the green power and impacts the level of infrared power. For these reasons, power control is difficult and requires operating on a stable laser mode.

We have monitored the infrared intracavity power over 15 hours at fixed temperature and pump power (1.65 W). We observed short term fluctuations of the order of 10 W (15%) and a long term drift mainly caused by variations of the ambient temperature.

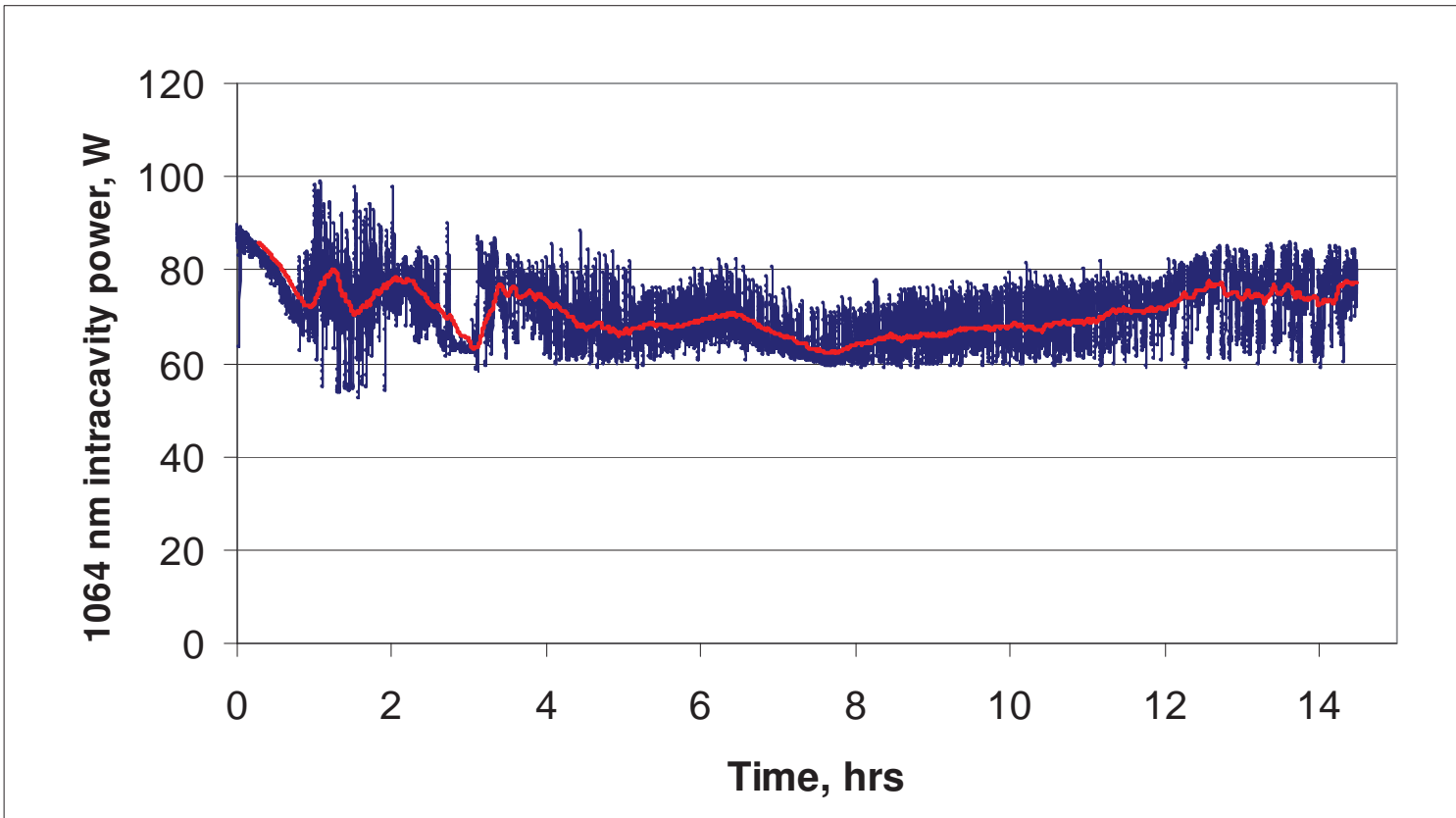
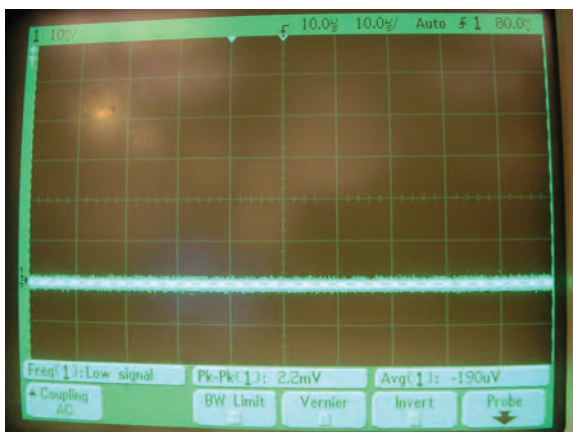


