

## PAPER

# Remote Control of Adaptive Alignment System Based on Analysis of the Spatial Characteristics of Solid-State Laser Radiation

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## ABSTRACT

The algorithm and equipment for automatic alignment of a solid-state laser resonator based on the analysis of the spatial characteristics of laser radiation are considered. The use of a remote-control system that allows precise alignment of optical components without the necessity for direct operator intervention is introduced and justified. The results of tests of a research laser bench equipped with a remote-control system are presented. The possibility of applying this technology in the educational process is analyzed, which allows for a significant improvement in the quality of education by demonstrating modern methods of automation and increasing the precision of laser system alignment.

## KEYWORDS

laser beam, beam quality, remote control, resonator, alignment of resonator, field distribution, output mirror, quality factor

## 1 ALIGNMENT QUALITY CRITERIA AND THEIR IMPACT ON LASER RADIATION

The concept of remote control of the resonator output mirror alignment is relevant and significant in view of the increasing demands for precision and efficiency of optical and laser systems. The configuration of the resonator plays a key role in the formation and amplification of laser radiation, and any imprecision in its alignment can significantly affect the quality and stability of the output signal.

Traditional alignment methods often require direct operator intervention, which is associated with the risk of human error, time consumption, and inconvenience, especially in conditions where access to optical equipment is limited or dangerous. With the development of automation and remote-control technologies, it has become possible to significantly improve the precision and convenience of alignment processes.

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The development of a remote control system for adjusting the output mirror of a resonator is aimed at solving several key tasks: ensuring high accuracy of alignment, increasing time efficiency, minimizing the influence of the human factor and increasing the overall reliability of the system [5]. These factors are particularly important in applications that require constant monitoring and correction of parameters, such as scientific research, industrial production, and medical technology.

The quality of alignment of a plane-parallel resonator in a solid-state pulse laser has a fundamental effect on the energy, spatial, and spectral characteristics of the radiation. Maximum Q-factor can only be achieved with strict parallelism of the mirrors. The influence of alignment quality on energy characteristics is discussed in [1, 2].

Analysis of the results of the study of the distribution of radiation intensity across the laser beam cross-sections made it possible to determine the criteria for the quality of alignment. When the resonator is misaligned, mode losses increase sharply, which leads to an increase in the generation threshold and a decrease in radiation energy. The physical reason for such a sharp increase in losses is obvious: with each pass through the resonator, the beam deviates from its initial direction by an angle of  $2\alpha$  ( $\alpha$  is the misalignment angle of the output mirror) and leaves the resonator very quickly. The number of passes of radiation through the resonator becomes dependent on the length of the resonator and the diameter of the intra-resonator diaphragm (see Figures 1, 2).

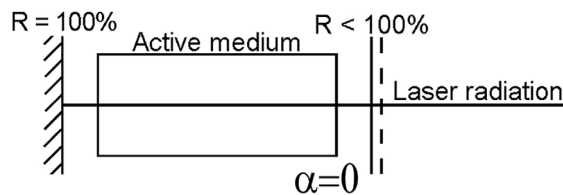


Fig. 1. No misalignment of the output mirror

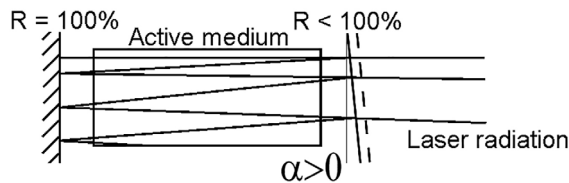


Fig. 2. Misalignment of the output mirror at angle  $\alpha$

At misalignment angles  $\alpha > \lambda/d$  ( $\lambda$  – radiation wavelength,  $d$  – diameter of the intra-resonator diaphragm), the field distribution in both the near field (on the resonator mirrors) and the far field becomes highly uneven. When misaligned, the energy center of the radiation pattern deviates from the normal to the surface of the output mirror. The presence of light scattering on any surfaces in the resonator (Fresnel reflections on the ends, light scattering on the side surface of the active element, etc.) can significantly distort the processes described above in a laser with a planar misaligned resonator.

## 2 SELECTING THE RESONATOR OUTPUT MIRROR ALIGNMENT PARAMETER

One of the metrics of alignment quality is the distribution of the field across the resonator cross-section. In order to achieve high-quality alignment, it is necessary to

analyze the field distribution. In other words, it can be used as a parameter for the alignment system feedback. If it is provided to change the angular position of the mirror in two coordinates using a computer-controlled system, then by analyzing the image obtained with a laser beam profilometer, a decision about the angular displacement of the mirror in one or two coordinates to a certain position can be made. By changing this position and analyzing the laser beam profile, it is possible to decide whether the alignment is being carried out in the correct direction or not. Depending on this decision, it is necessary to continue rotating the mirror in the selected direction or, conversely, change the direction of rotation. After passing through the maximum, the system must analyze how high-quality, symmetrical, and close to a Gaussian distribution the beam was when passing through certain points. If the quality of the field distribution worsened, it must be decided that the maximum (extremum) has been passed. This procedure must be carried out for two coordinates.

