High speed brightness amplifiers for diagnostics of fast processes obscured by intense background radiation

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Abstract: In this paper the results of using high-speed metal and halide metal vapor brightness amplifiers for visual non-destructive testing of objects and fast processes blocked from observation by the intense background light are given. In particular, the results of visualization of SHS-process, corona discharge and nanoparticle production process are presented. It has been shown that the visualization method proposed in this paper proves to be the most reliable one for obtaining information about the objects or processes in real-time mode.

Key-words: brightness amplifier, laser, laser monitor, visualization.

1 Introduction

At the end of the last century there were several scientific groups who studied the use of brightness amplifiers for active visual monitoring of objects, in particular for manufacturing integral microchips. They used an active optical system called a laser projection microscope. The key component of the laser microscope was an active element of a copper vapor laser operating as a brightness amplifier [1].

At the beginning of the 2000s the development of new technologies based on the impact of energy fluxes on the object, such as the modification of the material surface aiming at performance enhancement, production of new materials including nanostructures, welding and cutting processes, and the synthesis of new materials using self-propagating high-temperature synthesis (SHS), have renewed the interest in such optical systems. First of all, the processes mentioned above are blocked by the intense background radiation, which does not allow to visualize the object and to control fast processes [2-4]. The active media of lasers on self-terminating transitions in metal vapors operated in the brightness amplifier mode are capable of visualizing such objects due to the high spectral brightness and high gain in the narrow spectral band (2-5 pm), and in different spectral regions as well (from NUV to NIR) . A pulsed-periodic mode of radiation makes it possible to monitor the objects and perform diagnostics of fast processes with the time resolution corresponding to the pulse repetition frequency [5].

Nowadays several research groups study and apply copper vapor brightness amplifiers. A group of Prof. Prokoshev obtained significant results concerning the visualization of the processes of the interaction of intense energy fluxes with the surface [6]. Similar problems are studied by Dr. Kuznetzov and Prof. Buzhinsky with colleagues [7, 8].

Our research group presents the results of designing and using high speed brightness amplifier based on CuBr-active medium operating at pulse repetition frequency up to 100 kHz for diagnostics of fast processes through the strong background radiation. Among those are the visualizations of the SHS, the corona discharge in the air, the nanoparticles production process using a high-power fiber laser.

2 Laser monitor with frame-by-frame imaging for visual diagnostics of processes in real-time mode. Experimental setup and its testing

A simplified optical scheme of the laser monitor is shown in Fig. 1. The main elements of the device are as follows: a brightness amplifier (CuBr gas discharge tube), a power supply, a high speed CCD-camera, a synchro-circuit and optical elements.

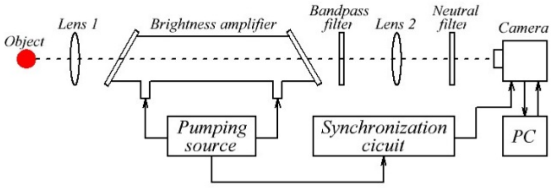

Fig. 1. A simplified optical scheme of the laser monitor

As brightness amplifiers for active optical systems we used the active media of copper bromide vapor lasers with the active HBr-additive. The HBr addition of 0.1 - 0.3 Torr allowed to improve frequency-energy characteristics and the radiation beam quality [9].The active medium was pumped by a high-voltage pulse-periodic discharge at a pulse repetition rate of 10-100 kHz. We used two types of pumping: traditional pumping, when the electrodes were placed inside the gas discharge tube (GDT) [10] and capacitive pumping, when electrodes were placed outside the GDT [11].