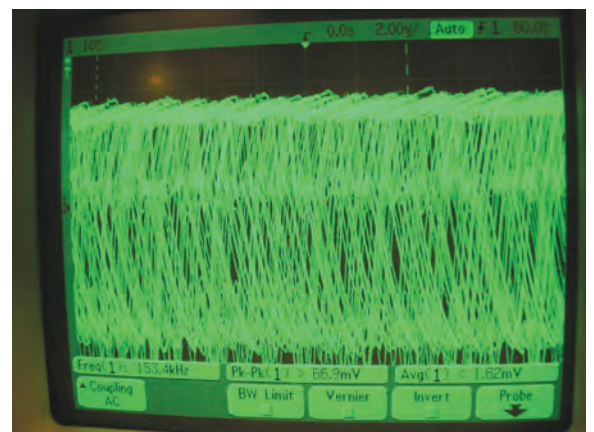
Figure 3 : Stability of intracavity 1064 nm power with constant diode current (2.2A corresponding to 1.65 W) and constant crystal temperatures.

### 2.3 Dynamics of 355 nm emission

We continued to characterize the laser using constant pump power (1.65 W) while the 355 nm power was monitored. We varied the amplifier temperature, T1 and the nonlinear crystal temperature, T2. Two kinds of dynamical behavior have been observed: a stable operation (figures 4a and 5a) and a “green noise”-like operation (figures 4b and 5b). In the latter, the signal consists in a series of random peaks superimposed upon a small dc background (Figure 4b). The signal to noise ratio (S/N) is 55dB at 1MHz and 3dB at 200kHz (Figure 5b).



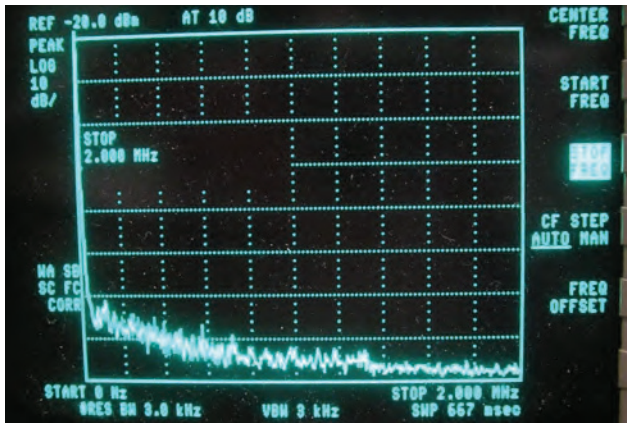
a)



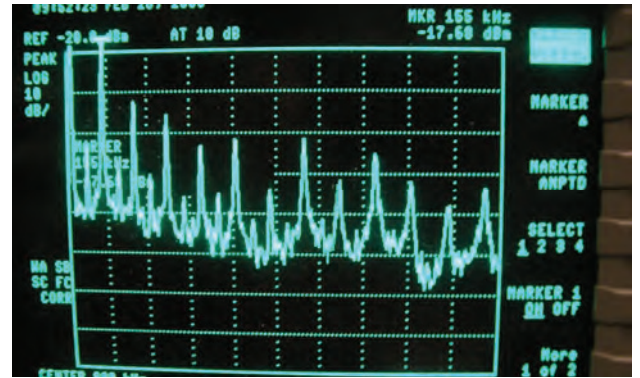
b)

