crystals

MDPI

Article

High Stability LED-Pumped Nd:YVO_4 Laser with a Cr:YAG for Passive Q-Switching

Hong Xiao [1,2,3], Tianzhuo Zhao [1,2,3,*], Wenqi Ge [1,2,3], Qixiu Zhong [1,2,3], Mingshan Li [1,2], Jiaqi Yu [1,2], Zhongwei Fan [1,2,3,*], Shengwei Bian [1,2,3] and Yanzhong Chen [1,2]

1 Aerospace Information Research Insititute, Chinese Academy of Science, Beijing 100094, China; xiaohong@aircas.ac.cn (H.X.); gewqi@aircas.ac.cn (W.G.); zhongqx@aircas.ac.cn (Q.Z.); limingshan@aoe.ac.cn (M.L.); yujiaqi@aoe.ac.cn (J.Y.); bianzw@aircas.ac.cn (S.B.); aoecyz@aoe.ac.cn (Y.C.)
2 National Engineering Research Center for DPSSL, Beijing 100094, China
3 University of Chinese Academy of Sciences, Beijing 100049, China
* Correspondence: zhaotz@aircas.ac.cn (T.Z.); fanzhongwei@aoe.ac.cn (Z.F.); Tel.: +86-10-8217-8681 (Z.F.)

Received: 23 February 2019; Accepted: 14 March 2019; Published: 10 April 2019

check for updates

Abstract: With improvements in light-emitting diode (LED) performance and a sharp decline in price, a light source with the irradiance of a laser and the cost of an LED is worthy of further study. We demonstrated a LED-pumped Nd:YVO_4 laser in quasi-continuous-wave (QCW) and passively Q-switched (PQS) regime. With an incident pump energy of 6.28 mJ (150 µs pulses at 1 Hz), the Nd:YVO_4 laser has an energy of 206 µJ at 1064 nm in the QCW regime. The optical conversion efficiency of the system is 4.1%, and the slope efficiency is 9.0%. A pulsed energy of 2.5 µJ was obtained with a duration of 897 ns (FWHM) in the PQS regime, which means the peak power is 2.79 W. The output energy stability is 97.54%.

Keywords: (140.3580) lasers; solid-state; (230.3670) light-emitting diodes; (140.3540) lasers; Q-switched; (140.5560) pumping

1. Introduction

The performance of commercial light-emitting diodes (LEDs) has been greatly improved in recent years. At the same time, LED prices have experienced a sharp decline due to mass production. According to Hait'z law [1], LED power has increased by a factor of 20, and its price has been divided by 10 in ten years. More importantly, laser diodes (LDs) are sensitive to temperature, electrostatic discharge, and have a short lifetime. The lifetime of LEDs are generally 3 to 4 times that of LDs. Since LED lighting has a very broad market, the performance of LEDs will continue to improve, and the price per Watt will continue to decrease in the future. Therefore, a light source with the irradiance of a laser and the cost of an LED is a possibility with solid-state lasers. Research on optical materials has also been ongoing [2,3].

An LED pumping laser was first verified in a Dy:CaF_2 crystal in 1964 [4]. In the 1970s, several types of LED-pumped neodymium lasers (such as Nd^{3+} doped crystals) were developed [5–9]. In these early years, the reported LED-pumped lasers were typically cooled by water or more complex structures. In recent years, more research on LED-pumped lasers has begun to be reported [10–12]. It is worth noting that Nd:YVO_4 was chosen as the laser medium because of its very broad absorption spectrum and a very high stimulated emission cross section [13–15]. Consequently, LED-pumped Nd:YVO_4 lasers bring considerable performance. In 2014, Adrien Barbet and his coworkers used an LED-pumped Nd:YVO_4 laser with a pump energy of 7.4 mJ. The maximum output energy of 40 µJ was obtained with a duration of 65 µs in the quasi-continuous-wave (QCW) regime [16]. In 2016, a pulsed energy of 360 µJ was obtained using a Ce:YAG luminescent concentrator in the QCW regime [17]. Adrien Barbet and his coworkers obtained an LED pumped laser that produced a pulsed energy of 6 mJ in the QCW regime in 2016 [18]. The optical conversion efficiency of the system was 2%. However, the laser pulse duration was on the order of microseconds, and the optical conversion efficiency in the above work was relatively low.