Radiation pulses were registered using a coaxial photo-element FK-22 with an accuracy of 1 ns. The signals registered from the photo-element were fed to a two-channel digital oscilloscope Tektronics TDS 3032 or to four-channel digital oscilloscopes LeCroy WJ-324 or Tektronics TDS 3054C, which allowed to register radiation pulses, GDT voltage and current through the GDT in-phase. The average radiation power was registered by power meters Ophir 20C-SH and Ophir 30C-SH. The study of radiation spectrum of the active element, as well as a background light source in the spectral range of 350 nm to 1000 nm was carried out with a spectrometer produced by Ocean Optics USB4000-VIS-NIR-ES. Images were registered with high-speed cameras MotionPro X3 and Fastcam HiSpec 1.

A distinctive feature of the designed instrument is the possibility of obtaining images generated in real time mode by a single pulse of the amplified spontaneous emission (ASE) of the brightness amplifier, which required the use of a synchronization circuit of radiation pulses with the camera. The synchronization system allowed to obtain pulses with the frequency which is multiple to the ASE frequency of the brightness amplifier that made possible to change the frame rate of the investigated process. Fig. 2 shows the principle of operation of the synchronization circuit.

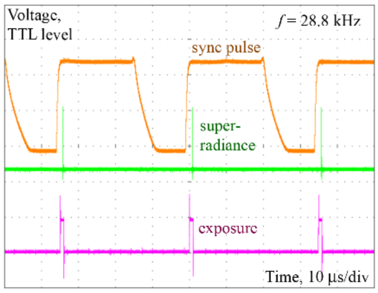

Fig. 2. The principle of operation of the synchronization circuit

As test objects in the first experiments we used metal grids which were hidden from observation by the candle light with a brightness temperature of about 1000 K (Fig. 3) or by the radiation of d.c. arc with argon buffer gas (T=10000 K) passing through it. As we expected, the background light between the object and brightness amplifier did not practically affect the image quality.

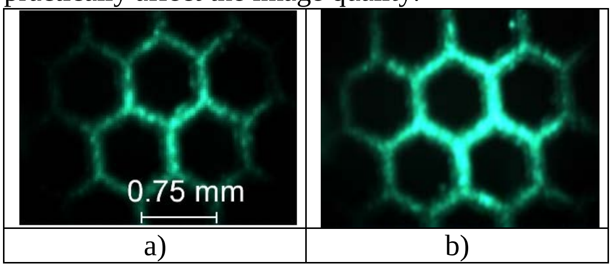

Fig. 3. The image of the test object with different camera exposure: a) 2 μs, b) 40 μs.

In addition to the visualization of static objects, we also visualized the real-time combustion process in the Bengal candle flame. The results are shown in Fig. 4.

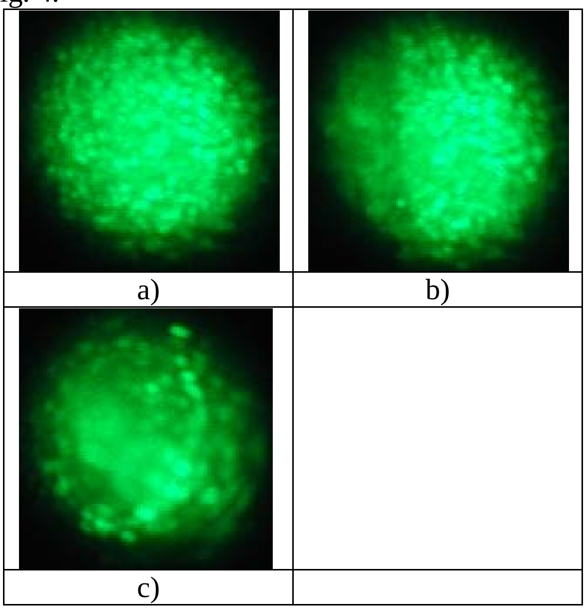

Fig. 4. Visualization of Bengal candle combustion process: a) beginning of combustion, b) combustion, c) end of combustion.

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The use of diffraction grating as an object allows to obtain the limiting spatial resolution of 0.5 microns.

3 Visualization of SHS-processes

This work is performed in collaboration with colleagues from the Department of Structural Macro-Kinetics of Tomsk Scientific Center SB RAS (Dr. Kirdyashkin et al.)

