

# Pulsed blue laser at 491nm by Nonlinear Cavity Dumping

Emilie Herault, Mickaël Lelek, François Balembois, Patrick Georges

Laboratoire Charles Laboratoire Charles Fabry de l'Institut d'Optique, CNRS, Univ Paris-Sud,  
Campus Polytechnique, RD 128, 91127 Palaiseau Cedex, France  
[francois.balembois@institutoptique.fr](mailto:francois.balembois@institutoptique.fr)

**Abstract:** A nonlinear cavity dumping process is applied for the first time to generate kW peak power pulses at 491 nm. The system is based on efficient sum-frequency mixing of 1063 nm and 912 nm radiations in a BiBO nonlinear crystal placed inside a Nd:GdVO<sub>4</sub> laser oscillator with a high finesse cavity at 912 nm. The nonlinear cavity dumping process is triggered by high peak power nanosecond pulses from a 1063 nm Q-switched Nd:GdVO<sub>4</sub> laser operating at 10 kHz. To reach the kW range at 491 nm a key point is to Q-switch the high finesse 912 nm cavity instead of continuous wave operation. Thus, the peak power (9.3 kW for 3 ns pulses) and the average power (280 mW) obtained at 491 nm are 14 times higher than the one obtained when the 912 nm laser operated in continuous wave.

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**OCIS codes:** (140.3580) Lasers, solid-state; (140.3540) Lasers, Q-switched; (140.7300) Visible lasers).

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## 1. Introduction

This last decade, the visible solid-state lasers have found increasing number of applications such as full-color displays, astronomy or biophotonic as they become more and more efficient

and compact. In particular, the blue radiation is absorbed by several popular fluorescent dyes (coumarin, rhodamine 6G ...). Currently, in one photon microscopy, the usual laser is an Ar-ion laser around 488 nm. As it is generally cumbersome and inefficient a lot of solutions have been investigated to replace it by diode-pumped solid-state lasers [1]. Nevertheless, blue lasers emits generally in continuous wave and pulsed laser in this wavelength range are very unusual. A pulsed blue source can be however a very precise tool for micromachining or for cell sorting and handling [2,3]. Moreover, by frequency conversion, a pulsed laser around 490 nm can be efficiently converted in the UV range at 245 nm by second harmonic generation driving applications such as fiber Bragg grating writing or optics characterizations. The development of a laser source emitting energetic pulses requires Q-switched operation with gain media having a relatively long fluorescence lifetime. Whereas optically pumped semiconductor lasers represent a nice solution for cw emission around 490 nm [4], they are useless for Q-switched operation due to a very short storage lifetime (in the nanosecond range). Sum frequency mixing between two vanadate lasers is a concept already demonstrated for cw emission at 491 nm [5]. This architecture can be investigated in pulsed regime as vanadate crystals are well known for their efficiency in Q-switched operation. Indeed sum frequency mixing in the Q-switched regime has already been investigated with vanadate crystals for red-orange emission resulting from the mixing of Nd:YVO<sub>4</sub> lasers at 1064 nm and 1342 nm [6,7]. In this configuration, the laser lines used are four level systems with relatively close spectroscopic parameters, leading to a relatively simple architecture with only one laser crystal [6].

In our case, the sum frequency mixing occurs between the quasi three level transition  ${}^4F_{3/2}$ - ${}^4I_{11/2}$  (912 nm in Nd:GdVO<sub>4</sub>) and the very efficient four level transition  ${}^4F_{3/2}$ - ${}^4I_{9/2}$  (1063 nm in Nd:GdVO<sub>4</sub>). As the spectroscopic properties of these lines are very different (much lower effective emission cross-section and reabsorption losses at 912 nm) the gain competition forbids dual-wavelength operation inside the same cavity with one single crystal. Moreover, due to the very low gain of the quasi-three laser transition, the Q-switched regime can lead to very long pulses at 912 nm compared to 1064 nm pulses: the bad temporal overlap can induce inefficient nonlinear conversion.

