Generation of spatial rogue waves in the actively Q-switched solid-state laser

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We report the generation of spatial rogue waves, or ”hot spots”, in the actively Q-switched Nd:YAG laser. We show experimentally that spatial rogue waves can emerge when the laser operates in a low-power regime well below the self-focusing limit. These results confirm that large nonlinearity in the cavity leading to the beam self-focusing in Kerr media is not a necessary factor in the process of spatial rogue waves formation in Q-switched solid-state lasers.

Key words: rogue wave, Nd:YAG laser, Q-switch, nonlinearity

Introduction

Spatial rogue waves (RWs), or “hot spots”, represent tightly focused spots in the transverse cross-section of the beam with peak intensities much higher than the average beam intensity. It was observed that in high-power lasers hot spots with extreme intensities can emerge spontaneously and lead to damage of the laser crystal or optical elements in the cavity [1]. The main mechanisms leading to the emergence of spatial rogue waves in lasers are still under investigation. One of them is spontaneous coupling of transverse and/or longitudinal laser modes [1, 2]. Another could be nonlinearity, which usually is an important necessary factor for rogue waves generation in many optical systems. For example, catastrophic self-focusing in Kerr media causes filamentation and further breakup of the beam, which leads to spatial RWs formation in fibers [3]. However, there are examples of purely linear optical systems where RWs generation was observed [4], so the exact role of nonlinearity in the process of rogue wave formation still requires further study. Here, we demonstrate experimentally the generation of spatial rogue waves in the actively Q-switched solid-state laser operating in a low-power regime, thus showing that large nonlinearity in the cavity is not necessary to obtain spatial rogue wave formation.

1. Experimental setup

To obtain spatial rogue wave generation in laser cavity with low nonlinearity, we used a Nd:YAG laser with several transverse modes operating in active Q-switch regime with low pump energy. The experimental setup is presented in Fig. 1.

The Nd:YAG laser with flashlamp pumping operates in a pulsed regime with a period of 270 ms and is synchronized with the camera that records the output beam transverse intensity distribution integrated over the duration of each Q-switched pulse. The output pulse temporal profile is displayed using a photodiode connected to an oscilloscope (not synchronized with the camera).

Typical Q-switched pulse energy and duration for pump energy of 7 J used in the experiment are about 9.4 mJ and 55 ns corresponding to the power in the cavity of 0.46 MW. This is much less than the minimal power required for self-focusing in Nd:YAG (5.3 MW).

2. Results

To characterize any extreme event as a rogue wave, it should fulfill three defining criteria of RWs that are commonly used in the literature [5]:

1. A rogue wave peak amplitude is more than twice the significant wave height (SWH), which is the mean amplitude of the highest third of waves.

2. Rogue waves have stochastic nature, i.e. they emerge and disappear unpredictably.
3. The probability distribution function of the wave amplitude has an L-shape (or another specific long-tail shape).

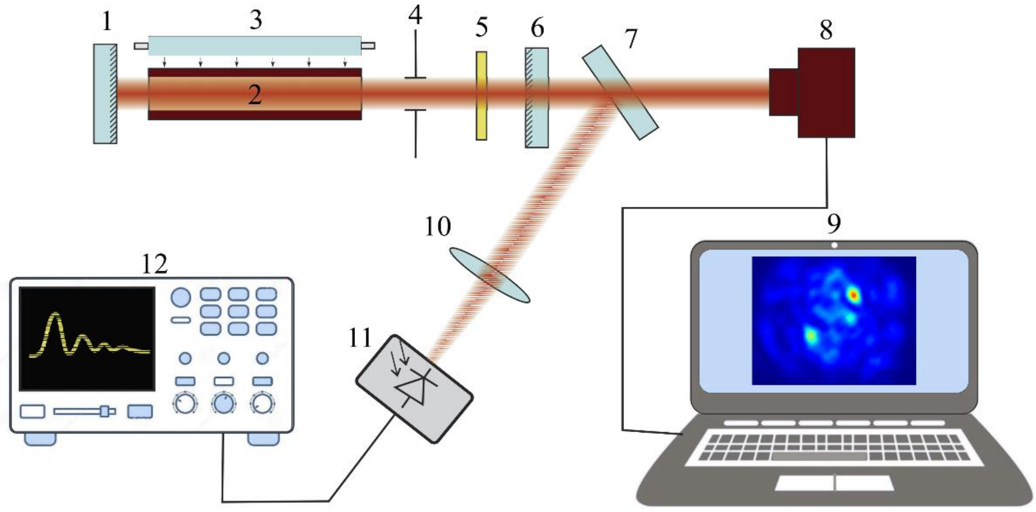

Fig. 1. – Setup scheme: 1 – highly-reflective mirror; 2, 3 – Nd:YAG active element with flashlamp pumping; 4 – iris diaphragm; 5 – electrooptic shutter; 6 – output mirror with a reflection coefficient of 63 %; 7 – beam splitter; 8 – camera registering the transverse profile of the laser beam; 9 – computer with software to control the camera; 10 – lens; 11 – photodiode; 12 – oscilloscope showing the temporal profile of the Q-switched pulse.

