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LED side-pumped $Nd^{3+}:YVO_4$ laser at room temperature

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ABSTRACT

The lighting market has recently improved LED performance by orders of magnitudes. In parallel, massive production decreases dramatically LED price. Those improvements triggered new interests for LED pumping of lasers which was first studied in the early 1980s on neodymium doped and ytterbium doped lasers at low temperature. Since the 2000's, several research teams started to revisit the concept of LED pumped lasers: polymer laser, fiber laser and semiconductors have recently demonstrated laser effect under visible LED pumping. However, no experimental results were reported on LED pumped bulk crystals. In this paper, we demonstrated for the first time a LED pumped $Nd:YVO_4$ laser operating at room temperature. We investigated two pumping wavelengths: in the amber around 600 nm and in the near infrared around 850 nm. The laser operated in quasi-cw-pumping regime to increase the LED intensity. We performed a two-mirror cavity transversely pumped by 36 LEDs. Laser operation was achieved at room temperature for the both pump wavelengths: a maximum output energy of 40µJ for an emitted energy of 7.4 mJ with infrared pumping and an energy of 11.7 µJ for an emitted energy or 2.3 mJ with amber pumping.

This works demonstrated that LED pumping has an interesting potential to realize ultra-low-cost solid-state lasers operating in pulsed regime at kHz repetition rate and with energies in the mJ range.

Keywords: Neodymium laser, Solid-state laser, Laser resonators, LED pumping, transverse pumping

1. INTRODUCTION

Shortly after the first demonstration of the flashlamp pumped ruby laser by Maiman[1], LED pumping was demonstrated for the first time in 1964 in $Dy:CaF_2$ crystal[2]. In the 1970s, different works on neodymium lasers (such as Nd:YAG or Nd-pentaphosphate) were published with LED as the pump source[3–8]. Laser effect was also demonstrated with an LED pumped Yb:YAG crystal[9]. LED pumped solid-state lasers were generally cooled below room temperature to increase the emission cross section of the gain media, the LEDs' efficiency, and hence the laser efficiency.

At the beginning of the 1980s, LED pumping was progressively forsaken with the emergence of laser diodes. Thanks to their high efficiency and brightness, laser diodes rapidly became the favorite sources to pump solid-state lasers. However, driven by the lighting market, LED performance has been recently improved by orders of magnitude. Starting from intensity of 0.1 to 10 W/cm^2 at cryogenic temperatures in the 70s, it now reaches up to 100 W/cm^2 (in continuous wave at 1 A) at room temperature with efficiencies greater than 200 lm/W[10]. In parallel, LED prices experienced a dramatic drop thanks to massive production. Moreover, contrary to laser diodes, LEDs are less sensitive to electrostatic discharges and have a lifetime 3 to 4 times higher than laser diodes.

Those improvements have triggered a new interest and LED pumping has started to be revisited since 2008. Turnbull and co-workers[11,12] took the opportunities offered by high performance visible blue LED to pump polymer lasers. By pulsing LEDs during few tens of ns, they succeeded to inject current in the LED up to 160 A, leading to a LED optical intensity of 255 W/cm^2 at 450 nm and demonstrated a laser effect at 568 nm from a polymer distributed feedback laser. Htein *et al.*[13,14] used white LED to exploit all absorption bands of erbium and neodymium doped fibers in the visible range. They obtained 12 dB (at 1550 nm) and 6 dB (at 1400 nm) of amplification gain. Liu *et al.*[15] demonstrated a laser effect from a semiconductor monolithically pumped by a LED which operates in a thermoelectrophotonic regime.

Surprisingly, LED pumping of bulk crystals as in the pioneer ages has not been revisited yet. Recently, a Korean team studied theoretically the pumping of five gain media (Nd:YAG, Nd:glass, Nd/Cr:YAG, Ti:sapphire, and solid dye) by two types of LEDs, white and blue[16], but gave no experimental demonstration of laser effect.

Furthermore, it is worth noting that many results were reported on LED pumped Nd:YAG lasers, but nothing with Nd:YVO_4 crystals (probably partly because a YVO_4 matrix appeared after the vanishing of LED pumping). Compared to Nd:YAG, the product of the emission cross section by the lifetime is still two times higher and can, therefore, theoretically produce a much higher optical gain. Consequently, combining Nd:YVO_4 laser material with new intensities of today's LEDs should result in promising performance. In this paper, we investigate both experimentally and theoretically an LED-pumped Nd:YVO_4 laser. We first carried out a LED pumping in the near infrared (sections 2 and 3) and then investigated the potential of LED pumping in the visible (section 4).