In this paper, we investigated the concept of nonlinear cavity dumping, which represents an elegant solution for sum frequency mixing of these two very different lines in pulsed operation. The basic principle is to confine the 912 nm radiation in a high finesse cavity where the power can reach few hundreds of watts. Next, the idea is to take part of the high peak power available from Q-switched lasers emitting at 1063 nm with very short cavities [8]. The sum frequency mixing process is then triggered by those short 1063 nm pulses. As the nonlinear crystal is put inside the 912 nm cavity, the depletion at 912 nm induced by the frequency conversion corresponds to an extraction of power from the high finesse cavity; hence the term of "Nonlinear cavity dumping".

This concept has already been implemented in the orange-red wavelength range with moderate peak power (100 W) [9]. In this paper, we report, for the first time, nonlinear cavity dumping at 491 nm with kW peak power pulses. We demonstrate this concept with a 912 nm Nd:GdVO<sub>4</sub> laser operating either in continuous wave or Q-switched operation. This laser is cavity dumped by a Q-switched 1063 nm Nd:GdVO<sub>4</sub> laser emitting high peak power nanosecond pulses.

## **2. Nonlinear cavity dumping with a cw Nd:GdVO<sub>4</sub> laser at 912 nm.**

### *2.1 The cw laser at 912 nm*

The choice of Nd:GdVO<sub>4</sub> for laser emission at 912 nm instead of Nd:YVO<sub>4</sub> (emission at 914 nm) is driven by a more favorable ratio between the emission cross section at 912 nm over the emission cross section at 1063 nm. We have indeed tested both vanadate crystals and concluded from experiments that wavelength selection is easier for Nd:GdVO<sub>4</sub> (less

requirements on mirror coatings) and that this crystal is less sensitive to parasitic emission at 1063 nm.

The experimental setup is shown in figure 1. We designed a four mirror cavity with two focus points: one for the Nd:GdVO<sub>4</sub> and the other for the nonlinear crystal. The latter was a BiBO crystal [10] chosen for its large nonlinear coefficient ( $d_{\text{eff}}=3.22$  pm/V) when it is cut for room temperature type I phase matching ( $\theta=164.1^\circ$ ,  $\phi=90^\circ$ ). It had a length of 10 mm and was both sides antireflection coated at 912 nm and 1063 nm. The mirrors M1, M2, M3 and M4 were highly reflecting at 912 nm. To prevent lasing oscillations at 1063 nm, they were also highly transmitting at 1063 nm. M4 acted as the input mirror for the pulses at 1063 nm. Its transmission was 72 % at this wavelength. The pump source was a fiber-coupled diode at 808 nm with a core diameter of 100  $\mu\text{m}$ , a numerical aperture of 0.22, providing a maximal power of 10 W. The polarization-maintaining fiber output was relay-imaged into the laser crystal by two doublets leading to a pump spot diameter of 170  $\mu\text{m}$  in the laser crystal. The Nd:GdVO<sub>4</sub> crystal was 0.2 % doped, 4 mm long and with a 3 mm  $\times$  3 mm section. The overall cavity length was 500 mm. We estimated the cavity beam sizes in the different crystals using ABCD calculations. The spot radius in the Nd:GdVO<sub>4</sub> was 100  $\mu\text{m}$ . The spot radius in the BiBO was 110  $\mu\text{m}$ . It is worth to note that even if a thermal lens exists in the gain medium, its influence on the cavity is strongly limited as the beam size in the crystal is relatively small. Indeed, we calculated that the cavity beam size is nearly not affected by the thermal lens as long as it remains higher than 40 mm.

By measuring the losses of mirror M2 and the output power through this mirror, we estimated that the intracavity power was around 200 W in this high finesse cavity.