Therefore, we need a parameter to evaluate the quality of the field distribution in the beam cross-section. The  $M^2$  parameter is ideal for this task. The  $M^2$  parameter is a parameter for quantifying the quality of a laser beam, a commonly accepted value for determining the optical quality of a laser beam. According to ISO Standard 11146, it is defined as the following ratio:

$$M^2 = \frac{BPP}{\lambda/\pi} \quad (1)$$

where BPP is a beam parameter product;  
 $\lambda$  is a minimum radius of the real beam.

The ratio  $\lambda/\pi$  is the BPP for a diffraction-limited Gaussian beam of the same wavelength.

$$BPP = \omega \cdot \theta, \quad (2)$$

where  $\theta$  – measure of the divergence of laser radiation in the far field;  
 $\omega$  – beam radius in beam tightening.

A Gaussian beam has a parameter  $M^2 = 1$ , while real radiation has a parameter greater than  $M^2 > 1$ . For a given beam radius, a Gaussian beam has the smallest possible beam divergence. The reverse is also true: for a given beam divergence, a Gaussian beam has the smallest possible beam radius.

A multimode beam has a beam tightening that is  $M^2$  times more than that of a fundamental Gaussian beam with the same beam divergence, or a beam divergence that is  $M^2$  times more than that of a fundamental Gaussian beam with the same beam tightening.

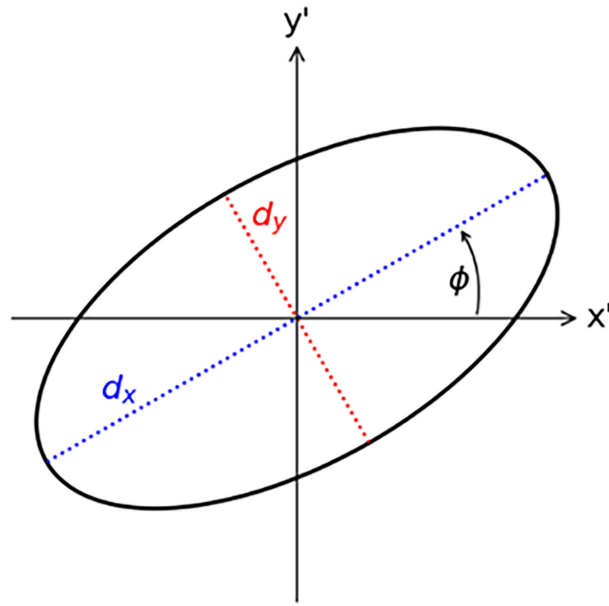
The basic idea of the measurement is to use a CCD matrix to record the change in the beam profile and determine the  $M^2$  parameter. Performing this action accurately is not an easy task, since the beam diameter must always match the camera matrix. In this case, a lens is used to simulate the field distribution in the far zone.

The International Organization for Standardization (ISO) provides the following instructions for measuring the  $M^2$  parameter in document 11146-1: if beam tightening is available for direct measurement, then the position of beam tightening, beam width, divergence angles, and beam propagation coefficients should be determined by hyperbolic approximation to various beam width measurements along the propagation axis. Therefore, measurements should be taken at no less than 10 different positions. Approximately half of the measurements should be distributed within one Rayleigh length on either side of the beam tightening, and approximately half of them should be distributed beyond two Rayleigh lengths from the beam tightening.

For simple astigmatic beams, this procedure should be applied separately for both principal directions.

A laser beam usually consists of a superposition of several modes. The radius of a single-mode beam is determined by the  $1/e^2$  level of the maximum value, but this is only true for a Gaussian beam. The ISO 11146 standard offers a simple and straightforward way to describe beam width.

The overall view of the laser beam in cross section is shown in Figure 3.



**Fig. 3.** Cross-section of the laser beam

In this case, the total power  $P$  is calculated by integrating the illuminance  $E$  across the whole beam:

$$P = \iint_{-\infty}^{\infty} E(x, y) dx dy, \quad (3)$$

where  $P$  is the total power;  $E$  is the illuminance value.