2. EXPERIMENTAL SETUP

2.1 IR LED array features

As a pump source, we used near-IR LEDs centered at 850 nm from Light Avenue. A dice of 1 mm by 1 mm emits an intensity of 25 W/cm^2 at a continuous drive current of 1 A. Basic calculations based on small signal gain (see below for theory) show that this value is currently too low to reach the laser threshold. Therefore, we operated the LEDs in QCW pumping regime. The current driven by PCO-6131 (Directed Energy, Inc) injected into the LEDs had a square shape, with a pulse duration of 100 µs (in accordance to the Nd:YVO_4 lifetime). By increasing the current, each chip emits a peak output intensity of 200 W/cm^2 at 40 A, eight times higher than in the CW operation. Beyond this current, the one mil (≈ 25 µm) gold wires between the dices and the electrical track evaporated. In QCW operation, we measured the emission spectrum (Fig. 1) and found that the spectral width increases from 35 to 60 nm between 10 and 40 A. This effect can be explained by the temperature increase of the LEDs at high current values.

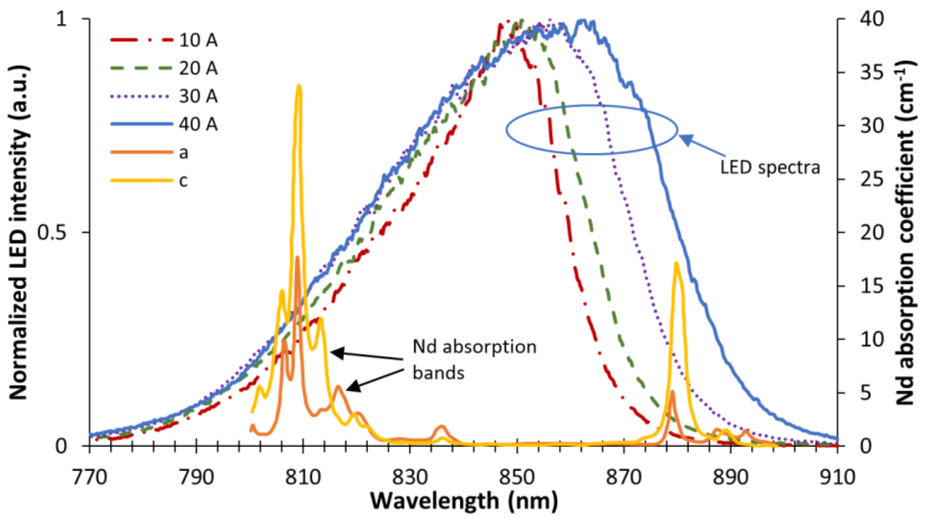

Figure. 1. Spectral deformation for different injected currents and Nd:YVO_4 absorption bands for 1 at. % doping concentration[23].

A LED array consists in a line of 18 1 mm × 1 mm chips. We used two arrays of LED, positioned on two opposite sides of the laser crystal. Chips are separated from each other by 0.3 mm (illustrated in the inset of the Fig. 2). Each LED array is placed on a water-cooled copper-mount heat sink to regulate the LED temperature. We studied the energy contained in a 100 µs pulse at 40 A versus the repetition rate of the LEDs. Figure 2 illustrates this measurement for all LEDs. We observed that, at this current level, the energy was stable (at 7.4 mJ) for frequencies below 250 Hz and began to drop slightly for higher frequencies, to finally stop emitting above 400 Hz. Indeed, at this frequency and this current, the gold wires melt. This is why, all of our measurements have been done far below this value (namely 250 Hz).

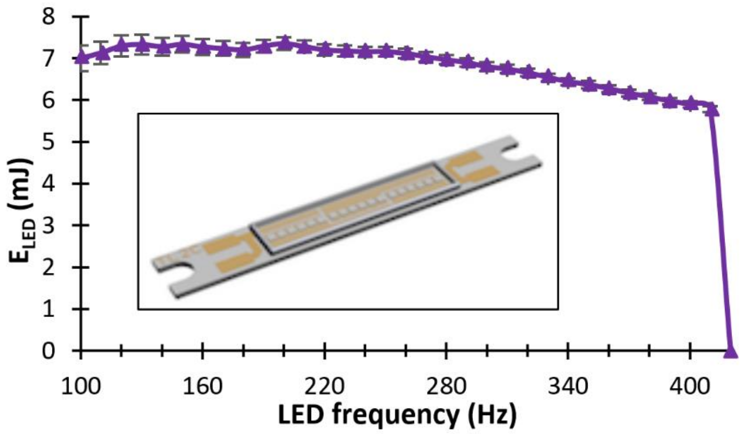

Figure. 2. Evolution of the pump energy emitted by the two LED arrays versus the repetition rate. Inset: illustration of the LED array.