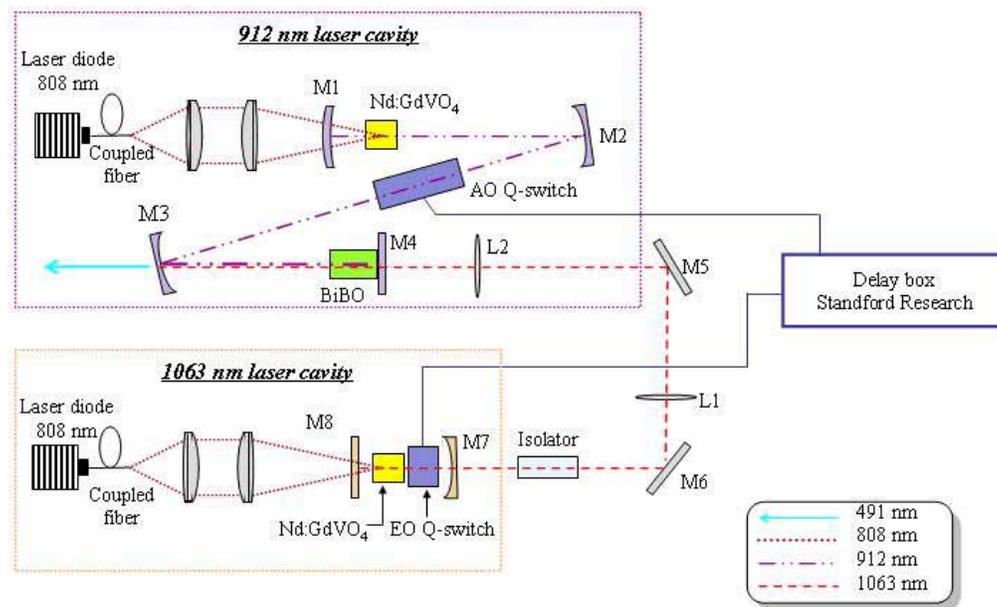


Fig. 1. Experimental setup. M1 radius of curvature is 50 mm, M2 radius of curvature is 200 mm, M3 radius of curvature is 200 mm, M4 is a plane mirror, M7 radius of curvature is 50 mm.

## 2.2 The Q-switched laser at 1063 nm

The design of the Q-switched laser was driven by two considerations: on the one hand, the peak power needs to be high in order to maximize the nonlinear process. On the other hand, the pulse duration must be adapted for the cavity dumping process itself. It should be at least

equal to the cavity roundtrip at 912 nm provided that the nonlinear coupling is strong enough to dump the whole circulating intracavity 912-nm field within a single pass of the cavity. In our setup the cavity M1-M4 described above, has a cavity roundtrip of 3.3 ns. Hence, we designed a relatively short cavity with a compact electro-optic modulator as previously reported [8]. The experimental setup for the laser at 1063 nm is given on the Fig. 1.

Preliminary experiments were done with a Nd:YVO<sub>4</sub> crystal [11]. However, we observed that this crystal was very sensitive to amplified spontaneous emission and to parasitic oscillation between the crystal faces (even anti-reflection coated) leading to unstable pulse amplitude in Q-switched operation. We obtained more stable pulses with a Nd:GdVO<sub>4</sub> crystal because of its lower emission cross section. This one was 0.1% doped, 10 mm long and with a 3 mm \* 3 mm section. Its surfaces were anti-reflection coated at 1063 nm. It was pumped by a 808 nm laser diode coupled in a polarization-maintaining fiber (200 μm diameter, numerical aperture of 0.2). The maximum pump power incident on the crystal was 10 W. We used a 9 mm long EO Q-switch modulator (Leysop). The resonator length was set to 45 mm. The output coupler had a transmission of 75% in order to reduce the pulse duration to a few nanoseconds.

In order to optimize the peak power while maintaining a large average power, we operated at a repetition rate corresponding to the inverse of the lifetime in Nd:GdVO<sub>4</sub> (100 μs). Thus, we obtained 3 ns pulses with an average output power of 800 mW at 10 kHz. This corresponds to a peak power of 20 kW.

### 2.3 Results in nonlinear cavity-dumping

In order to avoid any feedback in the 1063 nm laser, we introduce a Faraday isolator close to the output of the laser (Fig. 1). The output beam at 1063 nm was next collimated by the lens L1 (300 mm) and then focused in the BiBO crystal by the lens L2 (200 mm). The spot radius in the nonlinear crystal was then set to be 110 μm, close to the waist size at 912 nm. The mirrors M5, M6 were transport mirrors highly reflecting at 1064 nm and were used to superimpose the beam at 1063 nm on the beam at 912 nm in the BiBO.

The Fig. 2 presents the intracavity power at 912 nm (measured by a fast photodiode on a leakage of mirror M2) and also the pulses at 1063 nm and 491 nm.