Passive Q-switching (PQS) is a very convenient method for efficiently generating nanosecond pulses, compared to active Q-switched lasers. By using an efficient pump scheme and a saturated absorber, a pulsed energy of 1.42 mJ was obtained with a duration of 170 ns in a PQS LED-pumped Nd:YAG laser in 2017 [19]. Though the pump power density can be as high as 151.8 W/cm^2, there is still a need to greatly improve the beam quality for efficient applications. We firstly investigated a high-beam-quality 810 nm LED-pumped Nd^{3+}:YVO_4 laser with Cr^{4+}:YAG passive Q-switching, to the best of our knowledge. Additionally, the pump power density is about one tenth of the reports.

2. Materials and Methods

In our experiment, a side-pumped scheme was adopted in order to improve the total pump power. The pump source we chose is a near-infrared LED with an 810 nm center (OSRAM). LEDs were arranged in four rows. A total of 20,810-nm LEDs with 32-nm full-width-half-maximum (FWHM) were placed close to the Nd:YVO_4. The distance between the LEDs and the crystal was approximately 0.5 mm. The operating frequency of the LEDs was chosen to be 1 Hz with a pulse duration of 150 μs (approximately 1.5 times the Nd^{3+} lifetime in YVO_4). The maximum drive current for the LEDs is 4 A. In this state of operation, the maximum peak irradiance of all LEDs is 33.3 W. That is, each LED emits 0.25 mJ, and the total energy emitted by 20 LEDs is 5 mJ. During the drive time, the electric-to-optical conversion efficiency of these LEDs is approximately 12.7%.

We used an a-cut Nd:YVO_4 crystal as the gain medium. The size of the crystal is 4 mm × 4 mm and 25 mm long. The doping concentration of the crystal is 1.0%. The four facets on the pump side are frosted. The two end facets of the crystal have an anti-reflective (AR, R < 0.2%) coating at 1064 nm. The absorption spectra of Nd:YVO_4 that we used and the emission spectra of 810-nm LEDs are shown in Figure 1. Nd:YVO_4 has a strong absorption peak at 808 nm and a wide absorption band. It can be seen that the 808 nm absorption band of Nd^{3+} is very similar to the emission spectrum of the LED at 808 nm. Therefore, the 810-nm LED is suitable as a pump source for Nd:YVO_4.

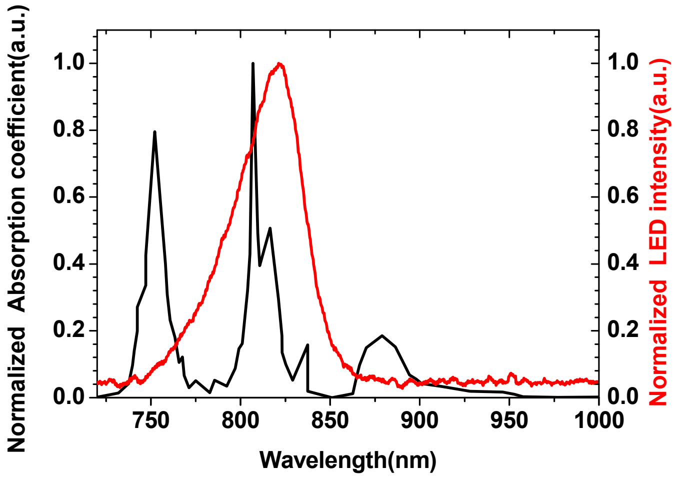

Figure 1. The absorption spectra of Nd:YVO_4 that we used and the experimental pump spectra of 810-nm light-emitting diodes (LEDs).

3. Results and Discussion

The fluorescence distribution of the gain medium was measured using a laser spot analyzer (Coherent. Inc., LaserCam-HR II 2/3″). In Figure 2, the fluorescence distribution in a cross-section of the crystal is shown using a false color diagram. It shows the relative intensity distribution horizontally through the center of the spot on the right, and the vertical distribution is plotted on the left. The results show that the fluorescence has a near flat-top distribution.