2.2 Laser cavity

As the emission diagram of LED is lambertian, it is very difficult to collect all the emitted flux with optics. It is nearly impossible to focus the LED beam with a higher intensity (in W/cm^2) than the intensity at the surface of the dice itself. Therefore, we chose to design a pumping configuration without optics, the LED beam being close coupled to the laser crystal. To increase the number of LED, we use a transverse pumping configuration to distribute the LED all along the crystal surfaces, as shown in Fig. 3.

The laser crystal is an a-cut 20 mm long Nd:YVO_4 crystal with a doping concentration of 1 at.% and a 2 mm × 2 mm square section. The orientation of the crystal has been picked to maximize the absorption. The pumping is then done along the (a,c) axes. The doping concentration has been chosen to be as high as possible while avoiding concentration quenching[17,18]. Two of the transverse surfaces are polished for the pumping. However, the transverse surfaces are not AR coated. The two other side-surfaces are used to cool the crystal. As the large emission cross section of Nd:YVO_4 is very sensitive to temperature changes[19,20], the crystal is held by two water-cooled copper mounts to extract the heat induced by the pumping. Both crystal laser facets are AR coated with a reflectivity below 0.1% at 1064 nm. We designed a plano–concave cavity with an HR-coated 500-mm-radius-of-curvature mirror and a plane output coupler. The cavity length can be adjusted from 200 to 500 mm to optimize the output energy versus the coupler value.

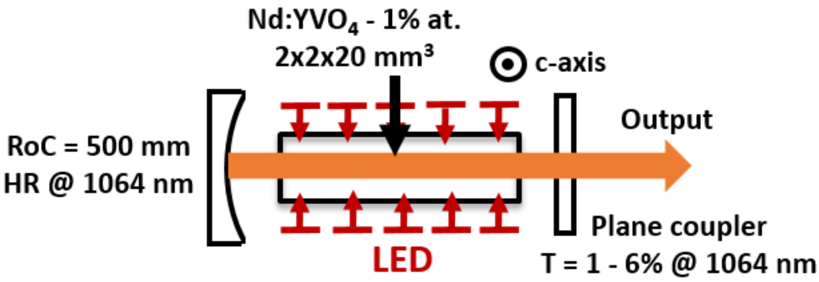

Figure 3. Experimental setup.

3. EXPERIMENTAL RESULTS

3.1 Laser characteristics

First, we measured the performance of our system for different transmissions of output couplers (Fig. 4). Our best results have been obtained with a 1% transmission output coupler. In this configuration, we found a pump energy threshold of 1.84 mJ and obtained nearly 40 µJ of laser energy for an input energy of 7.4 mJ at a repetition rate of 250 Hz. This corresponds to an optical efficiency between the laser energy and the total energy emitted by the LEDs of 0.5%. Additionally, we studied the spatial profile of our laser by imaging the beam waist with a 75 mm focal length lens in a 2f-2f configuration. The profile is given in Fig. 4. We measured an M^2 factor of 19, corresponding to the large pump volume related to the transverse pumping configuration. We have also monitored the laser pulse temporal shape (Fig. 4 inset). For a pump pulse duration of 100 µs, the laser pulse is about 65 µs long at 40 A. We clearly observe the transient buildup of the laser with the spiking behavior at the beginning of the pulse. Then, the laser converges to a continuous value in the second half of the pulse, corresponding to the quasi-continuous-wave regime.

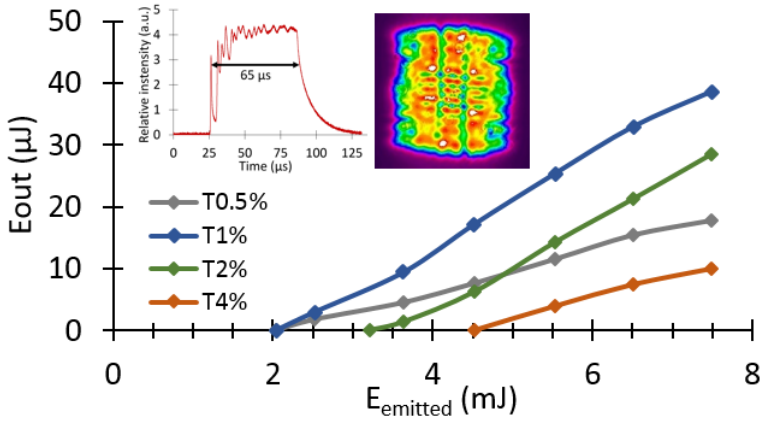

Figure 4. Evolution of the output energy versus the input pump energy. Inset: spatial and temporal profiles of the laser beam at maximum pump energy (7.4 mJ).