The main goal of the experiment was to obtain such generation regime that corresponds to spatial rogue waves formation in the output laser beam. For this, the laser transverse mode configuration was adjusted by tuning the mirrors' alignment and iris diaphragm size. The main criterion required to obtain rogue waves generation is a complex laser beam profile, formed by a large number of high-order transverse modes interacting in the cavity [2].

Example spatial rogue waves emerging in the output laser beam are shown in Fig. 2, *a* along with the "ordinary" output beam profiles without rogue waves that vary from one Q-switched pulse to another. In addition, intensity statistics over a number of typical 2D transverse beam profiles is analyzed to determine the rogue wave limit and compare it with the observed hot spots intensities (Fig. 2, *b*). It is seen that intensities of some hot spots (like those shown in Fig. 2, *a*) exceed the limit equal to $(2 \cdot \mathrm{SWH})^2$, thus meaning that they are indeed spatial rogue waves. Besides, the distribution plotted in logarithmic scale has an *L*-shaped form, which indicates that the probability of rogue wave formation is larger than predicted by using Gaussian statistics. Finally, Fig. 2c displays statistics of pulse-to-pulse peak intensity over the transverse intensity profile for all output beams captured during the experiment. One can see that peak intensities of the observed spatial rogue waves are about two times higher than the average peak intensity. This plot also displays the probability of rogue wave generation, which is about 0.24 %.

Conclusions

In conclusion, we demonstrated the experimental generation of spatial rogue waves in the actively Q-switched solid-state laser operating in a low-power regime well below the self-focusing limit. We demonstrated that large nonlinearity in the cavity causing self-focusing in Kerr media is not necessary for the spatial RWs to emerge. These results are important for future studies of the role of nonlinearity in the process of spatial rogue waves formation in lasers.

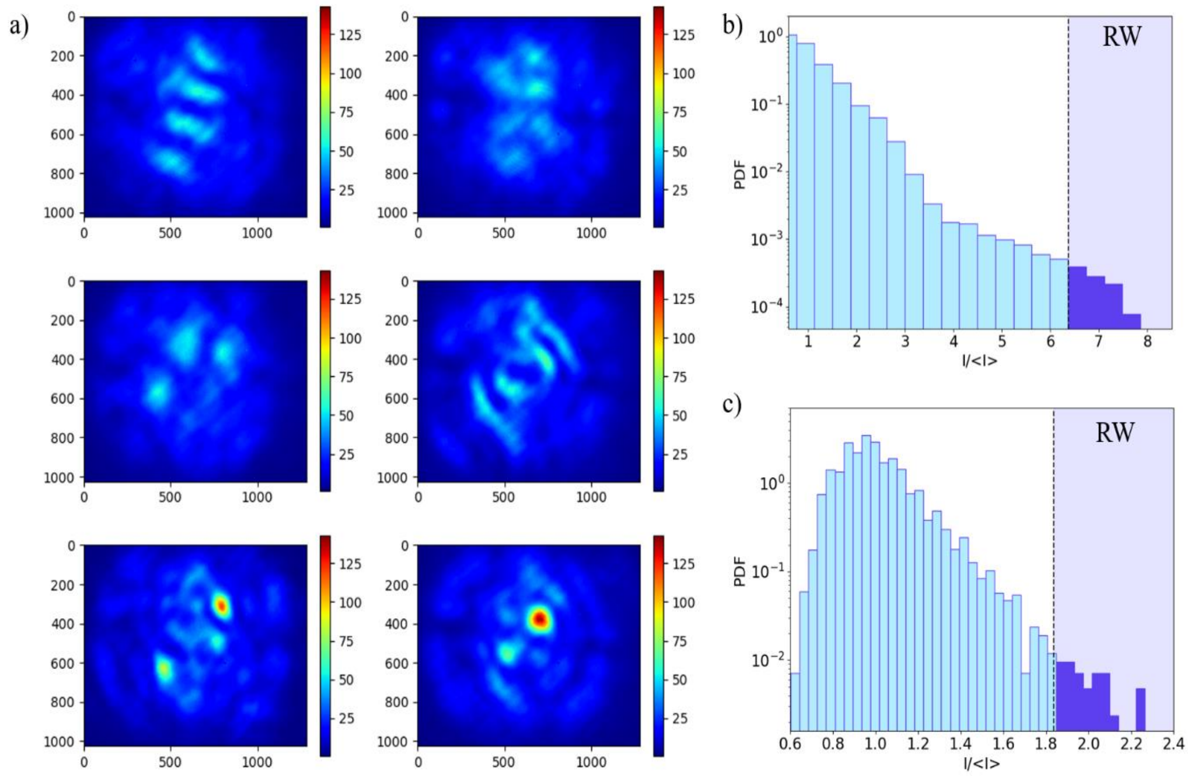

Fig. 2. – Generation of spatial rogue waves: *a*) typical output laser beam profiles without RWs (1st and 2nd rows) and with RWs (3rd row) (intensity in a.u., common scaling for all subplots); *b*) distribution of intensities over a number of 2D transverse beam profiles, the rogue wave limit shown with the dashed line corresponds to intensity equal to 116; *c*) distribution of pulse-to-pulse peak intensity over the transverse intensity profile, the dashed line indicates the RW limit calculated in Fig. 2, *b*.

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