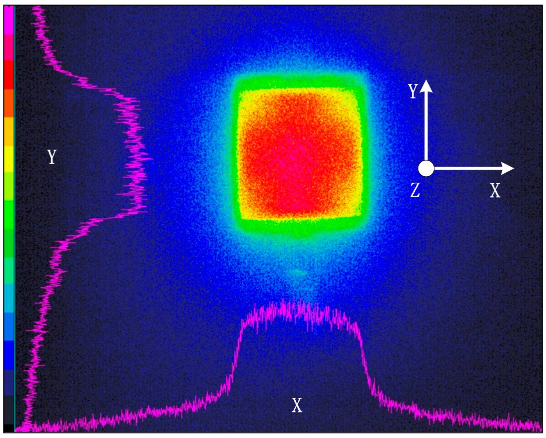

Figure 2. The fluorescence distribution on the end of the Nd:YVO_4 crystal.

At first, in order to evaluate the efficiency of the LED pumping, a linear cavity laser in the QCW mode was employed. The back cavity mirror is a concave mirror that is coated with a highly reflective coating (HR, R > 99.5%) at 1064 nm. The radius of curvature is 2000 mm. The output coupler is a plane mirror and the output couplings are 1.5%, 2%, and 3%. The laser cavity has a length of 63 mm.

With different output couplers, the laser output energy corresponding to different input pump energies was obtained (see Figure 3). The threshold input pump energy is approximately 2.6 mJ (150 µs pulse operation) in the QCW regime. The highest output laser energy was measured using a 1.5% transmission output coupler. When the incident pump energy is approximately 5.0 mJ, the output energy reaches 206 µJ, and the optical conversion efficiency is 4.1%. The slope efficiency is 9.0%. At the same pump level, the output energy decreases as the transmittance of the output coupler increases. The threshold input energy increases as the transmittance of the output coupler increases. In the process of increasing the pump energy from 1.8 mJ to 5.0 mJ, the output energy is increased to 160 µJ and 88 µJ, and the threshold points are 2.9 mJ and 3.5 mJ, respectively. In the process of increasing the pump energy, the output energy does not show obvious saturation. The slope efficiencies are 7.8% and 5.9% while the output mirror output rates are 2% and 3%, respectively. Another obvious advantage is that the energy stability of the output laser is 99.85% for ten minutes. The stability of the output laser energy for the highest peak power in a QCW regime is shown in Figure 4.

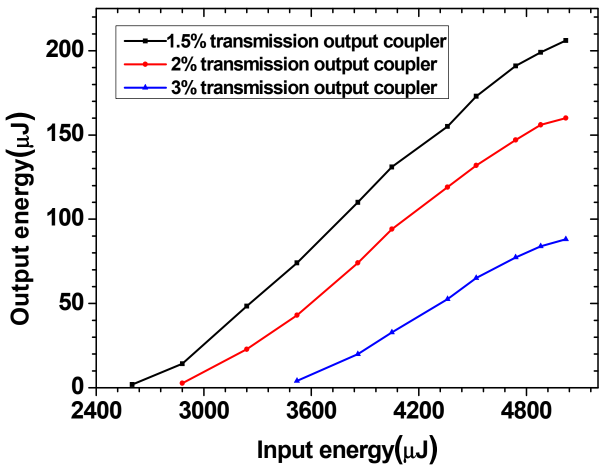

Figure 3. Measurements of the output laser energy with different output couplers in the quasi-continuous-wave (QCW) regime.

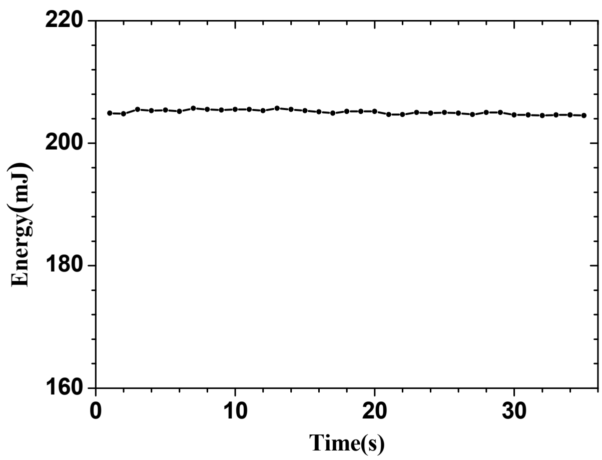

Figure 4. Stability of the laser energy in the QCW regime for the highest peak power (206 μJ). The LEDs are driven at 4 A with a pulse duration of 150 μs.

