Simulation of physical processes in light-emitting diode pumped lasers

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Разработана «end-to-end» симуляционная модель твердотельного лазера со светодиодной накачкой с использованием метода трассировки фотонов Монте-Карло. Модель учитывает полную специфику и спектральные характеристики светодиодов. Насколько нам известно, эта модель является первой в своем роде, позволяющая проводить комплексный анализ лазерных систем со светодиодной накачкой. Модель выявила несколько важных моментов, которые необходимо учитывать при практической реализации лазеров со светодиодной накачкой.

Ключевые слова: светодиод, лазеры со светодиодной накачкой, Ce:Nd:YAG.

We have developed an end-to-end simulation model for the light-emitting diode-pumped solid-state laser using the Monte Carlo photon tracing technique. The model considers complete specifics and spectral characteristics of light-emitting diodes. This model is the first of its kind to enable comprehensive analysis of light-emitting diode-pumped laser systems to the best of our knowledge. The model revealed several critical implications, which can be considered in the practical realization of light-emitting diode-pumped lasers.

Keywords: light-emitting diode, LED pumped lasers, Ce:Nd:YAG.

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I. Introduction

The development of energy-efficient and cheap lasers with pre-defined output characteristics is one of the most critical problems in laser physics. In this vein, light-emitting diode (LED) pumped solid-state lasers have attracted increasing attention [1]. The availability of increasingly powerful and efficient LEDs has contributed to this renewed interest. Indeed, in recent years, LEDs have become more powerful. Their price drops due to mass production, which, in turn, indicates the possibility of obtaining inexpensive solid-state lasers in the foreseeable future.

In solid-state lasers, the spectral characteristic of LEDs is an exciting choice since their spectral width is broader than that of laser diodes, which makes it possible to target several absorption peaks of the active medium simultaneously. However, compared to other broadband pumping sources, such as solar [2, 3] or lamp pumping, the LED spectrum is narrower, making it easier to combat adverse thermal effects. Here, a natural question arises: why LEDs have not found wide application in commercial lasers, even though the first experimental implementation of LED-pumped laser was carried out several decades ago in 1964 [4]? The review of the literature on the topic could not provide a definitive answer to this question. While the underlying reason is unclear, we can speculate that an inconvenient emission pattern from LEDs, the difficulty in integrating LEDs into laser resonators and the instability of LED output power might have contributed to an early stagnation of

LED pumped lasers. After several decades, LEDs have experienced unprecedented perfection in all aspects, nonetheless, these problems persist. At this point, there are encouraging advances: significant progress has been made in miniaturizing LEDs; electronic technologies have reached a certain level of maturity; the development of mathematical (simulation) models becomes less complex and widely available, which considerably saves time and cost in the early stages of the emergence of new LED pumped laser technologies. The latter point is the subject of this article.

Recently published experimental studies [5-13] on LED pumped lasers give evidence of the reality that the development of LED-pumped lasers is at an early stage in terms of efficiency and stability. In this regard, it became necessary to create accurate models of LED-pumped lasers. As far as we know, such end-to-end models are not found in the literature. Therefore, we studied the possibility of developing complex and accurate models of LED-pumped lasers.

Before proceeding further, we would like to emphasize one feature of the model. Currently, LEDs as a pump source can be divided into two groups: direct and indirect. In direct pumping, optical fields emitted from LEDs are concentrated to an active medium using some form of pumping chamber [5-9].

In the case of an indirect pumping scheme, the emission spectrum of the LED is frequency shifted to achieve a more suitable spectrum shape for targeting the absorption peaks of the active medium [1, 10-13]. Frequency shifting can be done using an intermediate medium, which in the literature is called luminescent concentrators [14]. The former, direct pumping, is studied in this paper.

