SPONTANEOUS SYNCHRONIZATION OF TRANSVERSE MODES. OCCURRENCE OF ANOMALOUS WAVES IN LASERS

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In this paper, we present the results of a computer algorithm designed to test the hypothesis that the so-called hot spots in a laser beam can be a consequence of the interaction of the transverse modes of the resonator. The intensity distribution in the beam was studied with the interference of several Gauss - Hermite modes

Key words: rogue wave; hot spot; Gauss-Hermite mode; mode interaction.

The phenomenon of rogue waves has been known in laser physics for many years. It has been observed that in high-power lasers, the optical elements or the laser crystal itself can be damaged by spontaneously occurring hot spots of extremely high intensity. It has been suggested that such hot spots arise due to the spontaneous interaction of transverse and/or longitudinal laser modes. However, despite years of research, the underlying factors thought to influence the appearance of hot spots remain elusive. For example, it is now a generally accepted fact that non-linearity is not strictly necessary to observe an increased probability of RW occurrence, and heavy-tailed wave intensity distribution statistics have been reported in purely linear systems. Rather, it is the complex interaction of a large number of resonator modes that leads to an increased likelihood of a hot spot [1].

To test this assumption, the following model was proposed: We limited ourselves to 8 transverse modes (TEM_{00}, TEM_{01}, ..., TEM_{22}, TEM_{32}) and one longitudinal. During the simulation, it was required to set the generation wavelength, the frequency difference between adjacent horizontal and vertical modes, resonator length they are respectively equal to 815 nm, 100 MHz, 82 MHz, 1m these parameters, judging by the results of the study, do not affect the overall picture and will only determine the rate of change of the resulting interference pattern.

To obtain the distribution of the amplitude values of the energy of each mode in the resonator, the following formula was used[2]:

$$U_{m_l} = HmHl \exp[\pi/d\lambda(x^2 + y\hat{}2)],$$

where Hm and Hl are the Hermitian polynomials of order m and l, respectively, d is the resonator length (for a confocal resonator), lambda is the generation wavelength, x and y - coordinates in the beam plane

For the reference point (t = 0), we set the moment of complete coincidence of the phases of all modes, while the created algorithm allows you to generate an interference pattern at any subsequent time splitting the modes in pairs and sequentially calculating the amplitudes of the resulting waves as:

$$A_r = \sqrt{A_1^2 + A_2^2 + 2A_1A_2\cos(\varphi_2 - \varphi_1)},$$

where A_1 and A_2 are the amplitudes of two waves, and φ_1 and $\varphi_2$are their phases, respectively. And the phase of the resulting wave is equal to the difference $\varphi_2 - \varphi_1$.

Next, the resulting image is divided into a grid of small equal squares, the intensity is measured in the center of each of them, and the average intensity over the entire picture is calculated. We create a diagram that reflects the distribution of these squares by intensities. Rogue wave can be identified by the presence of a long "tail" in this distribution (big kurtosis)[1].

Thus, at the moment of complete mode synchronization (t = 0) we obtain a typical hot spot:

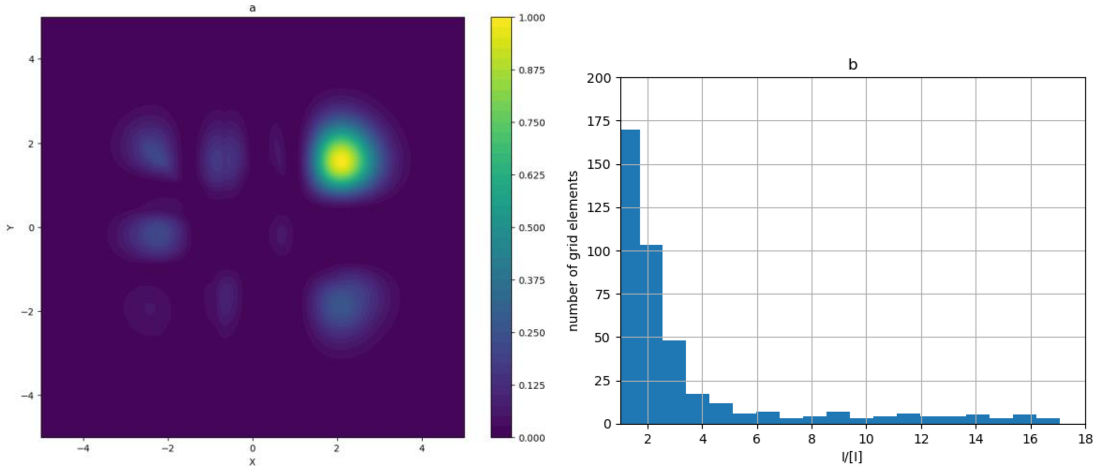

Fig. 1. intensity distribution in the plane of the beam *(a)*, distribution of grid elements (its squares) by intensity, where I – intensity of the element, [I] – average intensity*(b)*