3.2 Comparison with calculations

Subsequently, to explore the maximal gain available, we progressively increased the transmission of the output coupler and noted the corresponding pump energies required to reach the laser threshold. Figure 5 illustrates the small-signal gain G_0 as a function of the pump energy at the laser threshold. We deduced a single pass small signal gain G_0 up to 1.042. The solid and dash curves represent the theoretical evolutions from our simulations presented in the following paragraph.

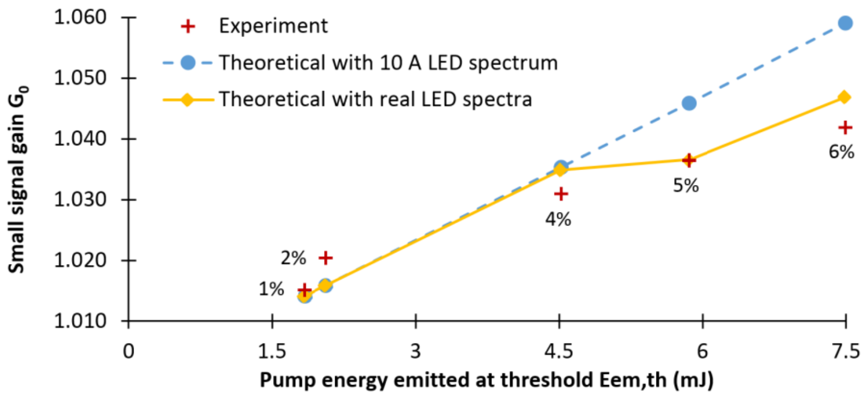

Figure 5. Theoretical and experimental small-signal gain as a function of the pump energy $E_{em,th}$ needed to reach the laser threshold, for different output couplers.

To describe the small signal gain available with this LED pumped system, we calculate the gain coefficient (cm^{-1}) described by Eq. (1), taking into account that LEDs are non-monochromatic sources:

$$g = \frac{n_t \sigma_{el} \tau}{hc} \int_{\lambda_{p1}}^{\lambda_{p2}} \sigma_{ap}(\lambda_p) \lambda_p \frac{dI_p}{d\lambda_p} d\lambda_p \quad (1)$$

where n_t is the total population density of Nd^{3+} ions in the YVO_4, σ_{ap} is the absorption cross section at the pump wavelength, σ_{el} is the emission cross section at the laser wavelength, I_p is the pump intensity (in W/cm^2), λ_p is the pump wavelength, h is the Planck constant, c is the speed of light in vacuum, and τ is the lifetime of the laser transition. Finally, as the pump pulse duration (100 µs) is the same order as the lifetime of Nd in YVO_4 (90 µs), the real gain is not the steady-state gain. To take the transient buildup into account, we defined a gain coefficient g' at the end of the pump pulse to be

$$g' = g\left(1 - e^{-\frac{\Delta t}{\tau}}\right) \tag{2}$$

where Δt is the pump pulse duration. Considering L as the crystal length, we can now calculate the small-signal gain G_0 (in single pass):

$$G_0 = e^{g'L}. \tag{3}$$

Crystal losses α were assumed to be negligible. The relations (1) and (3) show that we need to know I_p at any point in the crystal to have access to G_0. Thereby, we have used a commercial ray tracing software (LightTools) which allowed us to simulate our system numerically[21]. After entering all the parameters, we calculated the pump intensity at any point the crystal and determined the repartition of laser gain inside the crystal and hence the small signal gain.

These simulations allow us to highlight the effects of the LED's spectrum on the gain. Indeed, in Fig. 5, the dashed line represents the theoretical evolution of the small signal gain when we consider a constant typical 35-nm-wide spectrum (corresponding to 10 A driving current) regardless of the injected current, while the solid line is the result when we take into account the broadening of the spectrum versus the driving current. Thus, we deduce from our simulations that the LED spectral broadening is a critical parameter, strongly limiting the small signal gain and hence the laser performance.