II. Modeling method and LEDs

The simulation model is built by the Monte-Carlo photon tracing method, which was successfully used in our early studies [2, 3, 15], mainly for solar pumping lasers. It can be argued that this method best suits the development of the simulation model because of its flexibility to take into account the specifics of LED-pumped lasers, such as the randomness of photon emission (direction and wavelength initiated from the LED spectrum) and the structural complexity of the pump chamber.

Complete knowledge of the pumping source is an essential part of modeling in LED-based systems since the radiation pattern of LEDs varies depending on their design. Traditionally there are several emitting *p-n* junctions located between two substances. Physical properties of involved materials in LED manufacturing tailor the emission pattern. Therefore, it was crucial that the model had to start with the emission process. In Figure 1, the radiation pattern of one *p-n* junction is represented.

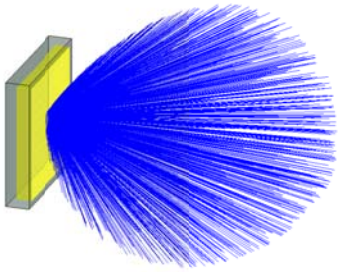


Figure 1. Emission pattern.

In this particular example, the pattern is a spherical Lambertian shape. Based on a pre-given emission pattern, the model can determine the direction or trajectory of the emitted photons. The reason for accurately determining the direction of the emitted photon is that it directly affects the model's accuracy. Another vital factor is the divergence of LED radiation, which is demonstrated in Figure 2. It can be seen how fast it spreads, even within a few millimeters. This non-directionality property of LED radiation plays a role in the design of pumping cavities.

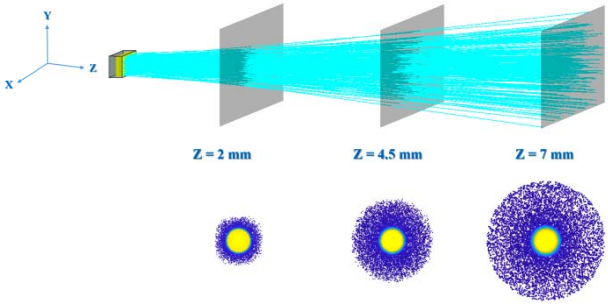


Figure 2. Divergence of LED radiation.

III. Model

One of the recent experimental studies was chosen as a reference for the development of the model [5]. A general view of the laser system for which the simulation model was used is shown in Fig. 3, where sample photon trajectories (blue lines) and their absorption coordinates (dots) in the active medium. The laser system consists of a cylindrical pumping chamber 25 mm in diameter with a 22×22 mm^2 square hole

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on each side for accommodating two LED arrays consisting of 10×10 elements on aluminum-coated ceramics. Blue LED and Ce: Nd:YAG were chosen as the active medium due to the broad spectral overlap of their emission and absorption spectra, respectively.

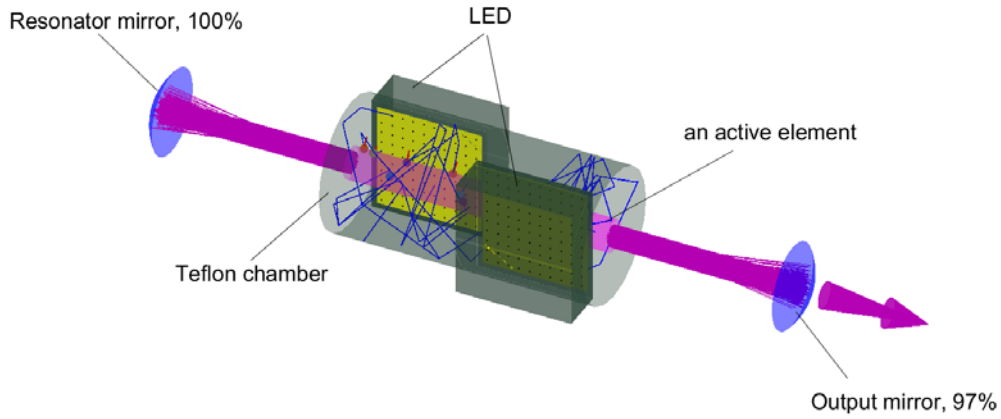


Figure 3. General view of the laser system.