Then the center of the beam can be found according to the following formulas:

$$x_c = \frac{1}{P} \iint_{-\infty}^{\infty} x \cdot E(x, y) dx dy, \quad (4)$$

$$y_c = \frac{1}{P} \iint_{-\infty}^{\infty} y \cdot E(x, y) dx dy, \quad (5)$$

where  $x_c$  is the coordinate of the laser beam center on the  $x$ -axis;  $y_c$  is the coordinate of the laser beam center on the  $y$ -axis.

Useful parameters characterizing the overall two-dimensional distribution  $E(x, y)$  are the dispersion in the  $x$  and  $y$  directions of the axes:

$$\sigma_x^2 = \frac{1}{P} \iint_{-\infty}^{\infty} (x - x_c)^2 \cdot E(x, y) dx dy, \quad (6)$$

$$\sigma_y^2 = \frac{1}{P} \iint_{-\infty}^{\infty} (y - y_c)^2 \cdot E(x, y) dx dy, \quad (7)$$

$$\sigma_{xy}^2 = \frac{1}{P} \iint_{-\infty}^{\infty} (x - x_c)(y - y_c) \cdot E(x, y) dx dy, \quad (8)$$

In general,  $\sigma_x \neq \sigma_y$ .

Then we can determine the major and minor axes of the laser beam according to the following formulas:

$$d_x = \sqrt{8(\sigma_x^2 + \sigma_y^2) + 8\text{sign}(\sigma_x^2 - \sigma_y^2)\sqrt{(\sigma_x^2 - \sigma_y^2)^2 + 4\sigma_{xy}^4}}, \quad (9)$$

$$d_y = \sqrt{8(\sigma_x^2 + \sigma_y^2) - 8\text{sign}(\sigma_x^2 - \sigma_y^2)\sqrt{(\sigma_x^2 - \sigma_y^2)^2 + 4\sigma_{xy}^4}}, \quad (10)$$

Since all parts of the laser stand are in a static position, and because one of the criteria for alignment was to obtain results as quickly as possible without unnecessary changes to the system, it was decided to use the following parameter as a measure of the quality of alignment:

$$S = d_x \cdot d_y, \quad (11)$$

where  $d_x$  is the semi-axis of the laser beam along the x-axis;  $d_y$  is the semi-axis of the laser beam along the y-axis;  $S$  is the parameter of alignment.

Accordingly, the greater the deviation of the beam from the Gaussian shape, the greater the value of this parameter, and conversely, the smaller the value of  $S$ , the closer the field distribution in the resonator is to Gaussian.

Measuring the  $M^2$  parameter requires a series of laser beam profile images in different planes along the propagation axis. This requires mechanical movement of the camera. Such measurements can take seconds or even minutes. This is unacceptable for an alignment algorithm that requires hundreds of iterations. In addition, calculating the  $M^2$  parameter requires significant computing resources and provides comprehensive information about the laser beam quality. However, this information is excessive for the alignment task. The alignment task requires not an absolute value of quality but a gradient—the direction in which the alignment mirror needs to be rotated.

The quality of focusing directly depends on the mode composition of the laser beam. The better the laser beam corresponds to TEM00, the lower its divergence and the smaller and brighter its focal spot, and accordingly, the higher the  $S$  parameter.

Calculating the  $S$  parameter requires significantly fewer computing resources and time. Combined with pulse energy measurement, this is sufficient to perform high-quality resonator alignment.

### 3 SPIRICON SP620U CAMERA INTERFACE

A special Spiricon SP620U camera from the Israeli company Ophir is used to obtain an image of the laser beam profile.

The camera captures, displays, and records the spatial intensity profile of the laser beam in a specified plane, transverse to the beam propagation path.

The Python3 programming language and the OpenCV computer vision library are used to organize the interaction interface. Once the image has been obtained, it is sent for processing using the ISO 11146 algorithm.

#### 4 ALGORITHM FOR ALIGNMENT OF THE OUTPUT MIRROR OF THE RESONATOR AND THE SCHEME OF THE EXPERIMENT

Based on the above, an algorithm for aligning the angular position of the mirror was developed, as shown in Figure 4.