3.3 Theoretical analysis

Since the simulation was validated by the experimental data (Fig. 5) it became a tool to investigate the influence of other key parameters coming from the pump geometry, namely the distance between the LED and the crystal (parameter X described in Fig. 6) and the misalignment between the two LED arrays, called Y and described in Fig. 6.

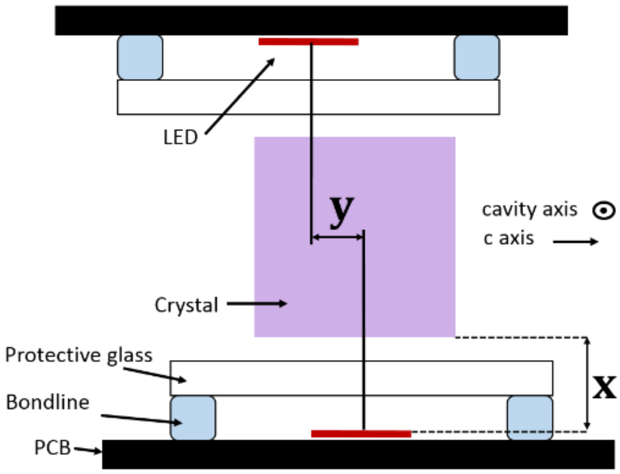

Figure. 6. Transversal view of the pumping scheme with the crystal at the center and the LED arrays on two opposite sides. *X* and *Y* are two key spatial parameters.

First, Fig. 7 shows that the small signal gain is very sensitive to the distance X between the LED arrays and the crystal; since the incident pump intensity (W/cm2) depends on the square of the distance to the crystal, a small increase of the LED-crystal distance can lead to an important decrease of the gain inside the crystal. In our setup, the working distance cannot be less than 700 µm due to the protective glass and to the bond line (see Fig. 6); this reduces the gain by a factor of 0.5 compared to the maximum value (reached when the LEDs and the crystal are almost in contact). Gain evolution versus a misalignment Y between the LEDs is less sensitive. However, one has to control this parameter carefully since a misalignment of 1 mm (namely half of the crystal size) between each LED array and the crystal can reduce the gain by 20%. On Fig. 7, we computed the small signal gain for the experimental distance between the LED and the crystal (namely 700 µm) versus the misalignment of the two LED arrays. We put the experimental gain on this curve (1.04) and obtained an estimation of the LED misalignment in our setup: close to 1.5 mm. This high value can be explained by the setup itself having no controlled adjustment to move the LED arrays precisely.

Our simulation can also estimate the absorbed energy. Indeed, only 78% of the LED energy reaches the crystal because of the distance between the latter and the LEDs. Then, another 10% is lost because of the non-AR coated pumped crystal faces. Moreover, as anticipated in Fig. 1, the absorption is relatively weak. It is partially compensated by the optical path inside the crystal by non-perpendicular rays or rays being trapped by total internal reflection. Taking into account all the rays coming from the LEDs, we estimated using LightTools that 30% of the pump energy is absorbed. Hence, from the 7.4 mJ emitted by the LED, only 1.5 mJ is really absorbed. This leads to an optical efficiency of 2.6% related to the absorbed energy.

Therefore, our simulations compared to experimental results demonstrated that Nd:YVO4 LED pumping is strongly limited by the