Notably, the blue LED and Ce:Nd:YAG peaks coincide around 460 nm, as shown in Fig. 4. Parameters were introduced for a diffusely reflecting pump chamber made of teflon due to its broadband reflection properties. The laser rod, 6 mm in diameter and 5 cm in length, is located in the center of the cylindrical chamber by two sliding end caps, they are also made of teflon.

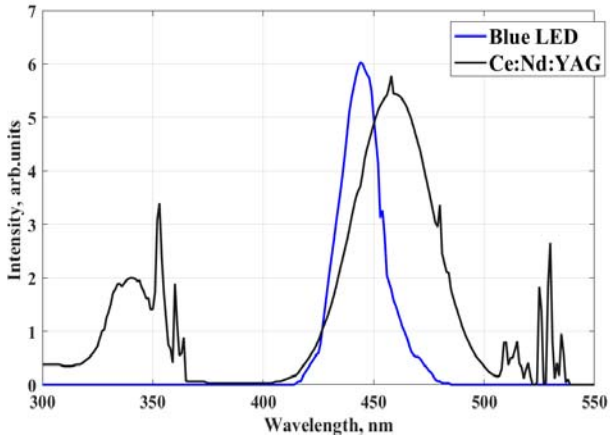


Figure 4. The emission spectrum of Blue LED and absorption spectrum of Ce:Nd:YAG.

IV. Results and discussions

We obtained the pumping (absorption) distribution within the active medium (Fig. 5), which dramatically impacts the quality of the output beam. In addition, pumping distributions can further be used to determine the temperature distribution.-

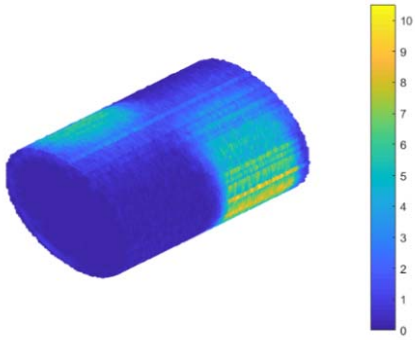


Figure 5. Pumping distribution of photons within the active medium.

The obtained distributions provide several implications for the design of LED lasers. First, using the temperature distribution, desired requirements for the cooling configuration can be predicted. Second, the efficiency and functionality of the pumping chamber can be assessed. For example, an examination of Fig. 5 in the radial direction reveals that the diffusive chamber walls, used in [5], on pumping distribution and hence efficiency is not as high as expected, meaning the need for further optimization of the cavity. The absorption of photons directly from the LED dominates over the absorption of photons after reflection from the chamber walls. However, only a tiny

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percentage of emitted photons less than 40% (calculated using the divergence of the LED radiation (Fig. 2)) can directly fall into the active medium. Examining the figure in the axial direction shows that pumping distribution seems to be uniform, as expected by placing two LEDs on opposite sides of the active medium and symmetrically shifting.

To calculate the LED laser output from our model, we set the electrical-to-optical conversion efficiency of each LED at a constant value of 15%. In this case, the optical-to-optical pumping efficiency determined from the simulation model, energy transfer from LED light to the active medium, was 14%. As a final step of the end-to-end model, LED pumped laser output power was calculated [3], taking into account resonator parameters (such as an output coupler, 97%, geometrical size, and optical properties of the active medium) and pumping efficiency.

Figure 6 shows a representative quasi-continuous wave (QCW) output pulse profile derived from the rate equations [16] with a pump power of 350 W. When operating in the QCW regime, the laser output exhibited strong relaxation oscillations with a frequency proportional to the pump power.

