Generation of spatial rogue waves in a Q-switched Nd:YAG laser

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Abstract: The generation of spatial rogue waves is demonstrated in a Q-switched Nd:YAG laser operating in a low-power regime under low Kerr nonlinearity. We investigate the dependence of rogue waves' statistics on the laser mode configuration. We show that spatial rogue waves can emerge when the lasing takes place at a large number of high-order transverse modes, while high Kerr or saturable absorption nonlinearity is not a necessary factor for their formation.

Spatial rogue waves are rare events that represent tightly focused spots in the transverse cross-section of the beam with extremely high intensities. They represent a particular case of general class of rogue waves (RWs) – extreme events that emerge and disappear spontaneously, and can be observed in different optical systems [1].

The exact mechanisms leading to the formation of spatial rogue waves are still under investigation. One of them concerns with the active role of nonlinearity. Typically, RWs are observed in optical systems with high medium nonlinearity, e.g. in fibers or lasers operating in a high-power regime with considerable Kerr nonlinearity or with intracavity saturable absorbers [1]. However, there are examples of purely linear optical systems that exhibit RWs generation. In such systems, RWs can be generated in the case of inhomogeneity and granularity of the beam profile [2], thus indicating the importance of spatial effects and modal dynamics. Spontaneous coupling of transverse laser modes possibly assisted by the longitudinal mode-locking can lead to the formation of complex output beam patterns with filamentary structure dynamically changing in time [3, 4]. In the extreme cases, the intensities of individual filaments can be high enough to damage the laser crystal or optical elements in the cavity [5].

Here, we demonstrate experimentally the generation of spatial RWs in a multimode Nd:YAG laser operating in the active and passive Q-switch regime [4,6]. The observed rogue wave statistics depend on the transverse mode configuration, as illustrated for example in Figure 1 for the laser generation in the active Q-switch regime. Thus, the spatial RWs were generated when a large number of high-order transverse modes were involved in the lasing (Figure 1b), while in the case of a smaller number of lasing modes with lower order the rogue wave generation was not observed (Figure 1a).

In addition, we performed a number of experiments for different pump powers to investigate the effect of Kerr nonlinearity on the properties of spatial RWs for the case of the laser operation below the self-focusing limit. In these experiments, the Nd:YAG laser was actively Q-switched without a saturable absorber in the cavity. We obtained the generation of spatial RWs under different pump powers corresponding to the output Q-switched pulse energies from 9 to 20 mJ [6]. The observed RWs had similar statistics and properties independent on the pump power. These results confirm that high Kerr nonlinearity or saturable absorption nonlinearity is not the main factor leading to the spatial rogue wave generation in a multimode solid-state laser.

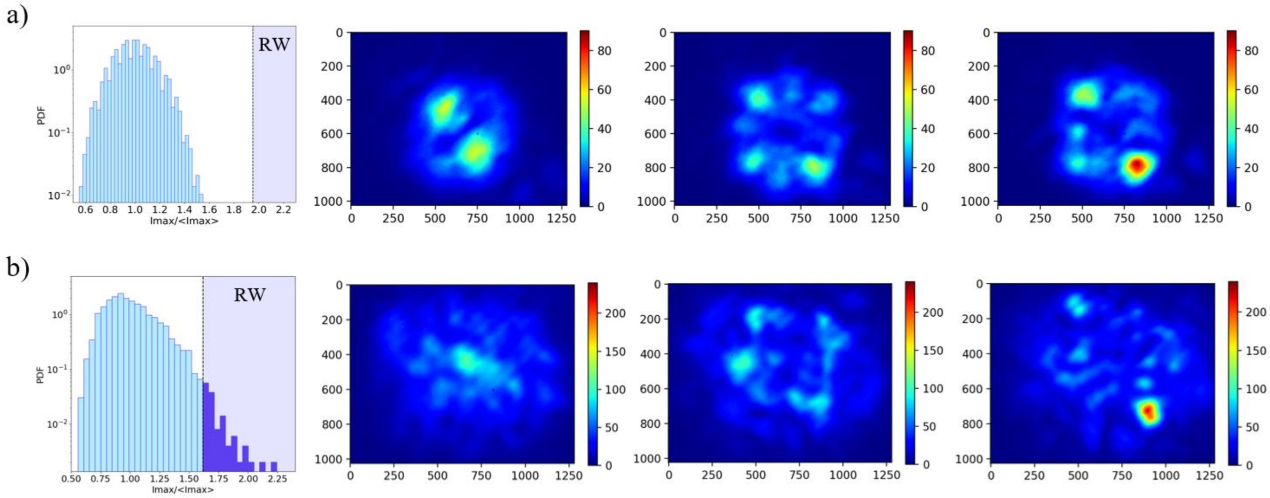

Figure 1. Statistics of pulse-to-pulse peak intensity over the transverse intensity profile and example output beam profiles for different laser mode configurations: a) small number of lasing modes with low order (spatial RWs are not observed); b) large number of high-order modes (the rightmost figure corresponds to a spatial rogue wave). The rogue wave limit is shown as a boundary of the shaded region in the statistics plots.

References

1. Akhmediev, N. et al., "Roadmap on optical rogue waves and extreme events", J. Opt.. **18**, 063001, 2016.
2. Arecchi, F., U. Bortolozzo, A. Montina, and S. Residori, "Granularity and inhomogeneity are the joint generators of optical rogue waves", Phys. Rev. Lett. **106**, 153901, 2011.
3. Encinas-Sanz, F., S. Melle, and O. G. Calderon, "Time-resolved dynamics of two-dimensional transverse patterns in broad area lasers", Phys. Rev. Lett, **93**, 21, 213904, 2004.
4. Navitskaya, R., I. Stashkevich, S. Derevyanko, and A. Karabchevsky, "Spatial rogue waves in the actively Q-switched Nd:YAG laser under low Kerr nonlinearity", Opt. Express **30**, 37076-37084, 2022.
5. Arisholm, G., "Self-focusing and optical damage in a diode-pumped neodymium laser", OSA TOPS, Vol. 10, Advanced Solid State Lasers (Optical Society of America, 1997).
6. Navitskaya, R., I. Stashkevich, S. Derevyanko, and A. Karabchevsky, "Experimental demonstration of spatial rogue waves in the passively Q-switched Nd:YAG laser", Opt. Lett. 46, 3773-3776, 2021.