Figure 4: Oscilloscope traces of output (1064 nm+532nm+355nm). a) Without “green noise” - Horizontal axis and vertical axis shows 10 $\mu$ s/div and 80 mv/div, respectively. b) With “green noise” - Horizontal axis and vertical axis shows 2 $\mu$ s/div and 60 mv/div, respectively





a)



b)

Figure 5: Spectrum analyser traces of output (1064 nm+532nm+355nm). Horizontal axis and vertical axis shows 200 kHz/div and 10 dB/div, respectively. Center frequency is 1 MHz, resolution bandwidth 3 kHz, and top level 20 dB. a) without “green noise”. b) with “green noise”

In the low noise operation, the noise level was below the sensitivity of our apparatus (0.5% rms).

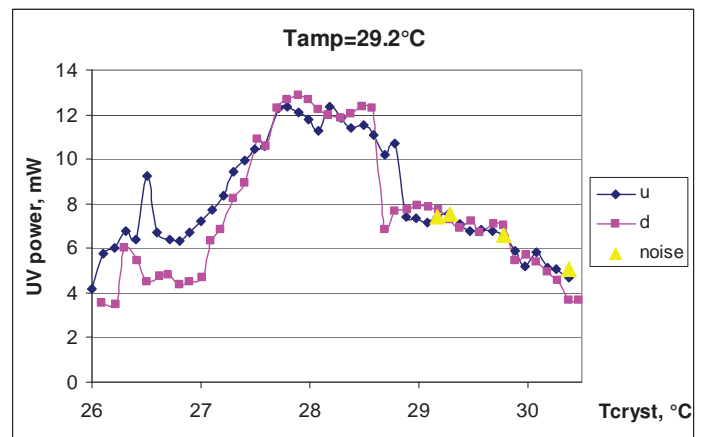
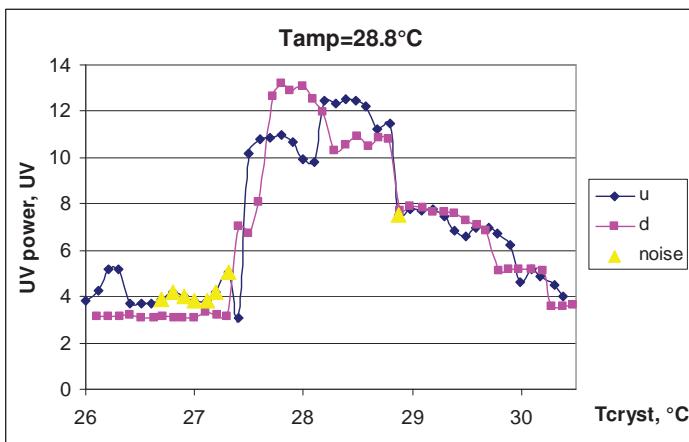
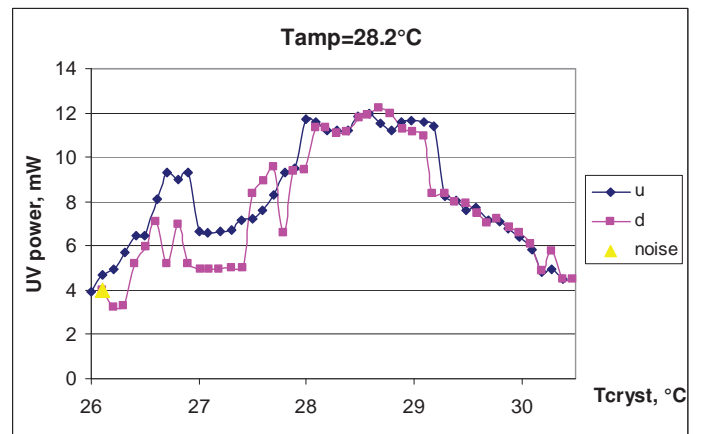
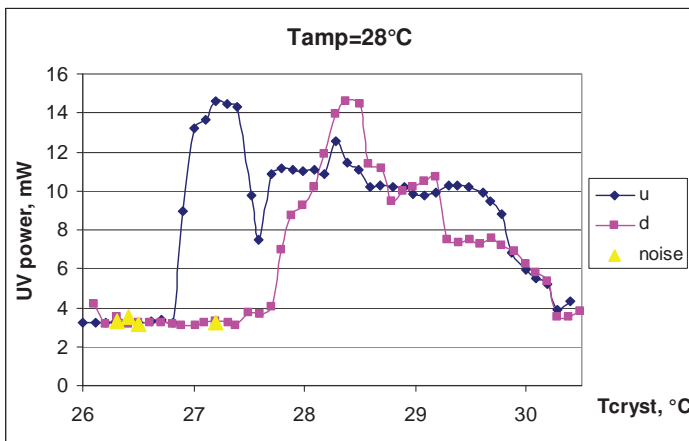