The spatial distribution and the temporal shape of the laser are shown in Figure 5. An oscilloscope (DPO4104, Tektronix, Beaverton, OR, USA) was used to measure the temporal pulse shape. The measured pulse duration of the output laser was approximately 100 μs, which is shorter than the pump pulse duration. The transverse distribution is multimode. The beam quality of the output laser was measured using a 150-mm focusing lens and a laser beam analyzer (LaserCam-HR II 2/3″, Coherent, Santa Clara, CA, USA). Here, we describe the relationship between the pump radius evolution and the M-square factors (M^2) by a relation of the type [20]:

$$\omega(z) = \omega_0 \sqrt{1 + \left(\frac{M^2 \lambda (z - z_0)}{n \pi \omega_0^2} \right)^2} \quad (1)$$

where ω_0 is the beam waist radius, $\omega(z)$ is the radius at z, n is the index of refraction, λ is the wavelength, and z and z_0 are coordinates of the optical axis direction and coordinate origin. The results show that M^2 is 45 in the horizontal direction and 45 in the vertical direction (see Figure 6).

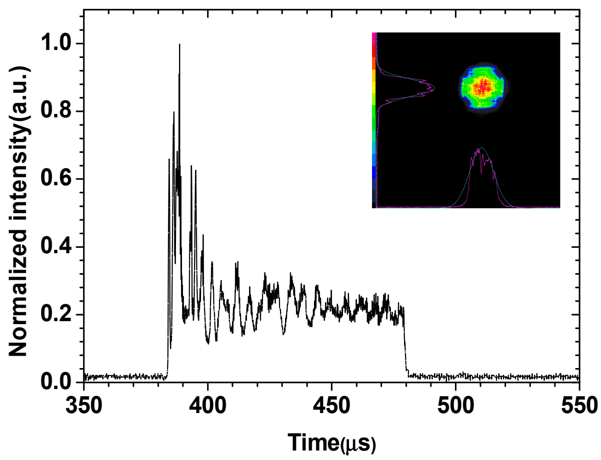

Figure 5. The spatial distribution and the temporal shape of the laser in the QCW regime for the highest output laser energy (206 μJ).

After the QCW regime test, a saturable absorber (Cr:YAG crystal) was inserted into the cavity. Its transmission was 97%. The length of the laser cavity remained at 63 mm. This solution is undoubtedly the lowest cost, and a simple structure. The experimental setup in the PQS regime is shown in Figure 7. The output coupler is a plane mirror and the output coupling transmission is 1.5%. This structure is small in size. The size of the amplifier is 50 mm × 30 mm × 20 mm. The pulse duration of the first pulse was 760 ns with FWHM point of the peak power in Figure 8a (the following pulse durations are all FWHM results). The duration of the first pulse was 440 ns and the second one was 560 ns in Figure 8b. This is because the duration of the pump was too long compared to the lifetime, so the time pulse has highly multimode peaks. These pulse spikes are separated by approximately 10 µs. The sum of the energy is very high, but the peak power of each pulse is low.

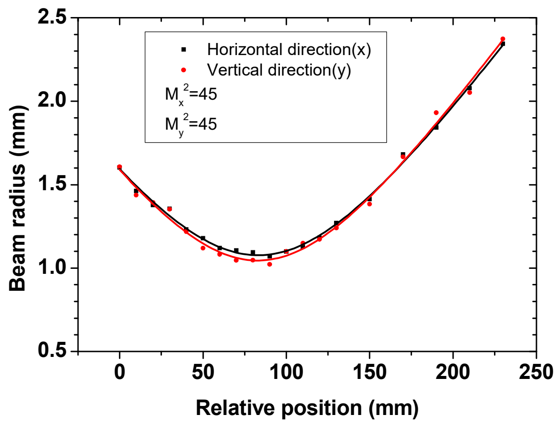

Figure 6. Beam quality at the highest output laser energy of 206 µJ from the linear cavity laser.