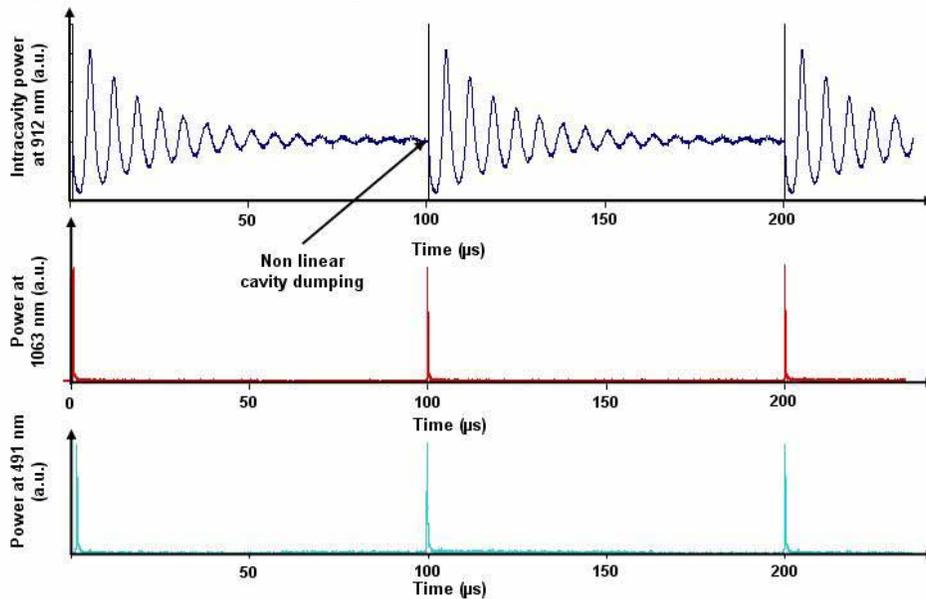


Fig. 2. Power recorded at 912 nm (intracavity, top), at 1063 nm (middle) and 491 nm (bottom) versus time.

The laser at 912 nm is strongly perturbed by the nonlinear cavity dumping process. A large amount of fundamental photons at 912 nm is used for the sum frequency mixing and as the cavity is significantly emptied, the cavity dumping is followed by relaxation oscillations. The Fig. 3 gives a closer view on the intracavity dumping process. This injection of 1063nm pulses through the 912 nm cavity had two effects : it converted the 912 nm photons to 491 nm photons leading to a sharp decrease in the 912 nm intracavity power. Moreover, it decreased the gain in the Nd:GdVO<sub>4</sub> crystal leading to a progressive decrease of the intracavity power. This unexpected effect was certainly due to parasitic reflexions of the 1063 nm pulses inside the cavity such as a part of the 1063 nm photons reached the gain medium and then burned the population inversion significantly leading to a gain decrease below the oscillation threshold.

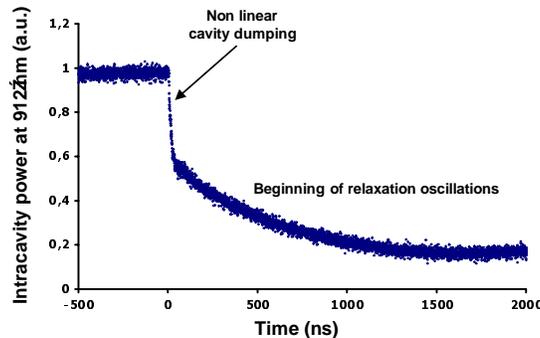


Fig. 3. Zoom on the intracavity power close to the nonlinear cavity dumping.

The Fig. 4 presents the pulse shape at 1063 nm and 491 nm. For the sake of comparison, the normalized maximum powers of the two pulses were superimposed. It shows that the pulse duration is larger at 491 nm (5.5 ns) than at 1063 nm (3 ns) and that the leading edge and the trailing edge are longer in the blue. This difference can be explained by a saturation effect in the nonlinear process induced by the small number of photons at 912 nm with respect to the number of photons at 1063 nm.