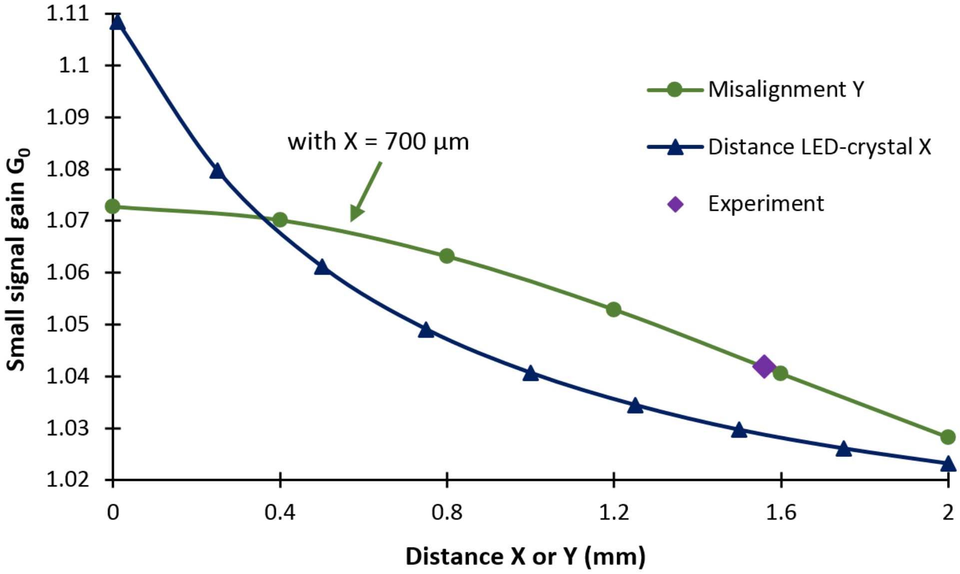

Figure. 7. Evolution of the theoretical small signal gain G_0 as a function of the misalignment between the two LEDs (Y) and the distance between LEDs and the crystal (X). This calculations are used to estimate the misalignment Y in our experiment.

mismatching between the broad LED emission spectrum in the near infrared and the narrow absorption lines of neodymium in the range 800-900 nm. In the next part, we investigate LED pumping of Nd:YVO4 in the visible where the spectral mismatching can be reduced.

4. VISIBLE LED PUMPING

One of the advantages of LED is the coverage of the visible spectrum. In this part, we studied the potential of Nd:YVO_4 LED pumping in the visible and demonstrated laser operation with LED pumping in the amber.

4.1 Potential of $Nd:YVO_4$ pumping in the visible

Fig. 8 presents absorption bands of $Nd:YVO_4$ in the visible and in the near infrared. This crystal has absorption bands in the blue and in the amber that are slightly broader and less structured than absorption bands in the near infrared.

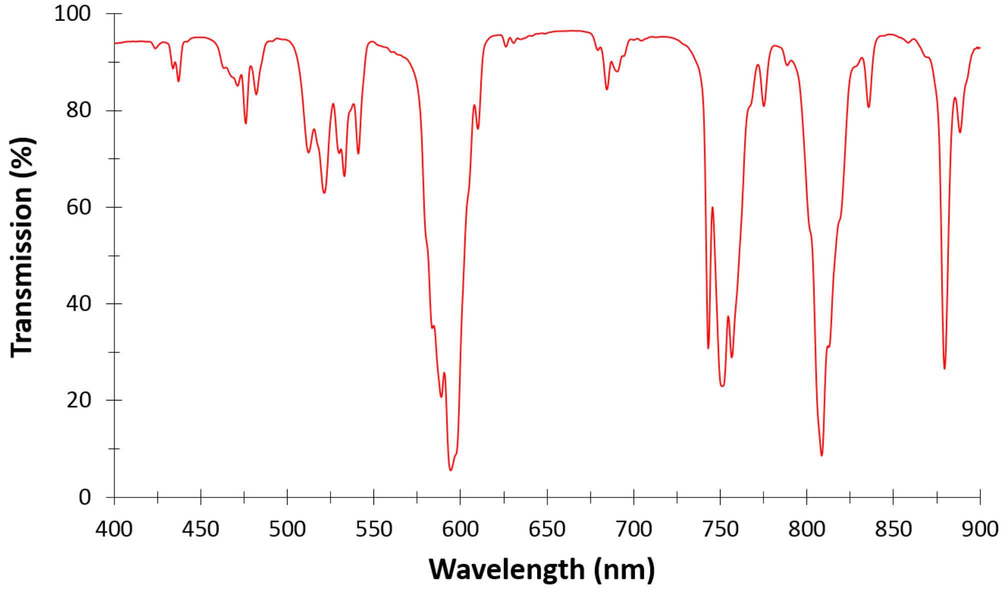

Figure. 8. Absorption spectrum of 1 at. % doped $Nd:YVO_4$ after a propagation of 2 mm. The absorption corresponds to the average between the two polarizations a and c.

In addition, Fig. 9 presents typical spectral width of LED versus the central wavelength. It shows clearly narrower spectra in the visible.

Therefore, to reduce spectrum mismatching between LED and $Nd:YVO_4$, pumping in the amber represents an interesting alternative.