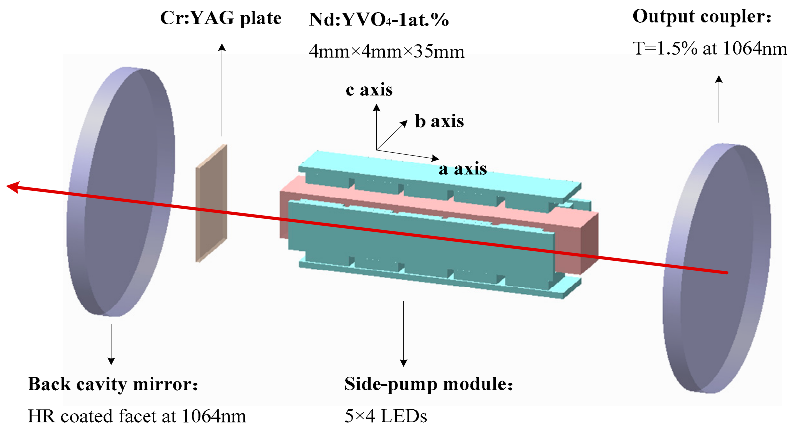

Figure 7. The experimental setup of the LED-pumped Nd:YVO_4 laser in the passive Q-switching (PQS) regime.

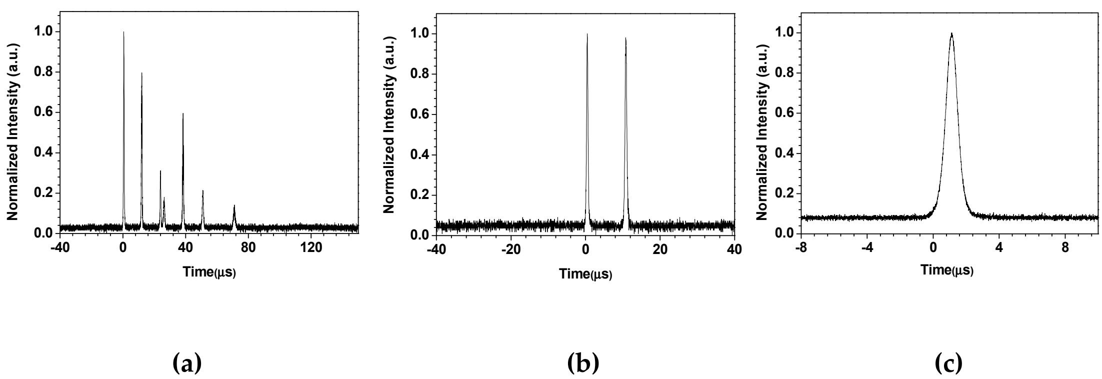

Figure 8. Temporal representation of the modes when LEDs are driven with a pulse duration of (**a**) 300 µs, (**b**) 160 µs, and (**c**) 150 µs.

This phenomenon does not exist when we reduce the pump pulse duration to a suitable value. The output pulse energy of the laser is approximately 2.5 μJ at 1064 nm in the PQS regime after optimization, while the LED is using a 150 μs duration at 1 Hz (the current for the LEDs is 4 A and the incident pump energy is approximately 5.0 mJ). The output energy stability is 97.5% with the Q-switching. It is less stable than the energy stability in the QCW regime because it is not saturated. The TEM_{10} mode is obtained when the output laser is 2.5 μJ. The temporal pulse shape is smooth, as depicted in Figure 8c. The laser pulse duration is approximately 897 ns. This means that the peak power is 2.79 W. When keeping these working parameters and carefully adjusting the cavity, the TEM_{00} mode is obtained. The least squares Gaussian fit coefficients of the cross-section beam profiles are 0.981 and 0.982 in two directions. These coefficients are provided by the software of the laser spot analyzer. At this time, the output laser is less than 2.0 μJ. (see Figure 9).

