A comprehensive study of impulse pumping of Ti:Sapphire by AlInGaN LEDs

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Abstract. LEDs operating under high pulsed current density, which excludes self-heating, are of great interest for different applications, in particular, for pumping lasers with a short time of activator relaxation, such as Ti:Sapphire. The current dependences of the efficiency emission spectra as well as the rise and fall times of high-power blue and green LEDs were investigated under extremely high pulse current density up to 7 kA/cm² and a pulse duration of 100 ns to 3 μs. An analysis of the pulse behaviour of the LEDs reveals that the main droop in efficiency and a change in the spectrum occur up to the current densities ~ 1 kA/cm² and seem to be non-thermal. The energy and spectral pulse characteristics of the radiation were studied with simultaneous recording the excited Ti:Sapphire photoluminescence in order to determine the optimal pumping conditions.

1. Introduction

The scope of application of light-emitting diodes (LEDs) of different colors keeps expanding. The study of the operation of LEDs in pulsed mode to exclude self-heating at high excitation levels is of great interest for establishing the injection and recombination mechanisms and identifying the reasons that limit the energy capabilities of devices [1,2]. From a practical point of view, these modes are interesting for pumping lasers [3-7] with a short time of activator relaxation, such as Ti:Sapphire [8-10].

Previous studies of commercially available LEDs of three different designs (flip-chip, vertical, face-up) have shown that, despite the significant difference in the design, similar dependences of the optical power and radiation spectrum under high current are observed [11]. The main changes in the efficiency droop, short-wavelength shift of the peak wavelength, and spectrum broadening take place in the current density range < 1 kA/cm². Their origin is related to electronic processes rather than thermal ones.

In this work, we studied blue and green commercial LEDs of «vertical» design [12]. The energy and spectral pulse characteristics of radiation were studied with simultaneous recording the excited photoluminescence of Ti:Sapphire (Ti³⁺:Al₂O₃) in order to determine the optimal pumping regimes [8,9,13].
2. Experimental
The research was carried out on commercial LEDs of blue and green spectral range ($\lambda_{\text{peak}} = 460$ and 530 nm) produced by SemiLEDs [12]. The LED chips had a «vertical» design with a total thickness of 145 μm, representing a heterostructure of about 5 μm, disposed on a conducting Cu substrate, with an active area of 1 mm$^2$. The Ti:Sapphire active element was a rectangular rod with an absorption length of 6 mm [14].

The optical parameters of the devices under test were measured in pulsed regime. To ensure the predetermined pulse regime, an Agilent 8114A pulse generator was used with a PicoLAS LDP-V 80-100 V3.3 external amplifier. The pulse width and duty cycle were monitored with a Tektronix TDS3044B oscilloscope. To measure the light pulse, a Si-based THORLABS DET02AFC/M photo detector was used. Spectral characteristics were recorded with an OL 770-LED High-speed LED Test and Measurement System [15]. The duty cycle was chosen to avoid self-heating at $f = 50$ Hz. The pulse duration was varied in the range 100 – 3000 ns, which corresponds to the operating conditions of a pulsed laser.

3. Results and discussion
Blue and green LEDs are known to have different values of the maximum external quantum efficiency (EQE) [16]. Blue LEDs are more efficient than green ones. The study of the EQE dependence on current (figure 1) shows a sharp drop in the EQE with an increase in current densities up to 1 kA/cm$^2$. Thus, the efficiencies of green and blue LEDS become comparable at current densities > 1 kA/cm$^2$ (see figure 1).

![Figure 1. The dependences of EQE on current density in blue (1) and green (2) LEDs](image)

As can be seen in figure 2, the absorption spectrum of Ti:Sapphire has a maximum at 490 nm.

To a first approximation, without taking into account the short-wavelength shift, the spectrum of blue LEDs is most suitable for pumping Ti:Sapphire lasers. However, at high current densities, the efficiency of LEDs with a wavelength of 460 nm drops sharply, and the spectrum shifts to shorter wavelengths up to 440 nm when the current reaches 10 A (1 kA/cm$^2$), which reduces the absorption coefficient of Ti:Sapphire. External temperature heating of the p-n junction (figure 2) helps to partially compensate for half of this shift, which is insufficient to get into the zone of maximum absorption of Ti:Sapphire. This leads to the conclusion that the use of blue LEDs is not very suitable for pumping.
Figure 2. The experimental curves of: absorption spectrum of Ti:Sapphire (1); emission spectrum of green LEDs at $J = 1$ kA/cm$^2$ (2); emission spectrum of blue LED at $J = 1$ kA/cm$^2$ $T_{\text{junction}} = 25^\circ$ C (2) emission and spectrum of blue LEDs at $J = 1$ kA/cm$^2$, $T_{\text{junction}} = 125^\circ$ C (3)

Green LEDs are usually not considered for these applications due to their inherently low efficiency. However, we decided to carry out similar tests for green LEDs, since the EQE of blue LEDs at high current density drops to a few percent. Taking into consideration the fact that the short-wavelength shift is also observed in green LEDs, we can conclude that at an initial wavelength of 520 nm, these conditions are favorable to enhance the absorption efficiency of Ti:Sapphire.

Figure 1 shows that the EQE values of blue LEDs at high currents ($I = 10$ A) exceed the EQE of green LEDs twofold. In this case, it is interesting to study in detail the spectral characteristics of green LEDs with regard to pumping. The study of green LEDs shows that the peak wavelength shifts from 530 nm to 520 nm at $\sim 10$ A. Therefore, the short wavelength shift plays a positive role in the overlap of LED emission spectrum and the absorption spectrum of Ti:Sapphire.