Figure 6 : UV output power at several amplifier temperatures (from 28 to 29.2°C) and varying nonlinear crystal temperature up from 26 to 31°C (u) and then down from 31 to 26°C (d). Noisy operation points are highlighted by large yellow triangles.

In an amplifier temperature range from 27.5°C to 29.5°C, a large crystal temperature window (wider than 1°C) allowed a 10+ mW UV operation without “green-noise”-like behaviour (figure 6). A slight hysteresis was observed between raising and reducing the temperature. However, this behavior should not be a problem for the UV power control.

## 2.4 Long term operation at 355 nm with power control

We have packaged the laser in a 110x55x28 mm<sup>3</sup> box and we have used the common driver of the SLIM series of Oxixus. The heat load in the source was small enough to avoid any use of active external cooling (Figure 7).

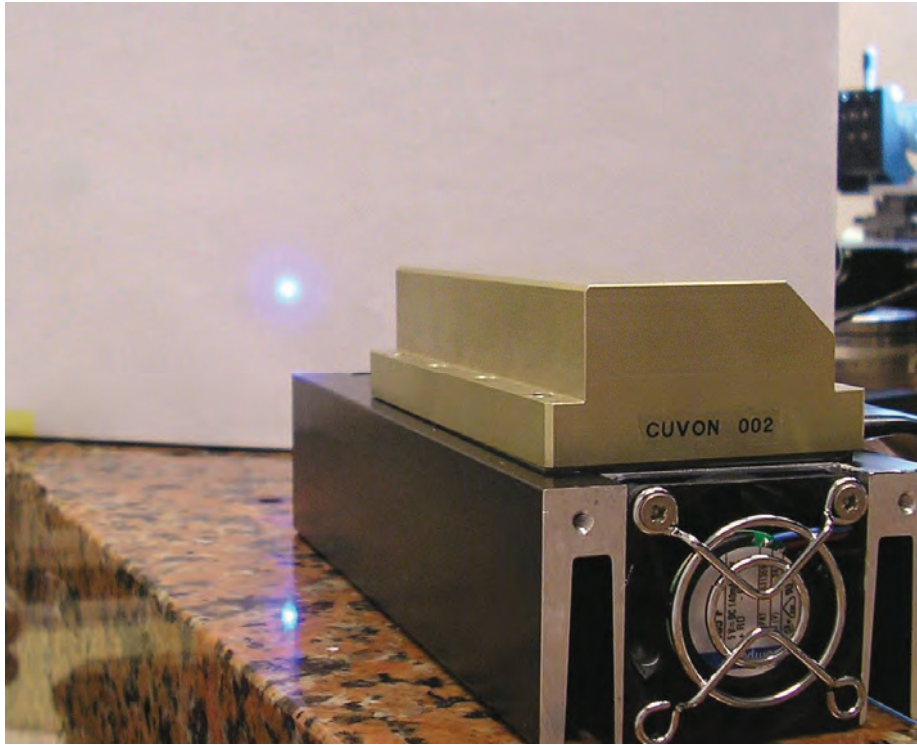


Figure 7 : UV laser in operation

As a first experiment, we increased the pump power up to 2.5 W. Although the 1064 nm beam waist was reduced (down to 45 μm in diameter) and the mismatch between pump and signal size increased, the 1064 nm and consequently the UV power increased. At 2.5 W pump power, we were able to maintain the UV power beyond 30 mW over several minutes. When the power dropped below 30 mW, we could recover 30 mW by fine tuning the nonlinear crystal temperature.