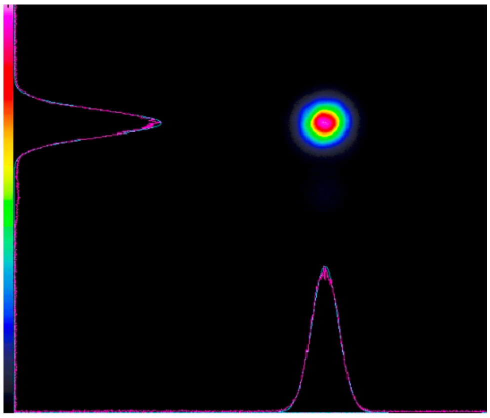

Figure 9. TEM_{00} mode is obtained by careful adjustment of the cavity.

4. Conclusions

The passively Q-switched working mode is demonstrated on an LED-side-pumped $Nd{:}YVO_4$ laser, and a high stability and high beam quality LED-pumped laser is obtained in the PQS regime. With an incident pump energy of 6.28 mJ (150 μs pulses at 1 Hz), the $Nd{:}YVO_4$ laser has an energy of 206 μJ at 1064 nm, with an output coupler transmission of 1.5%. The optical conversion efficiency of the system is 4.1%, and the slope efficiency is 9.0%. A pulsed energy of 2.5 μJ is obtained with a duration of 897 ns in the PQS regime, which means the peak power is 2.79 W. The output energy stability is 97.54% with Q-switching. Finally, this LED-pumped, passively Q-switched $Nd{:}YVO_4$ laser not only combines the advantages of LEDs, but also has a compact structure and is a very stable and reliable light source. One has to mention that it is the first high stability LED-pumped $Nd{:}YVO_4$ laser with Cr:YAG passive Q switching. As we have seen, future work around LED-pumped lasers should focus on increasing the input power density. This point makes the laser output have much narrower pulse widths and sufficient energy. If this problem is solved, LED-pumped laser can be widely used in a series of fields.

Author Contributions: Conceptualization, H.X., T.Z.; methodology, Z.F., W.G.; validation, Q.Z., M.L., J.Y.; formal analysis, S.B., Y.C.

Funding: This research was funded by National Natural Science Foundation of China (NSFC), grant number 61675210, Youth Innovation Promotion Association of CAS, grant number 2014136; China Innovative Talent Promotion Plans for Innovation Team in Priority Fields, grant number 2014RA4051.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Graydon, O.; Jenkins, A.; Won, R.P.C.; Gevaux, D. Haitz's law. *Nat. Photonics* **2007**, *1*, 23.
2. Ernst, H.-J.; Charra, F.; Douillard, L. Interband electronic excitation-assisted atomic-scale restructuring of metal surfaces by nanosecond pulsed laser light. *Science* **1998**, *279*, 679–681. [CrossRef] [PubMed]

