Spatial rogue waves in a Q-switched solid-state laser with transverse mode locking

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Spatial rogue waves represent hot spots with extremely high intensities in transverse cross-section of the laser beam. Here, we study theoretically the generation of spatial rogue waves in an actively Q-switched solid-state laser with several transverse modes. We show that in the absence of nonlinear mode interaction and other nonlinear effects in the cavity spatial rogue waves in the output laser beam can be generated as a result of coherent superposition of the transverse modes. The probability of rogue wave emergence depends on the laser mode configuration and is higher in the case of highly anisotropic mode distribution and reduced frequency spacing between the modes.

Keywords: rogue wave; transverse mode locking; active Q-switching; multi-mode laser.

Генерация пространственных аномальных волн в твердотельном лазере с активной модуляцией добротности и синхронизацией поперечных мод

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Пространственные аномальные волны представляют собой «горячие точки» с экстремально высокими интенсивностями в поперечном сечении лазерного пучка. В данной работе мы исследуем теоретически генерацию пространственных аномальных волн в твердотельном лазере с несколькими поперечными модами, работающем в режиме активной модуляции добротности. В случае отсутствия нелинейного взаимодействия мод и других нелинейных эффектов в резонаторе пространственные аномальные волны в поперечном сечении выходного лазерного пучка могут возникать в результате когерентной суперпозиции поперечных мод. Вероятность генерации аномальных волн зависит от модовой конфигурации лазера и увеличивается в случае более анизотропного распределения мод и меньшей разности частот между модами.

Ключевые слова: аномальная волна; синхронизация поперечных мод; активная модуляция добротности; многомодовый лазер.

Introduction

The phenomenon of rogue waves (RWs) generation has been observed in different complex optical systems including laser systems [1–3]. Spatial rogue waves represent one of the RWs types that can emerge in multi-mode optical systems and correspond to hot spots with extremely high intensities in the transverse cross-section of the beam [4]. Spatial rogue wave formation in lasers can be governed by different factors such as spatial and nonlinear effects, gain, dispersion, and cavity configuration [2, 5, 6]. In the case of reduced or negligible nonlinearity in the cavity, one of the possible mechanisms that can lead to the onset of RWs generation is spontaneous mode-locking [4, 7].

As follows, we discuss a theoretical model that allows for simulating the spatial RWs generation in a Q-switched solid-state laser as a result of the spontaneous transverse mode locking assuming negligible nonlinear effects in the cavity.

1. Theoretical model

Transverse mode locking in lasers is a well-known effect that results in a confined pattern in the transverse cross-section of the beam [8, 9]. By analogy with the longitudinal mode locking, the dynamics of the beam profile is defined by the frequency spacing between the transverse modes [8, 10].

The total field inside the laser cavity can be described through the superposition of individual mode fields [11]:

$$E(x,y,t) = \sum_{q,m,n} A_{qmn}(t) U_{mn}(x,y) e^{2\pi i \nu_{qmn} t + i\varphi_{qmn}} \quad (1)$$

where $A_{qmn}(t)$, ν_{qmn}, and φ_{qmn} stand for the slowly varying amplitude, frequency, and phase of the mode with a longitudinal index q and transverse field distribution $U_{mn}(x, y)$.

Considering an actively Q-switched solid-state laser, the time dependence of modal amplitudes $A_{qmn}(t)$ is calculated using the rate equations under the approximation of a point model of the laser cavity [12] adapted for the multi-mode case. The nonlinear gain competition is neglected in the model as well as other nonlinear effects, corresponding to a linear superposition of the laser modes.

In the case of a cylindrical symmetry of the cavity, the laser modes can be approximated by Laguerre-Gaussian (LG) modes [13, 10]. In the following analysis, we consider one longitudinal mode ($q = 0$) and 15 transverse modes that are defined using the basis of LG modes. The modes are characterized by different losses in the cavity, which results in specific spatially anisotropic configurations of the output laser beam. The frequency separation between the modes depends on the cavity configuration and is considered a free parameter in the simulation.