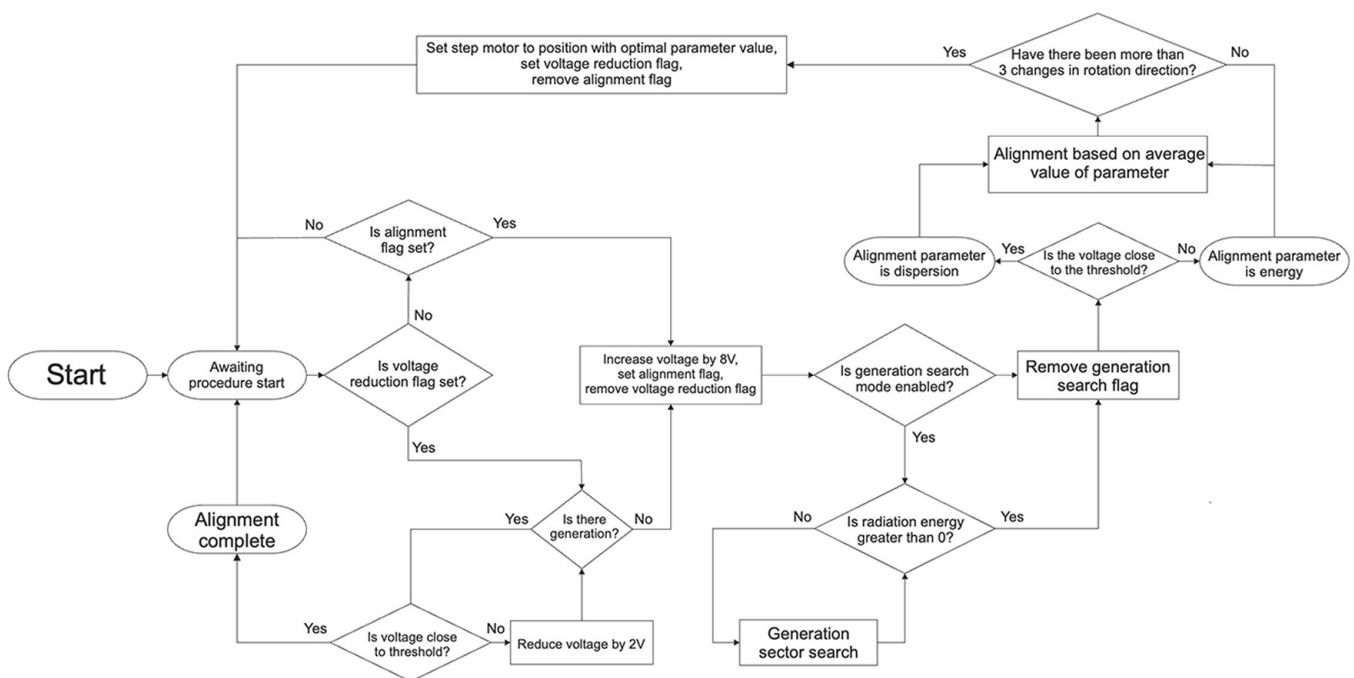


Fig. 4. Algorithm for alignment of the output mirror of the resonator

The stand, created in the 'Fundamentals of Quantum Electronics' laboratory of the 'Radioelectronic Systems and Devices' department at Bauman Moscow State Technical University, is a model of a YAG:Nd3+ laser that allows the stand configuration to be quickly adjusted for specific research [1]. The research on energy and time parameters was described in detail in [2, 3, 4]. Let us focus on the research of spatial characteristics and mode composition of laser radiation. An experiment was conducted on the basis of the stand, the diagram of which is shown in Figure 5.

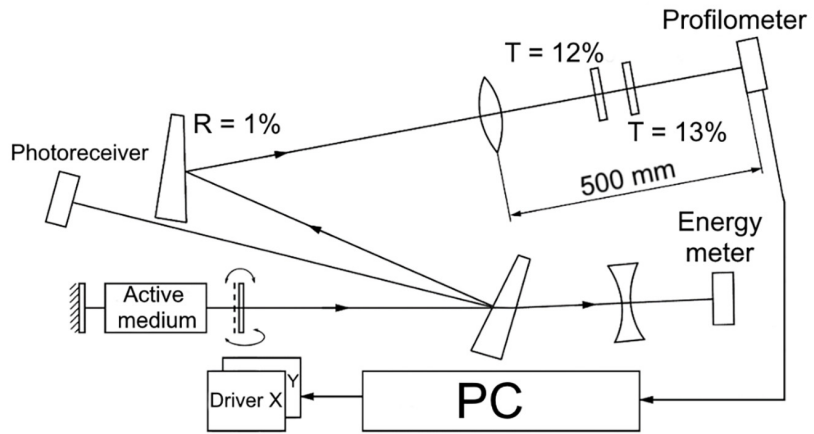


Fig. 5. The scheme of the experiment

Laser radiation is generated in the resonator, passes through the output mirror installed on the alignment table, then the mirror splits the laser radiation into three components, one of which goes to the photodetector, another follows to the Ophir Nova2 laser energy meter, and the third component passes through a collecting lens installed to simulate the far field, passes through optical filters necessary to eliminate camera saturation, and hits the CCD matrix of the laser profilometer, the image from which is sent to a computer for further processing. Signals from the computer are sent to the alignment table. Figure 6 shows a block diagram of the resonator output mirror position control system.