3. Majchrowski, A.; Kityk, I.V.; Ebothé, J. Influence of YAB: Cr^{3+} nanocrystallite sizes on two-photon absorption of YAB: Cr^{3+}. *Physica Stat. Sol. (b)* **2004**, *241*, 3047–3055. [CrossRef]
4. Ochs, S.A.; Pankove, J.I. Injection-luminescence pumping of a CaF_2:Dy^{2+} laser. *Proc. IEEE* **1964**, *52*, 713–714. [CrossRef]
5. Reinberg, A.R.; Riseberg, L.A.; Brown, R.M.; Wacker, R.; Holton, W.C. GaAs:Si LED Pumped Yb-Doped YAG Laser. *Appl. Phys. Lett.* **1971**, *19*, 11–13. [CrossRef]
6. Farmer, G.I.; Kiang, Y.C. Low-current-density LED-pumped Nd:YAG laser using a solid cylindrical reflector. *J. Appl. Phys.* **1974**, *45*, 1356–1371. [CrossRef]
7. Stone, J.; Burrus, C.A. Self-contained LED-pumped single-crystal Nd:YAG fiber laser. *Fiber Integr. Opt.* **1979**, *2*, 19–46. [CrossRef]
8. Bilak, V.I.; Goldobin, I.S.; Georgii; Zverev, M.; Kuratev, I.I.; Pashkov, V.A.; Stel'makh, M.F.; Tsvetkov, Y.V.; Solov'eva, N.M. Neodymium YAG lasers pumped by light-emitting diodes. *Sov. J. Quantum Electron.* **1981**, *11*, 1471. [CrossRef]
9. Allen, R.B.; Scalise, S.J. Continuous operation of a Nd:YAG laser by injection luminescent pumping. *Appl. Phys. Lett.* **1969**, *14*, 188–190. [CrossRef]
10. Huang, K.; Su, C.; Lin, M.; Chiu, Y.; Huang, Y. 750-nm LED-pumped Nd: YAG laser with 9% optical efficiency. In Proceedings of the Conference on Lasers and Electro-Optics, San Jose, CA, USA, 5–10 June 2016; Optical Society of America: Washington, DC, USA, 2016.
11. Herrnsdorf, J.; Wang, Y.; McKendry, J.J.D.; Gong, Z.; Massoubre, D.; Guilhabert, B.; Tsiminis, G.; Turnbull, G.; Samuel, I.D.W.; Laurand, N.; et al. Micro-LED pumped polymer laser: A discussion of future pump sources for organic lasers. *Laser Photonics Rev.* **2013**, *7*, 1065–1078. [CrossRef]
12. Pichon, P.; Barbet, A.; Blanchot, J.; Druon, F.; Balembois, F.; Georges, P. Light-emitting diodes: A new paradigm for Ti:sapphire pumping. *Optica* **2018**, *5*, 1236–1239. [CrossRef]
13. Tucker, A.W.; Birnbaum, M.; Fincher, C.L.; Erler, J.W. Stimulated-emission cross section at 1064 and 1342 nm in Nd: YVO_4. *J. Appl. Phys.* **1977**, *48*, 4907–4911. [CrossRef]
14. Lin, D.; Clarkson, W. End-pumped Nd:YVO_4 laser with reduced thermal lensing via the use of a ring-shaped pump beam. *Opt. Lett.* **2017**, *42*, 2910–2913. [CrossRef] [PubMed]
15. Chen, Y.; Huang, T.M.; Wang, C.L. Passively Q-switched diode-pumped Nd:YVO_4/Cr^{4+}: YAG single-frequency microchip laser. *Electron. Lett.* **1997**, *33*, 1880–1881. [CrossRef]
16. Barbet, A.; Balembois, F.; Paul, A.; Blanchot, J.; Viotti, A.; Sabater, J.; Druon, F.; Georges, P. Revisiting of LED pumped bulk laser: First demonstration of Nd:YVO_4 LED pumped laser. *Opt. Lett.* **2014**, *39*, 6731–6734. [CrossRef] [PubMed]
17. Barbet, A.; Paul, A.; Gallinelli, T.; Balembois, F.; Blanchot, J.; Forget, S.; Chénais, S.; Druon, F.; Georges, P. Light-emitting diode pumped luminescent concentrators: A new opportunity for low-cost solid-state lasers. *Optica* **2016**, *3*, 465–468. [CrossRef]
18. Barbet, A.; Paul, A.; Gallinelli, T.; Balembois, F.; Blanchot, J.; Forget, S.; Chénais, S.; Druon, F.; Georges, P. New scheme for pumping solid-state lasers based on LED-pumped luminescent concentrators. In Proceedings of the Lasers Congress 2016 (ASSL, LSC, LAC), Boston, MA, USA, 30 October 2016; Optical Society of America: Washington, DC, USA, 2016.
19. Cho, C.Y.; Pu, C.C.; Su, K.W.; Chen, Y.F. LED-side-pumped Nd: YAG laser with >20% optical efficiency and the demonstration of an efficient passively Q-switched LED-pumped solid-state laser. *Opt. Lett.* **2017**, *42*, 2394–2397. [CrossRef] [PubMed]
20. Chenais, S.; Balembois, F.; Druon, F.; Lucas-Leclin, G.; Georges, P. Thermal lensing in diode-pumped ytterbium Lasers-Part I: Theoretical analysis and wavefront measurements. *IEEE J. Quantum Electron.* **2004**, *40*, 1217–1234. [CrossRef]