The time-averaged intensity distribution at the laser output (as captured experimentally by the camera [4]) is given by:

$$I_{average}(x,y) = \frac{1}{T_{exp}} \int_0^{T_{exp}} k_{out} \left|E(x,y,t)\right|^2 dt \quad (2)$$

where k_{out} is the fraction of photons emitted through the output mirror, T_{exp} is the camera exposition time that is equal to the Q-switched pulse duration.

2. Results

To analyze the spatial rogue waves generated in the time-averaged output laser beam and investigate their statistical properties, we calculated a number of output beam profiles given by (2) for different realizations of random initial phases of the modes φ_{qmn}. In the described laser system, the number of lasing modes is fixed and the probability of RWs generation depends on the frequency spacing between the modes and anisotropy of the mode configuration, which is governed by the mode-dependent losses. Figure 1 shows example intensity statistics and output beam profiles for the frequency spacing between the modes equal to 2 MHz for two limiting cases of the laser mode configuration. The first case corresponds to an isotropic configuration, when all modes are characterized by equal losses, while the second case describes the most anisotropic configuration, when the group of modes with sin-like angular dependence of the phase has losses much higher than the other group of modes with cos-like phase patterns.

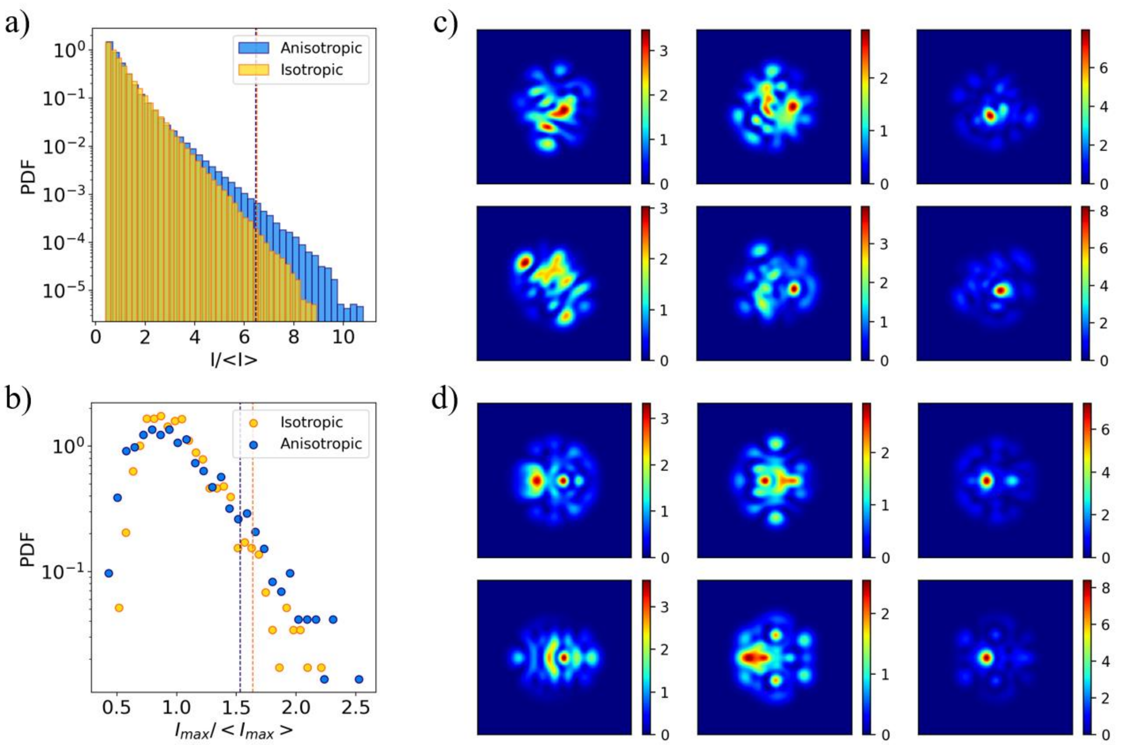

Fig. 1. Statistics of *a*) 2D intensity and *b*) peak intensity over the beam profile for isotropic and anisotropic mode configurations; example output beam profiles (intensity relative to average) for *c*) isotropic and *d*) anisotropic mode configurations (beam profiles with spatial RWs are shown in the rightmost columns). Dashed lines indicate the rogue wave limits