We have built 5 more lasers with the same design. The maximum power that we could extract from each laser did not vary much from one laser to another and always exceeded 30 mW.

We then conducted power control experiments. We chose to reduce the pumping power down to 1.65 W again and to stabilize the UV power at 10 mW. Over 1°C amplifier temperature range and crystal temperature range, a simple feedback on the diode current could stabilize the power. No “green-noise”-like behaviour was observed, but at some temperatures, mode hops induced power fluctuations (first 3 hours of figure 8). Other temperatures settings however seem exempt from mode hops (figure 8) and are compatible with a stable operation.

With a proper choice of temperatures and in a controlled environment (air-conditioned room), we have monitored the UV power over several days. The laser never turned into a noisy operation. We are now optimizing the robustness of the laser with respect to external temperature variations.

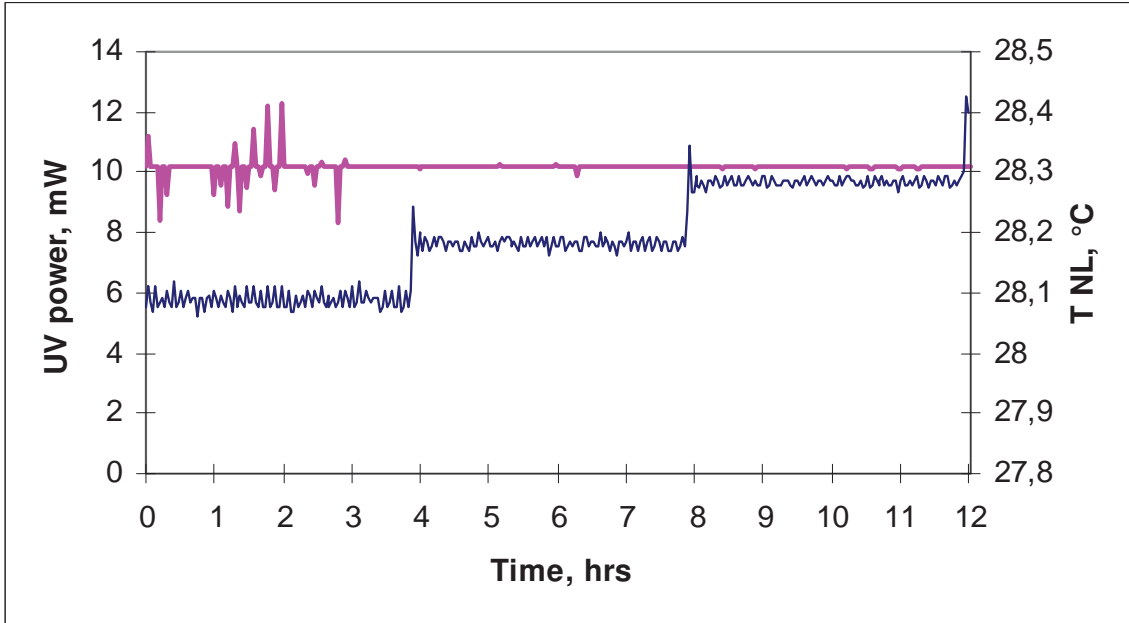


Figure 8 : UV power with control at three different crystal temperatures.

### 3. CONCLUSION

To our best knowledge, we have presented the highest 355 nm CW power obtained by a single emitter diode pumped laser. This was achieved thanks to a better control of the cavity loss and a better overlap between pump and signal in the amplifier (best at 1.65 W pumping). Several lasers were operated at more than 30 mW at 355 nm and 15 mW of UV power was reached at 1.65 W of diode power. Further improvements of UV power and optical conversion efficiency will be possible by optimizing the pump to signal overlap at 3W pump power. We were able to control the oscillating modes through the amplifier and the nonlinear crystal temperatures and through the pump power. We have demonstrated that most of the operating points did not suffer from the “green noise” and the noise level was below the sensitivity of our apparatus (0.5% rms). We have shown that for 10 mW output power, the temperature range is large enough (greater than 1°C) to allow a long term power control and we have demonstrated overnight operation without mode hop or noise.

### ACKNOWLEDGEMENT

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