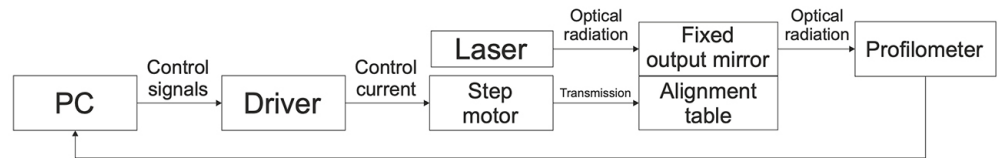


Fig. 6. Block diagram of the resonator output mirror position control system

## 5 SOFTWARE

A client-server application was developed in Python using the TCP/IP protocol stack, allowing no more than three users to observe the operation of the laser stand, with one user controlling and operating the laser stand (see Figure 7).

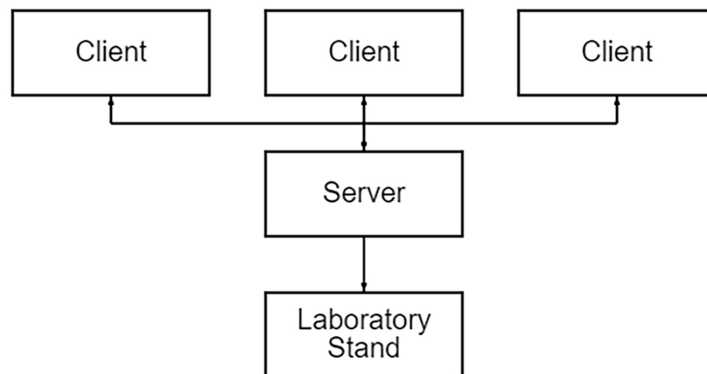


Fig. 7. Client-server application architecture

The developed software allows real-time reading of images from the SP620U camera, control of the Nova2 energy/power meter according to its command system, construction of a 3D image of the laser beam profile, and saving of images. The software also allows you to control the laser power supply. It processes the image in real time and displays the parameters in the user interface (see Figure 8).

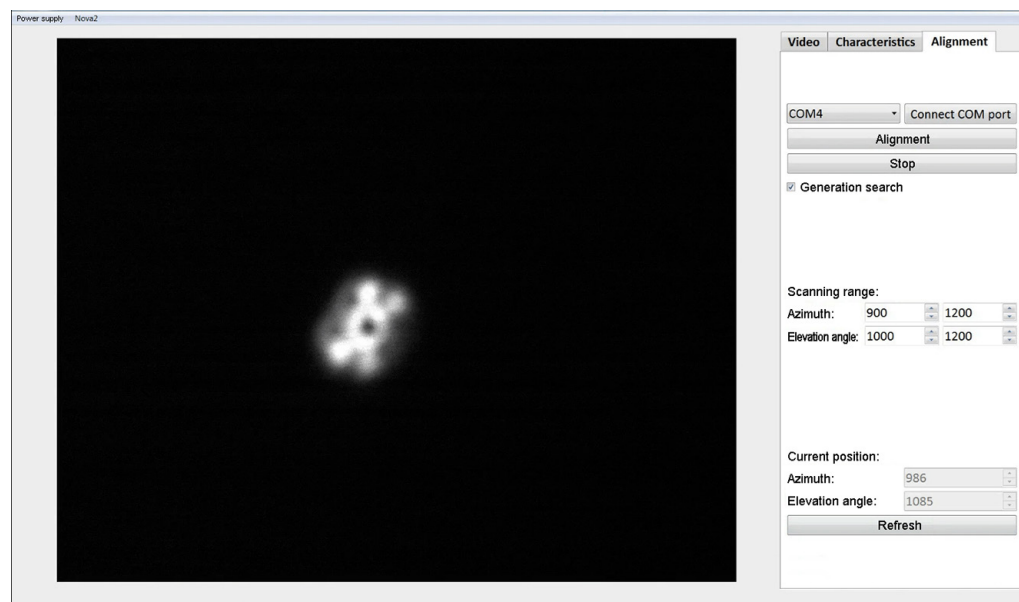


Fig. 8. Visualization of the generation process in the user interface

The generation search mode is provided in case the pump energy is below the generation threshold for the current position of the resonator mirrors at the start of operation («Generation search» option). The client application user can observe the alignment process in real time. The distribution shown in the figure corresponds to the multimode operation observed during the alignment process. The current parameters are displayed in the client window. In addition, it is possible to observe the status of the stand on a video channel.

The alignment of the drives is controlled and managed by an Atmega328 microcontroller, which receives commands from a computer based on image analysis.

## 6 RESULTS OF THE EXPERIMENT

The experiment was conducted without an intra-resonator diaphragm with a full aperture of the active medium with a diameter of 6.3 mm. Therefore, at pump energy significantly exceeding the threshold, a saturated mode composition of radiation was observed.