It is seen that in the latter case, the 2D intensity statistics has more pronounced L-shaped form and maximal values of 2D and peak intensity are higher, indicating that spatially anisotropic mode configuration provides more favorable conditions for spatial RWs generation. In the example shown in Fig. 1, the frequency spacing between the modes corresponds to the period of beating of 500 ns, which is much larger than the Q-switched pulse duration (about 100 ns). This allows for the spatial rogue waves emergence in time-averaged beam profiles for specific values of the modes' initial phases which correspond to constructive interference of the transverse modes. For larger values of frequency spacing (>5-10 MHz) that correspond to the period of beating comparable or smaller than the Q-switched pulse duration, the spatial rogue waves were not generated as the beating effects between the modes were averaged out in the output beam profiles.

Conclusion

We simulated theoretically the spatial rogue waves generation in the time-averaged output laser beams as a result of coherent transverse mode superposition in a multi-mode Q-switched solid-state laser. In the absence of nonlinear effects in the cavity, the main parameters affecting the rogue wave statistics are the frequency spacing between the transverse modes and spatial anisotropy of the laser mode configuration. The reduced frequency spacing and more spatially anisotropic mode configuration are favorable for the increased probability of the rogue waves emergence.

References

1. Optical rogue waves / D. R. Solli [et al.] // Nature. 2007. Vol. 450. P. 1054.
2. Roadmap on optical rogue waves and extreme events / N. Akhmediev [et al] // J. Opt. 2016. Vol. 18. P. 063001.
3. Recent progress on optical rogue waves in fiber lasers: status, challenges, and perspectives / Y. Song [et al.] // Advanced Photonics. 2020. Vol. 2. P. 024001.
4. Spatial rogue waves in the actively Q-switched Nd:YAG laser under low Kerr nonlinearity / R. Navitskaya [et al.] // Optics Express. 2022. Vol. 30. P. 37076–3708.
5. Rogue waves and analogies in optics and oceanography / J. M. Dudley [et al.] // Nature Reviews Physics. 2019. Vol. 1. P. 675–689.
6. Extreme events and single-pulse spatial patterns observed in a self-pulsing all-solid-state laser / C. Bonazzola [et al.] // Phys. Rev. E. 2018. Vol. 97. P. 032215.
7. *Arisholm G.* Self-focusing and optical damage in a diode-pumped neodymium laser // OSA TOPS, Advanced Solid State Lasers (Optical Soc. Am., 1997). 1997. Vol. 10. P. 109.
8. *Auston D. H.* Transverse mode locking // IEEE Journal of Quantum Electronics. 1968. Vol. 4. P. 420–422.
9. *Smith P. W.* Mode-locking of lasers // Proc. IEEE. 1970. Vol. 58. P. 1342–1357.
10. *Kogelnik H., Li T.* Laser beams and resonators // Applied Optics. 1966. Vol. 5. P. 1550–1567.
11. Modal reconstruction of transverse mode-locked laser beams / F. Schepers [et al.] // Applied Physics B. 2022. Vol. 126. P. 168.
12. *Navitskaya R. I.* Cavity Dumping by the Second Harmonic Generation in the Q-switched Nd:YAG Laser / R. I. Navitskaya, I. V. Stashkevitch, Y. S. Varapay // Журнал Белорусского государственного университета. Физика. 2020. № 1. С. 28–33.
13. *Zhang Z., Zhao C.* Spontaneous phase and frequency locking of transverse modes in different orders // Physical Review Applied. 2020. Vol. 13. P. 0240109.