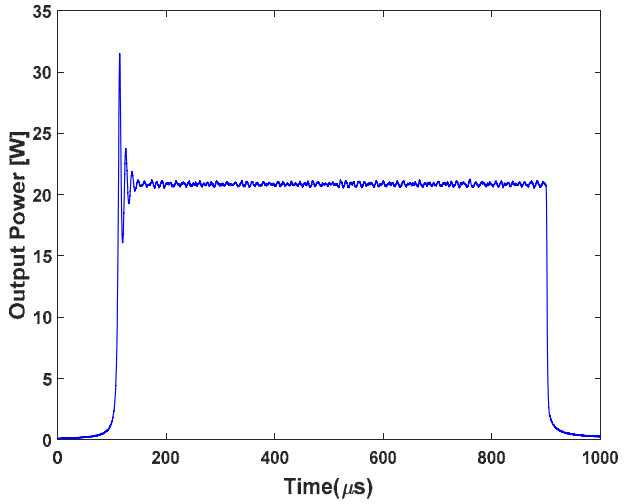


Figure 6. QCW lasing output profile.

The calculated input-output relationship of the LED-pumped laser system is plotted in Fig. 7, showing 4.8% efficiency. The correspondence in the output characteristics shown by both Fig. 6 and Fig. 7 indicates that the developed simulation model is consistent and stable.

It should be noted that electrical-to-optical conversion (energy from power grid to LED light power) is not present in the Fig. 7. If the electrical to optical efficiency of LED is considered, the overall conversion efficiency further decreases.

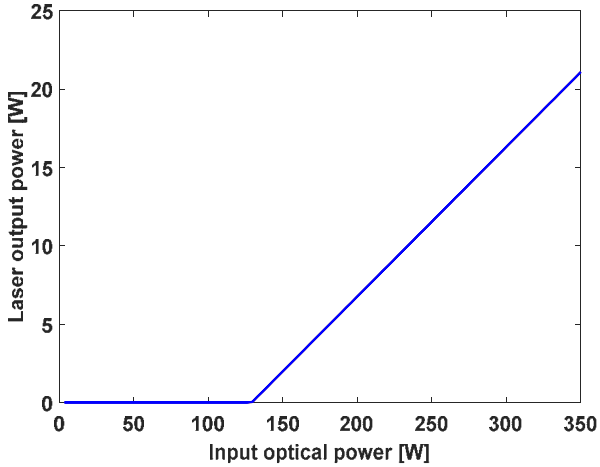


Figure 7. Input-output power relationship.

V. Conclusions

The developed model makes it possible to evaluate a broad class of LED-pumped laser systems. The model is powerful enough to provide detailed information about the operation of every detail of the system. The developed simulation model revealed several critical implications, which can be very useful in designing LED pumped lasers. We are convinced that validated and easily accessible simulation models of LED lasers can be an outstanding contribution to the field development. For this reason, full validation of the developed model with experimental data and its optimization is the topic of our future studies.

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Ёруғлик диод орқали оптик дамланган лазерлардаги физик жараёнлар симуляцияси

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Монте-Карло фотон трассировка методи ёрдамида ёруғлик диоди орқали оптик дамланган қаттиқ жисм лазерининг “end-to-end” симуляция модели яратилди. Моделда ёруғлик диодларининг тўлиқ спецификаси ва спектрал хусусиятларини ҳисобга олинган. Биздаги маълумотларга кўра, бу ёруғлик диоди оркали оптик дамланган лазер тизимларини ҳар томонлама таҳлил қилиш имконини берадиган биринчи модел. Моделлаштириш орқали ёруғлик диоди орқали оптик дамланган лазерларни амалиётда қўллашда ҳисобга олиниши керак бўлган бир нечта муҳим жиҳатлар аниқланди.

Калит сўзлар: ёруғлик диоди, ёруғлик диоди орқали оптик дамланган лазерлар, Ce:Nd:YAG.

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