We observe the outlines of the distribution pattern for the highest order mode (TEM_{32}), however, the intensity in almost all “nodes” of the pattern is extremely low, only in the upper right corner (coordinates (3,3)) we can observe a hot spot - a small region of space with abnormally high intensity. The kurtosis of the distribution shown is K = 21.25. Over time, the intensity distribution approached normal, it was still possible to distinguish the pattern characteristic of the TEM_{32} mode, the various nodes of which became brighter or dimmer in a random order, rogue waves were repeatedly observed after the initial moment of time. It is noteworthy that it was at t=0 that the kurtosis was the greatest, although it must be borne in mind that the search for hot spots was carried out manually, and the algorithm needs to be refined to check this, but now it can be assumed that it is at the moment of complete phase synchronization that the hot spots most pronounced. It is also characteristic that hot spots were found only at corner nodes (this was also established using manual search - sequential study of the interference pattern at different points in time, therefore verification by a more advanced algorithm is required).

Next, we added higher order transverse modes (TEM_{33}, TEM_{34}). The processes already described above were observed, the only significant difference is that in this case, the brightness of the nodes of the TEM_{34} mode (higher order mode) dynamically changed over time. Several interference patterns will be shown below to visualize the described dynamics.

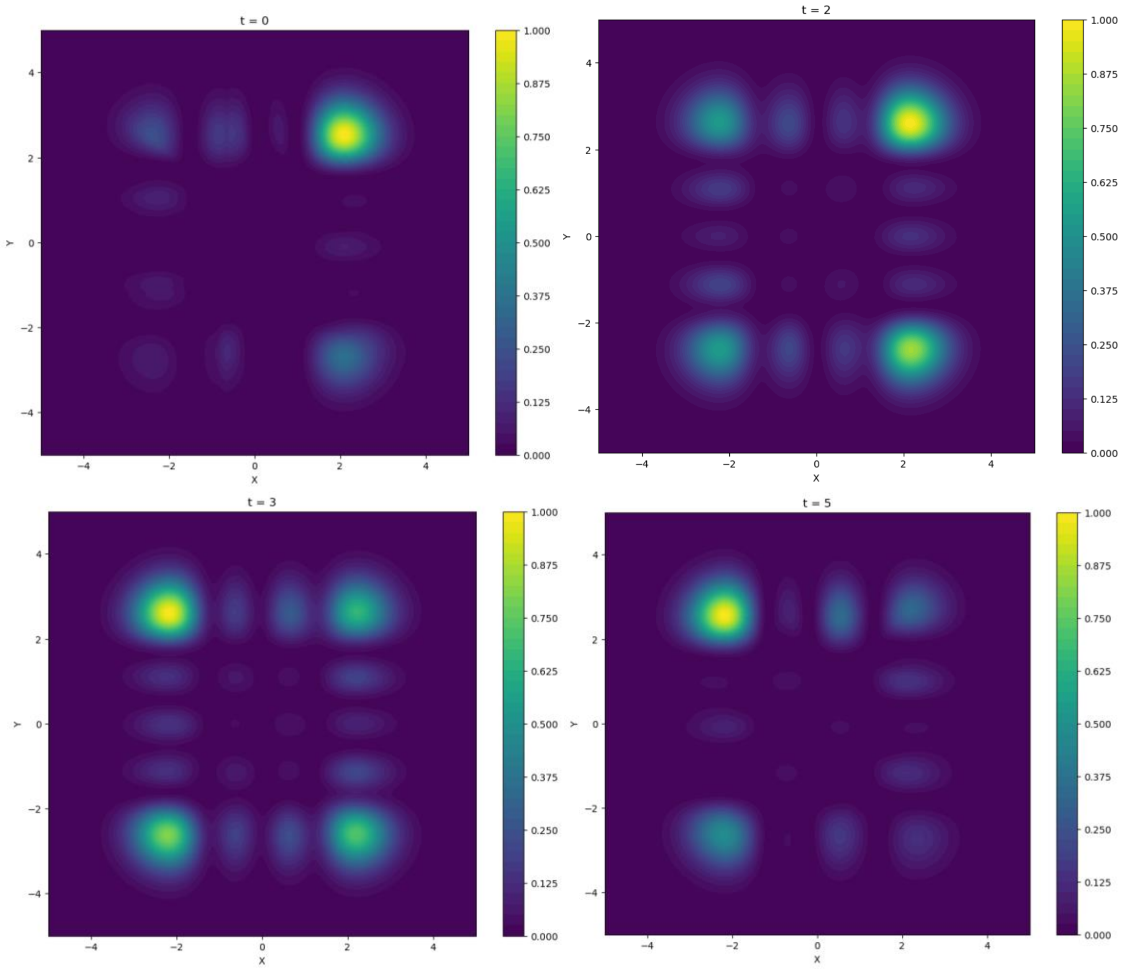

Fig. 2. intensity distribution in the plane of the beam at different points in time (t = 0, 2, 3, 5 ns after the moment of complete synchronization)