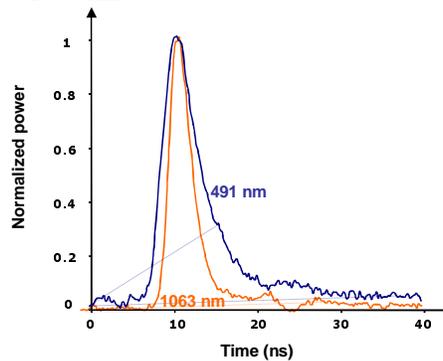


Fig. 4. Temporal pulse shape at 1063 nm and 491 nm obtained with the nonlinear cavity dumping process in case of a cw 912 nm laser. Secondary peaks are due to the pulse response of the photodiodes.

With the setup, we obtained only one output at 491 nm, in the same direction with the 1063 nm laser beam, despite the use of a linear cavity at 912 nm. This is one of the advantages of the nonlinear cavity process. We obtained an average power of 20 mW at 491 nm. This corresponds to a peak power of 360 W for the blue pulses. The beam profiles for the 912 nm

laser and the 1064 nm laser were TEM<sub>00</sub>. The beam profile at 491 nm was elliptical (ratio 1 to 2), limited in one direction by the angular acceptance of the BiBO crystal (1.4 mrad/cm). The average power is here strongly limited by the number of photons at 912 nm available during the pulse duration of the Q-switched laser at 1063 nm. One way to improve the performance is to increase the peak power at 912 nm by operating the quasi three-level laser in Q-switched regime.

### 3. Nonlinear cavity dumping with a Q-switched Nd:GdVO<sub>4</sub> laser at 912 nm.

#### 3.1 Q-switched operation at 912 nm and pulse synchronization

The 912 nm laser was actively Q-switched by an acousto-optic modulator (IntraAction corp.) inserted between M2 and M3 in the 912 nm cavity, where the beam is collimated. It operated at the same repetition rate as the 1063 nm laser : 10kHz. The cavity beam sizes in the Nd:GdVO<sub>4</sub> and in the BiBO were not affected by this modification. The Fig. 5(a) shows the pulse duration measured on a leakage of mirror M2.

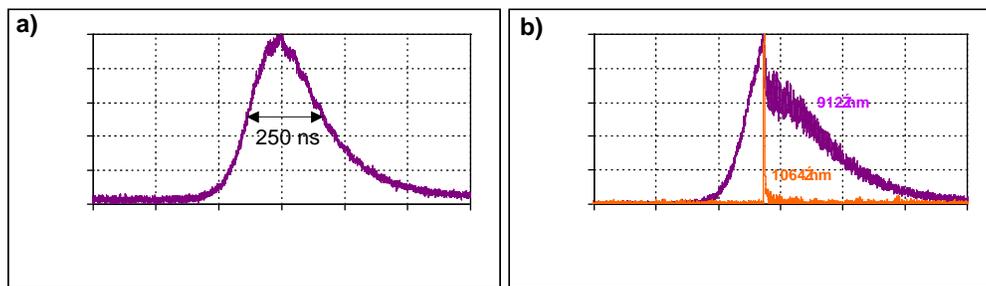


Fig. 5. (a) Pulse duration at 912 nm from the Nd:GdVO<sub>4</sub> Q-switched laser. (b) Temporal evolution of the intracavity power at 912 nm during the cavity dumping process.

As expected, the pulse width at 912 nm is much larger than that at 1063 nm: 250 ns. Nevertheless, the intracavity peak power is strongly improved: 30 kW (compared to 200 W in continuous wave operation).

The two Q-switched lasers need to be synchronized correctly in order to cavity dump the 912 nm cavity when the intracavity power reaches its maximum. The synchronization is achieved by a delay box triggering the drivers of the electro-optic modulator (for the laser at 1063 nm) and of the acousto-optic modulator (for the laser at 912 nm). As the laser build-up times are strongly different (much shorter for the 1063 nm laser), the delay box sent two electrical pulses shifted in time: the first one for the 912 nm laser and the second one for the 1063 nm. Timing jitter between the two optical laser pulses is a critical parameter for the stability in the blue. It comes from variations in buildup times induced by vibrations or pump fluctuations or by the triggering process itself. In our case, we observed a relative timing jitter between the 1063 nm and the 912 nm pulses to be about 40 ns. As the pulse width at 912 nm is much larger than this value, the intracavity power at 912 nm remains higher than 90 % of its maximum when the cavity dumping process is triggered for the all range of the timing jitter. The peak power stability at 491 nm was measured to be 10 % (from peak to peak).