Using the designed laser monitor a series of experiments on visualization of various SHS structures were made. As one of the structures, mixture (65%$FeTiO_3$+35%Al)+35% of kaolin was studied.

a)

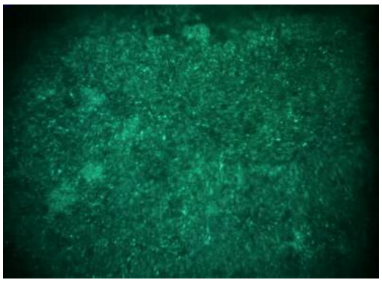
b)

c)

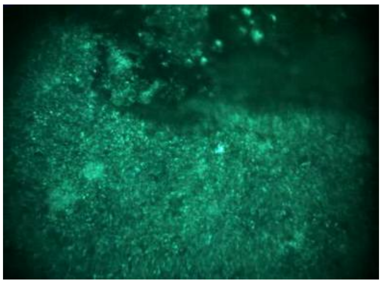
Fig. 5. SHS-structure combustion: a) beginning of combustion, b) combustion, c) end of combustion.

Fig. 5 shows the processes of ignition (a) and combustion (b and c) of the mixture. The combustion process is obscured by its broadband background radiation with the temperature above 1700 K. It is evident that the analysis of structural transformations using conventional visualization methods is impossible.

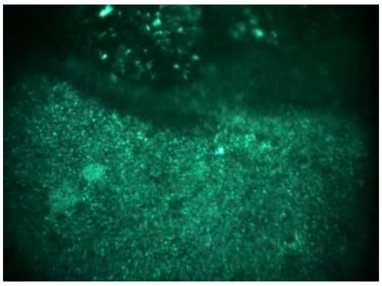
Using a laser monitor the dynamics of the process (Fig. 6) was observed. In the experiments, the frame rate was 2808 frames/sec., and the field of view was 1.5 mm. Using laser monitor the dynamics of the process (Fig. 6) was observed. In the experiments, the frame rate was 2808 frames/sec., and field of view was 1.5 mm.



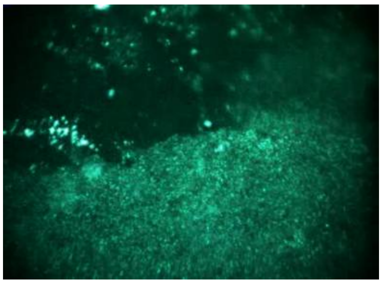
0 ms



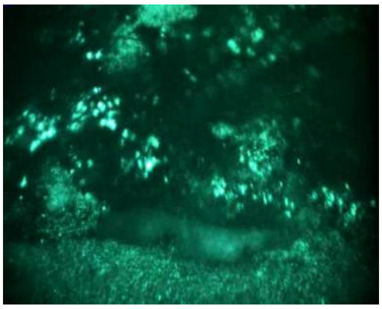
210 ms



250 ms



470 ms



550 ms

Fig. 6. Visualization of SHS-structure combustion process.

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The visual analysis of the results allowed us to determine the characteristics of the combustion process of such a structure. It is seen that the burning takes place unevenly. At the initial stage, the surface material is absorbed (upward movement) and pores are being formed. Then the next part of the structure is heated. After a certain time the process is repeated. The time delay is likely to be specified by the increase in the temperature from the center towards the surface and the thickness of the sample.

The results correspond to those obtained by other methods and allow to analyze the structural transformations in different phases of the process and to estimate the rate of the SHS process [12].

4 Visualization of corona discharge in air at atmospheric pressure

This work is performed in collaboration with colleagues from the Institute of High Current Electronics SB RAS (prof. Tarasenko et al.).