Also, during the simulation, some repeatability of the observed pattern was noticed, which may indicate periodicity (verification is required).

It is also worth studying the case of a small number of modes, for this we will work with the following configuration: TEM_{00}, TEM_{01}, TEM_{10}, TEM_{11}, TEM_{21}. It was suggested that with an insufficiently large number of interacting modes, the observation of anomalous waves is impossible or unlikely. After a long study by manually searching for these phenomena, I can say that at the moment it is difficult to disagree with this assumption (I have not found hot spots). Initially, this assumption appeared due to the small size of the highest order mode in comparison with the size of its nodal peaks, this issue is worth investigating at other laser parameters. As already mentioned, with full mode locking, before that it was always possible to obtain a hot spot, and at this moment it was most pronounced, so we will present the distribution of the intensity of the interference pattern at this very moment(K = 2.45).

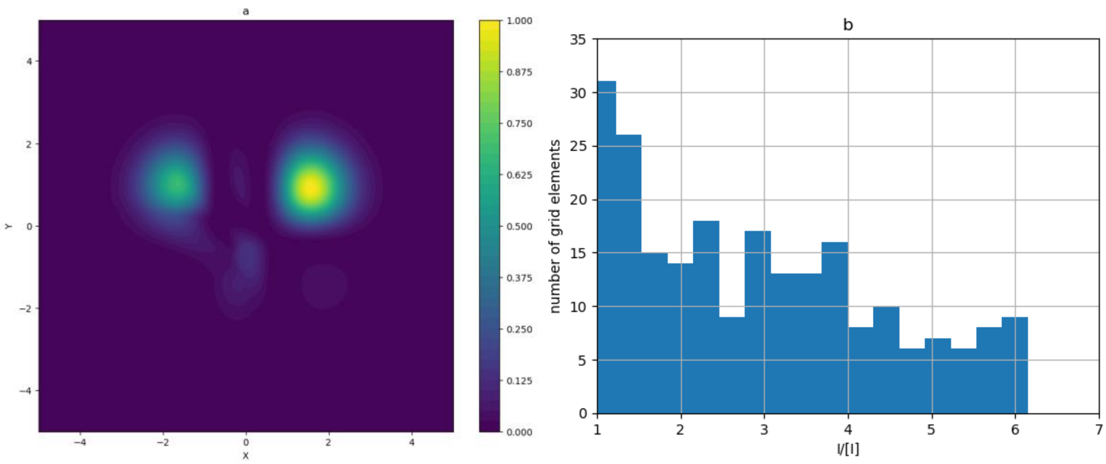

Fig. 3. intensity distribution in the plane of the beam *(a)*, distribution of grid elements by intensity *(b)*

Based on the results of the work done, it can be concluded that the interaction and spontaneous synchronization of many transverse cavity modes can be responsible for at least some of the events associated with anomalous waves. Our model, limited only by mode interference, allowed us to register the appearance of "hot spots" many times. However, at the moment, the study remains purely qualitative, although it has been demonstrated that the developed algorithm and technique make it possible to investigate rogue waves, significant improvements are required to test the hypotheses put forward.

References

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