The alignment was carried out in several stages:

1. The pump energy was reduced in steps.
2. Alignment was performed at the current pump energy.
3. Return to step 1.

This results in a field distribution close to Gaussian at pump energy close to the threshold value, at which only the fundamental mode propagates in the resonator. The results of the experiments are presented in Figures 9–13.

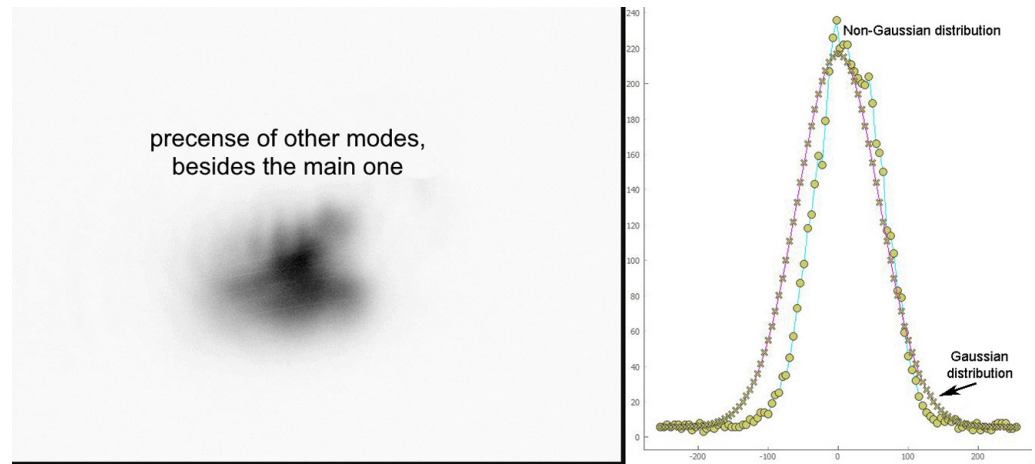


Fig. 9. Start of alignment

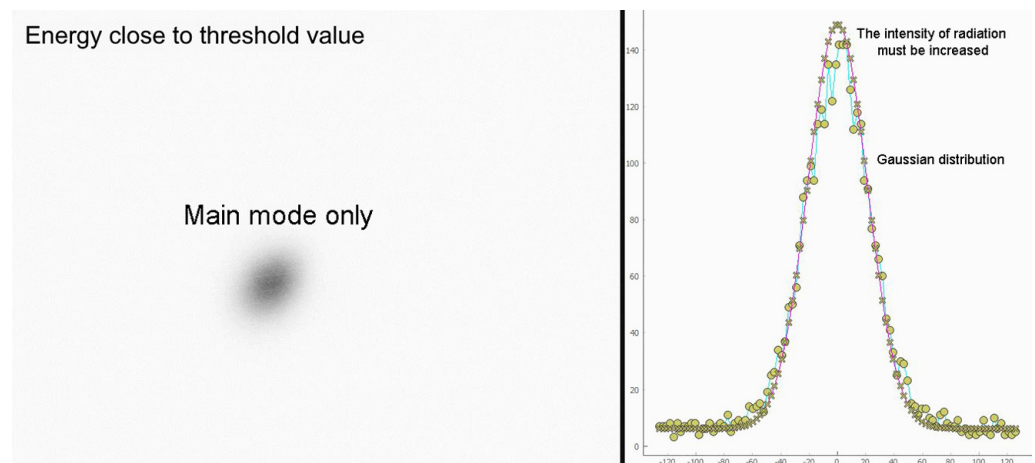


Fig. 10. Intermediate alignment stage

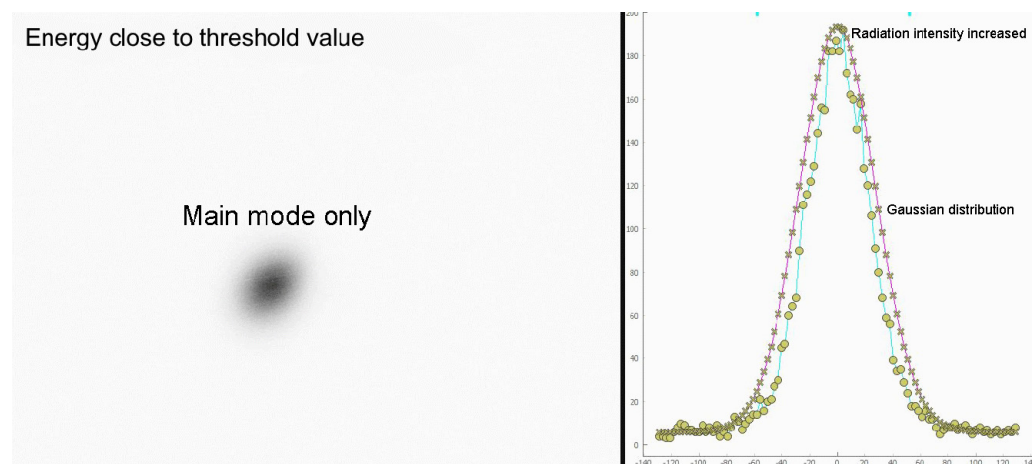


Fig. 11. Final alignment stage

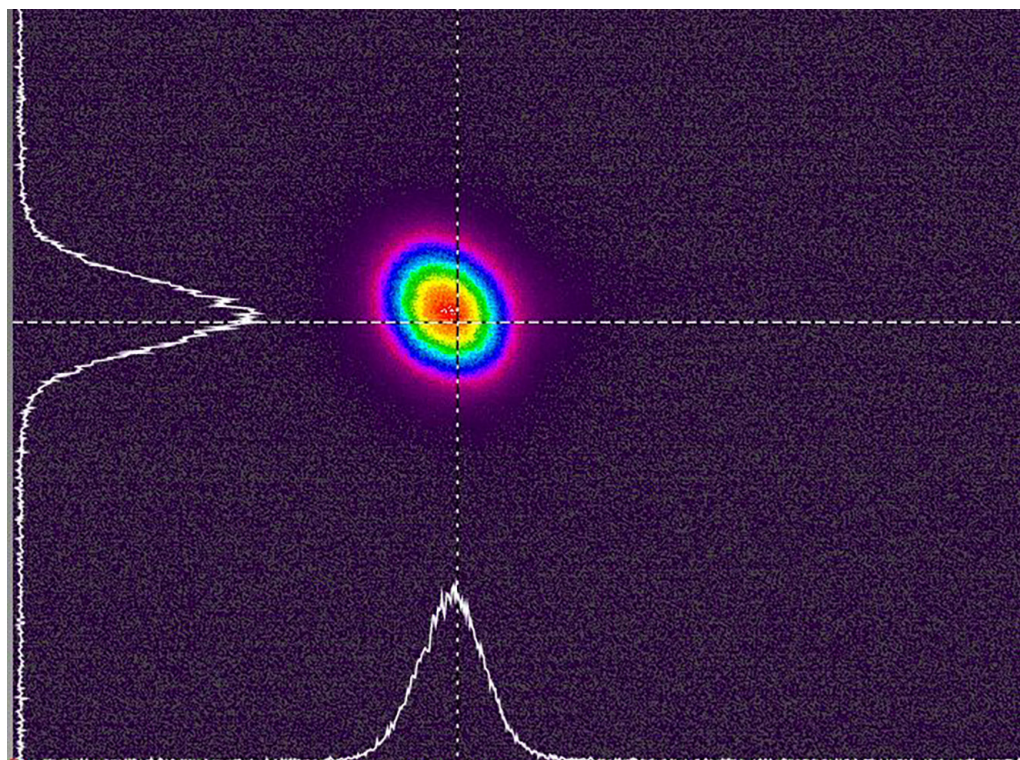


Fig. 12. Field distribution after alignment at a pump energy close to the generation threshold