#### 3.2 Experimental Results

The Fig. 5(b) shows the cavity dumping process at 912 nm measured on a leakage after mirror M2.

More than 30 % of the power at 912 nm is converted in the blue. This time, the dumping process is limited by the peak power at 1064 nm (20 kW) which is lower than the intracavity peak power at 912 nm (30 kW).

It appears that the 912 nm signal became modulated after the dumping process as it is shown on the Fig. 5(b). We measured that the modulation period equals the cavity roundtrip of the 912 nm cavity. One possible explanation could be an effect of the 1063 nm pulse duration (slightly lower than the cavity roundtrip, 3 ns versus 3,3 ns) and pulse bell shape at 1063 nm: When the 1063 nm photons are inside the 912 nm cavity, the 1063 nm peak power is not the same for all positions inside the cavity. This means that all the 912 nm photons in the cavity did not experience the same amount of conversion to 491 nm : the cavity dumping process depends on the position inside the cavity.

The Fig. 6 compares the pulse duration at 1063 nm with the one at 491 nm.

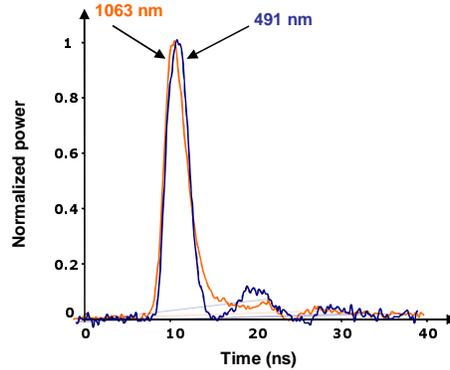


Fig. 6. Temporal pulse shape at 1063 nm and 491 nm from the nonlinear cavity dumping configuration with the Q-switched 912 nm laser. Secondary peaks are due to the pulse response of the photodiodes.

As opposed to the previous setup operating in cw at 912 nm, pulse durations are nearly the same, around 3 ns. The average output power at 491 nm is 280 mW at 10 kHz, leading to a pulse energy of 28  $\mu$ J and to a peak power of 9.3 kW. The beam profiles are unchanged compared to the continuous wave regime.

We used the SNLO freeware [12] to calculate the pulse energy at 491 nm. The instantaneous power at 1063 nm is known from the Fig. 6. Concerning the instantaneous power at 912 nm, we assumed a square shape with a pulse duration of the cavity roundtrip. We found by simulation an energy of 35  $\mu$ J slightly higher but in agreement with the experimental results.

#### 4. Conclusion

In conclusion, we present, for the first time, the generation of 491 nm laser pulses based on nonlinear cavity dumping of a laser at 912 nm by a frequency mixing process triggered by a pulsed laser at 1063 nm.

We compared 491 nm performance when the 912 nm laser operated in continuous wave or in Q-switched. At 10 kHz, we obtained nanosecond blue pulses with an average power of 20 mW for a cw 912 nm laser and 280 mW for a Q-switched 912 nm laser. This corresponds to a maximum peak power of 9.3 kW.

Compared to an ordinary sum frequency mixing between two Q-switched lasers, the originality of nonlinear cavity dumping stands in the location of the nonlinear crystal. Indeed, it is placed in the cavity of the laser having the lowest gain and producing the longest pulses. The problem of pulse overlap is then solved and the frequency conversion remains efficient even if the pulse durations of the two Q-switched lasers are very different.

The high peak power obtained opens the way for further nonlinear processes to reach several useful wavelengths in the UV band. For example, the sum frequency mixing of the blue pulse with the remaining 912 nm beam will produce pulses at 320 nm of particular

interest in Biology. This wavelength is rather difficult to produce by other ways with solid-state lasers in the present state of the art. Moreover, by second harmonic generation in CLBO, it should be possible to obtain few tens of milliwatt at 245.5 nm from the output beam at 491 nm. This wavelength corresponds to diffraction gratings engraving particularly in fibers. Finally, it would be even possible to create a sum-frequency between the pulse at 912 nm and the pulse at 245.5 nm and to obtain a pulse at 193 nm useful for UV optic characterizations.