A study concerning Ti:Sapphire pumping by green LEDs at high currents was also carried out. The spectra of green LEDs and the luminescence of Ti:Sapphire are shown in figure 3.

Figure 3. Experimental curves of luminescence spectrum of Ti:Sapphire under pumping by blue LEDs (3) and green LEDs (4). Normalized spectrum of blue LEDs (1) and green LEDs (2)

The light pulse energy was calculated from the experimental data on the optical power characteristics of LEDs [17]. The pulse duration was chosen $\sim 3 \mu$s, which corresponds to the lifetime
of the Ti:Sapphire excited state. The absorbed energy was calculated from the spectral overlap of Ti:Sapphire and LEDs. The results are presented in table 1.

|       | Falling energy at \( I = 10 \text{ A} \) | Absorbed energy at \( I = 10 \text{ A} \) |
|-------|----------------------------------------|----------------------------------------|
| Blue  | 12 \( \mu \text{J} \)                  | 9.5 \( \mu \text{J} \)                 |
| Green | 6.15 \( \mu \text{J} \)                | 5.8 \( \mu \text{J} \)                 |

Various sources show that the energy necessary to generate laser radiation in Ti:Sapphire is about 1 mJ [9], which means that laser pumping requires a system containing several hundreds of LEDs.

4. Conclusion

The study shows that the efficiency of LED pumping of Ti:Sapphire depends on the combination of optical power, emission spectra, time and thermal operation modes of LEDs. In this regard, the search for the optimal mode was carried out by testing the combinations of these parameters. It has been shown that the currents through LEDs should not exceed 10 A to maintain efficiency and to provide light energy for pumping. This, in turn, makes it possible to use a pulse duration of 3 \( \mu \text{s} \). The short wavelength shift in green LEDs at high currents improves the absorption for better spectral overlaps.

Reaching the threshold pump in Ti-sapphire lasers at current energy levels in blue and green AlGaInN LEDs remains a difficult task that requires further research.

The possibilities to enhance the efficiency of blue LEDs seem exhausted. At the same time, there is undeniable progress in the technology of green LEDs [18]. Moreover, green LEDs prove to exhibit better spectral overlaps. Considering this, the study of green LEDs for the pumping system seems to be promising.

According to [9], we can conclude that at the current level of efficiency of AlInGaN LEDs, the pumping system should contain at least several hundreds of LEDs, whose emission should be concentrated in the active material.

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References

[1] Yadaev A, Titkov I, Socolovskii G, Karpov S, Dudelev V, Soboleva K, Pietzonka I, Lugauer H-J and Rafailov E 2016 LEDs: Materials, Devices, and Applications for Solid State Lighting XX 9768 doi:10.1117/12.2213344
[2] Karpov S, Galler B, Strabburg M and Rafailov E 2014 IEEE J. Quantum Electron 50 11 911
[3] Beyatli E, Baali I, Sumpf B, Erbert G, Leitenstorfer A, Sennaroglu A and Demirbas U (2013) J. Opt. Society America B 30 3184
[4] Demirbas U, Eggert S and Leitenstorfer A 2012 J. Opt. Society America B 29 1894
[5] Roth P W, Maclean A J, Burns D and Kemp A J 2011 Optics Lett. 36 304
[6] Wang S-C, Hsu C-Y, Yang T-T, Jheng D-Y, Yang T-I, Ho T-S and Huang S-L 2016 Optics Lett. 41 3217
[7] Castro-Marin P, Mitchell T, Sun J and Reid D T 2019 Optics Lett. 44 5270
[8] Pichon P, Barbet A, Blanchot J-P, Druon F, Balembois F and Georges P 2018 Optica 5 1236
[9] Moulton P F 1986 J. Opt. Society of America B 3 125
[10] Grivas C, Corbari C, Brambilla G and Lagoudakis P G 2012 Optics Lett. 37 4630
[11] Aladov A, Chernyakov A, Ivanov A and Zakgeim A 2020 High-power AlGaInN LEDs operated under high pulsed current density (up to 7 kA/cm2) 19th Int. Conf. Laser Optics Preprint
[12] LED datasheets blue https://www.semileds.com/system/files/EV-B45A.pdf and green https://www.semileds.com/system/files/EV-G45A
[13] Stelian C, Alombert-Goget G, Sen G, Barthalay N, Lebbou K and Duffar T 2017 Optical Materials 69 73
[14] Ti-doped Sapphire crystal (https://www.laser-crylink.com/wp-content/uploads/2019/07/Ti-Sapphire-laser-crystal-datasheet-Laser-crylink.pdf)
[15] Zakgeim A and Chernyakov A 2013 Light & Engineering 21 64
[16] Shubert E F 2018 Light Emitting Diodes (Cambridge University Press, Cambridge, 3rd Edition) 672
[17] Wayne R P 1988 Principles and Applications of Photochemistry (Oxford University Press, Oxford) 304
[18] Lundin W V, Nikolaev A E, Sakharov A V, Zavarin E E, Valkovskiy G A, Yagovkina M A, Usov S O, Kryzhanovskaya N V, Sizov V S, Brunkov P N, Zakgeim A L, Cherniakov A E, Cherkashin N A, Hytch M J, Yakovlev E V, Bazarvskiy D S, Rozhavskaya M M and Tsatsulnikov A V 2011 J. Crystal Growth 315 267