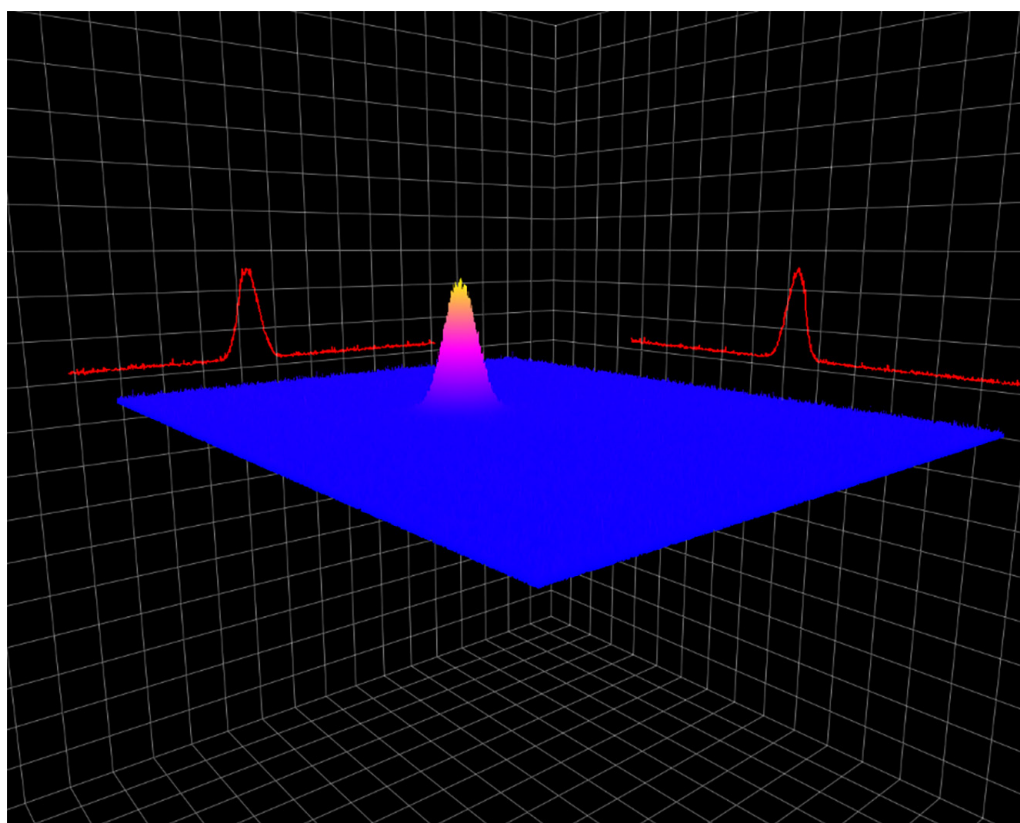


Fig. 13. Field distribution after alignment in 3D

Therefore, based on the results of modeling, prototyping, and experimental testing, it can be concluded that the developed stand can be used in educational and research work on the research of spatial characteristics of lasers.

During the alignment process, according to the algorithm, the pump energy changes from significant values of about 25 J, followed by a decrease to the generation threshold level (about 7 J).

During this change, generation is searched for, the maximum signal level is determined, and the pumping intensity is sequentially reduced to obtain a field distribution across the beam cross-section close to normal.

During the experiment, dependencies of the pump energy change during alignment were also obtained (see Figure 14), and a change in energy was recorded, obtained by integrating the area of a two-dimensional image from a laser beam profilometer using formula 3 (see Figure 15).

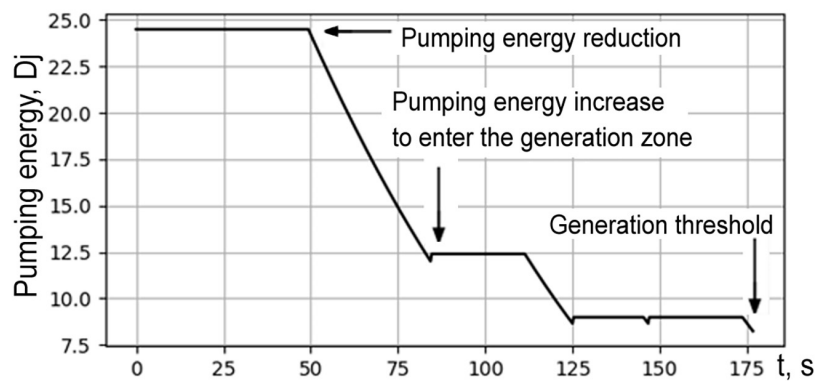


Fig. 14. Pump energy change during alignment

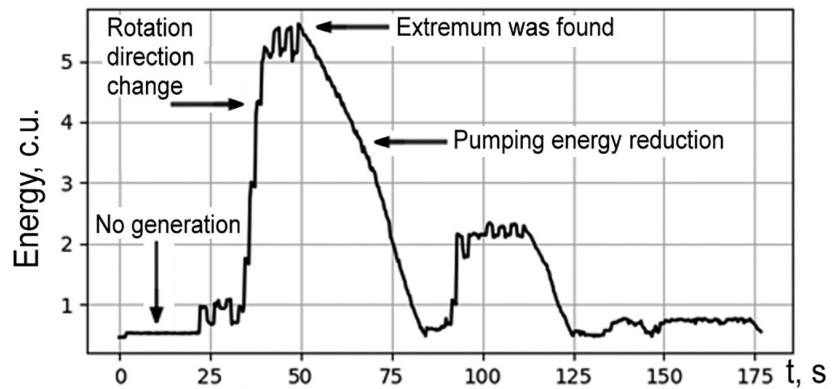


Fig. 15. Energy change during alignment

By analyzing the dependence shown in Figure 15, we can conclude that the energy calculated using formula 3 is correct.

Therefore, based on the results of modeling, prototyping, and experimental testing, it can be concluded that the developed remote-controlled stand can be used in educational and research work on the research of spatial characteristics of lasers.

## 7 ACKNOWLEDGEMENTS

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