For the experiment, we use two amber LED arrays composed of 18 chips of 1 mm by 1 mm. In continuous wave, each chip can emit 270 mW at 1 A and up to 640 mW in QCW operation (100 µs duration). Fig. 10 shows that the pulsed operation slightly modifies the emission spectrum for amber LEDs, as opposed to IR LEDs undergoing a strong spectral broadening (see Fig.1). Fig. 10 shows also

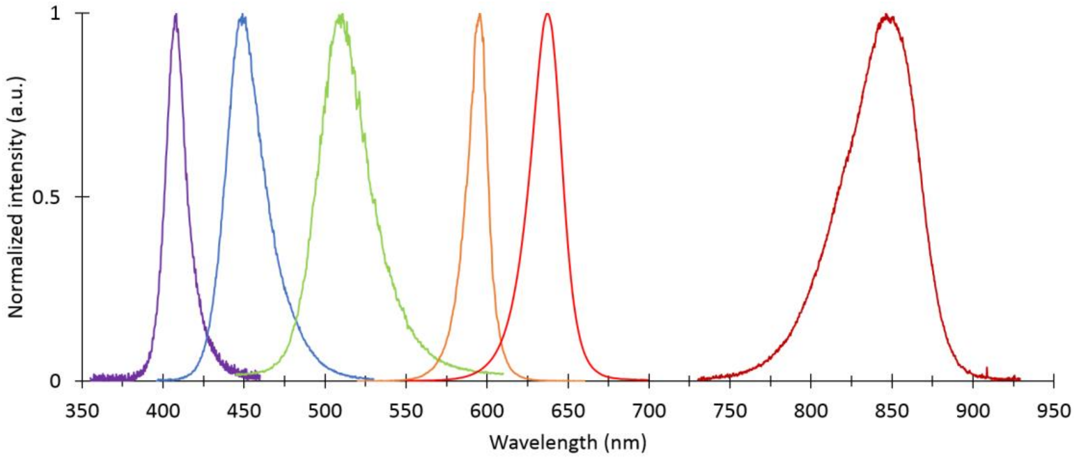

Figure. 9. Typical spectral width of LED versus the central wavelength.

that the LED spectrum and the Nd:YVO_4 absorption spectrum match well in this wavelength range. For our 2 mm by 2 mm 1%doped Nd:YVO_4 crystal, we estimated that 72% of the light entering in the crystal is absorbed. It is considerably higher than the absorption in the IR estimated in the part 3.

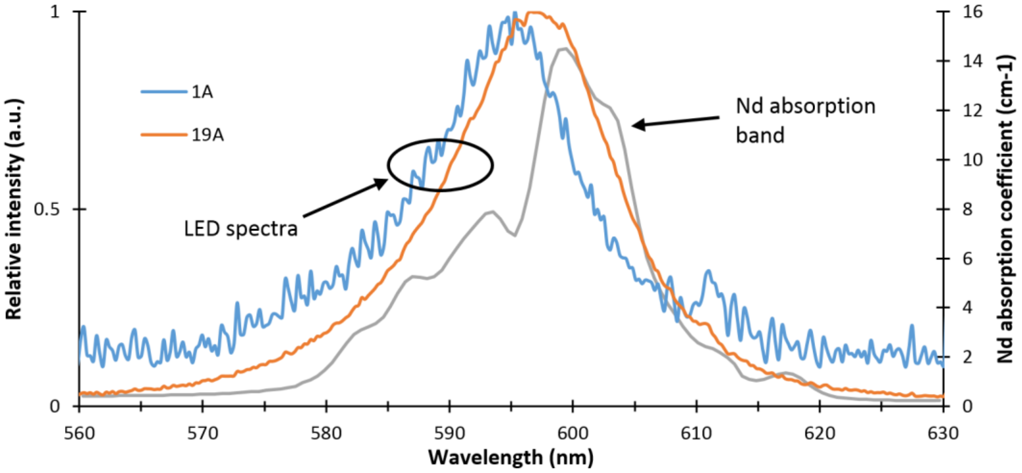

Figure. 10. Emission spectra of amber LED at two driving currents (1A in cw and 19A in pulsed operation). Comparison with absorption spectrum of Nd:YVO_4 in the same wavelength range (obtained by averaging the absorption of the two polarizations a and c).

However, amber LED are much less efficient than IR LED, with 100 µs pulses of driving current, we obtained only an energy of 2.3 mJ emitted by the two arrays. Moreover, we observed that amber LEDs are much more sensitive to thermal effects: during the 100 µs pumping window, we observed a continuous decrease of the emitted power, becoming 30 % lower at the end of the pulse.

Taking into account the LED beam propagation up to the crystal and the non-AR coating crystal interfaces, we estimated that an energy of 1.1 mJ is absorbed in the Nd:YVO_4. This absorbed energy is in the same order of magnitude than in the previous experiment (1.5 mJ). It corresponds to 3.3 10^{15} Nd atoms arriving in the excited state during the pump pulse. In the case of IR LED pumping, this number was 6.4 10^{15}, mainly due to the higher pump wavelength and to the higher emitted energy. Despite the reduction by two of the excited atoms, it should be possible to realize laser effect with amber LED pumping. The experiment is described in the next subpart.

4.2 Experimental results

For crystal availability reasons, the experimental setup for amber LED pumping is slightly different to the one described on Fig. 3. The output coupler is a concave mirror having a radius of curvature of 100 mm and the end mirror was an HR coating on the laser facet of the crystal. This allows smaller laser beam and consequently lower threshold. We made this choice considering that the gain coefficient should be twice lower than in the IR pumping considering the number of excited atoms.

In this experiment, we limited the repetition rate to 30 Hz, taking amber LED thermal issues into account. The laser performances are described in Fig. 11. The maximum energy was 11.7 µJ corresponding to an optical efficiency of 1.1 % with respect to the absorbed energy. Laser operation was achieved for output couplings up to 4 %.

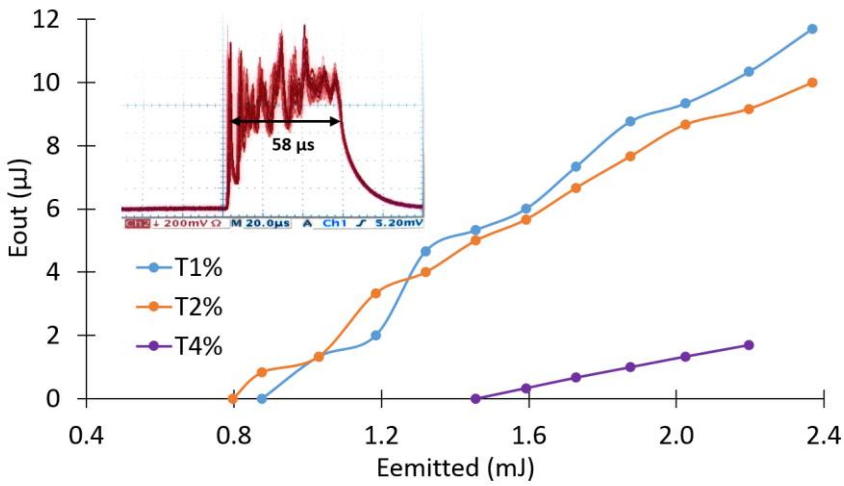

Figure. 11. Output energy versus input energy emitted by the amber LEDs

5. CONCLUSION

In conclusion, we have demonstrated laser effect, at a room temperature, with a Nd:YVO_4 laser transversely pumped by LEDs at two different wavelengths: in the amber (600 nm) and in the near infrared (850 nm). To the best of our knowledge, this gain medium was never LED pumped before this work and represents the first LED pumped Nd:YVO_4 laser.

The output energy was in the 10-40 µJ range corresponding to an optical efficiency in the 1-2.6 % range depending on the pumping wavelength. The comparison between the two pumping configurations emphasizes the problematic and challenge related to LED pumping.

The first one corresponds to the spectral mismatching between LED emission and Nd absorption. This leads to reduced absorption and consequently reduced efficiency. A solution is to use visible pumping where the LED spectral width is lower.

The second one come from the LED intensity: in the case of amber LED, the intensity is limited to 60 W/cm^2 instead of 200 W/cm^2 for IR LED. Indeed emission by semiconductors in the amber are less efficient and more sensitive to thermal issues. Therefore improvement of performance relies mainly then on LED technology. A solution relies on the potential of LED dices to support higher driving currents by increasing the size of gold wires connecting the LED to the driver. Another solution may be to take advantage of the strong technological development of blue LED driven by the lighting market. Indeed, blue LEDs are even more efficient than IR LED, reaching up to 1 kW/cm^2 in pulsed regime. To match neodymium absorption bands, blue emission can be efficiently converted in the amber by phosphors directly deposited on the LED surface. This technology represents an opportunity of energy scaling of the laser.

LED pumping can be considered as an intermediate between diode pumping and flash pumping. It combines many advantages of these two technologies: the pulse to pulse stability of laser diodes, the low cost and simplicity of use of flashlamps. In addition, LED have longer lifetimes than laser diodes. Consequently, in case of Nd doped laser, LED pumping have the potential for ultralow cost laser sources emitting mJ pulses in the kHz repetition rate.

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