The corona discharge in air at atmospheric pressure was studied. The discharge was formed by a high-voltage pulse generator. The generator formed voltage pulses which consisted of separate trains with the duration of 10 ms and the frequency of 50 Hz. Each train consisted of a sinusoidal signal with an oscillation frequency of 290 kHz. A high voltage electrode was made of copper. When the ground electrode was removed at a distance of 40 cm from the tip or farther, a corona discharge was formed.

To study the dynamics of the discharge the radiation was brought to the high-speed camera Fastcam HiSpec 1 either directly or after passing through the high-speed brightness amplifier (laser monitor mode). In the first case, the total duration of pulses corresponded to the duration of modulated voltage pulses. In the second case, to increase the image contrast we set the mirror behind the object. The frame rate of 2665 frames per second was used, and each frame was formed during the time corresponding to the ASE pulse width of 40 ns. The visualization results obtained with the laser monitor are shown in Fig. 7. In the second image (375 microseconds) the end of the diffuse channel formation is indicated by the arrow. In the experiments, the duration of the voltage pulse train was 10 ms, the amplitude of the pulses in the train was up to 300 kV and the duration of one pulse in a train was 1 ms.

Fig. 7. The visualization of corona discharge using the laser monitor [13].

The data obtained with a laser monitor extend the knowledge of the development of the corona discharge. In particular, it is possible to estimate the speed of propagation of a diffuse discharge, which is equal to 16.3 m/s. It appeared to be much higher than the speed of the thermal expansion of the channel, which was estimated when the discharge was recorded directly, that is without a laser monitor.

It can be seen that the laser monitor allows us to visualize processes that occur during the evolution of the corona discharge and to study their dynamics. In particular, using frame-by-frame imaging it is possible to calculate the velocity of the discharge evolution and thermal expansion of the discharge channel.

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5 Visualization of laser-surface interaction. Nanoparticle production process

Another area of laser monitor applications can be the production of nanoparticles of refractory oxides obtained by the laser ablation of the target, which requires the visualization of processes hidden from viewing by the intense background light. To study the dynamics of a cloud of nanoparticles we can illuminate the laser torch by a high-power light source and register the scattered light. And the influence of the glow of the torch can be reduced by a bandpass filter. This method is called laser illumination [2]. For this purpose, it is suitable to use a copper bromide laser which can generate laser pulses with the duration of tens of nanoseconds at a repetition rate up to 700 kHz [14]. The use of the laser monitor with a copper bromide brightness amplifier allows to almost get rid of the background light.

For the evaporation of targets and formation of a laser torch, the fiber laser LS-07N (l=1070 nm) generating a single squared wave pulse of radiation with the pulse power of 720 W and the duration of 200 µs to 4 ms was used. Part of the work was carried out at the Institute of Electrophysics, Ural Branch of Russian Academy of Sciences in cooperation with the Laboratory of Quantum Electronics and Institute of Atmospheric Optics SB RAS [15]. To visualize the processes of nanomaterials production we used a compact copper bromide laser (and the laser monitor on its base) with a semiconductor pump source.

Fig. 8 shows the results of the study of the torch dynamics, which is formed by the evaporation of a semitransparent target 1%$Nd:Y_2O_3$ with the absorption index 30.7 cm^{-1}, with CuBr-laser illumination at two wavelengths 510.6 nm (green) and 578.2 nm (yellow) without using a bandpass filter. During first 300 µs from the initial moment of the torch formation after the impact its own glare is so high which makes it impossible to determine its structure and dimensions. Only at the time of 296 microseconds on the upper tip of the torch there appear some glowing yellow-green drops which gradually become larger. After the end of the fiber laser pulse, i.e. 1370 µs later after the moment the evaporation has started, the glare of the laser torch sharply reduces. In the images, we can clearly see the clouds which scatter mainly green light (because the illumination power at this wavelength is 2 times higher than at the yellow one).

At the second stage of experiments we investigated the dynamics of a laser torch using a laser monitor. Fig. 8,b shows the shadow images of the laser torch, where its own glare does not interfere with the observation. This allows to view the structure and dynamics of the torch, including the initial period of its development.

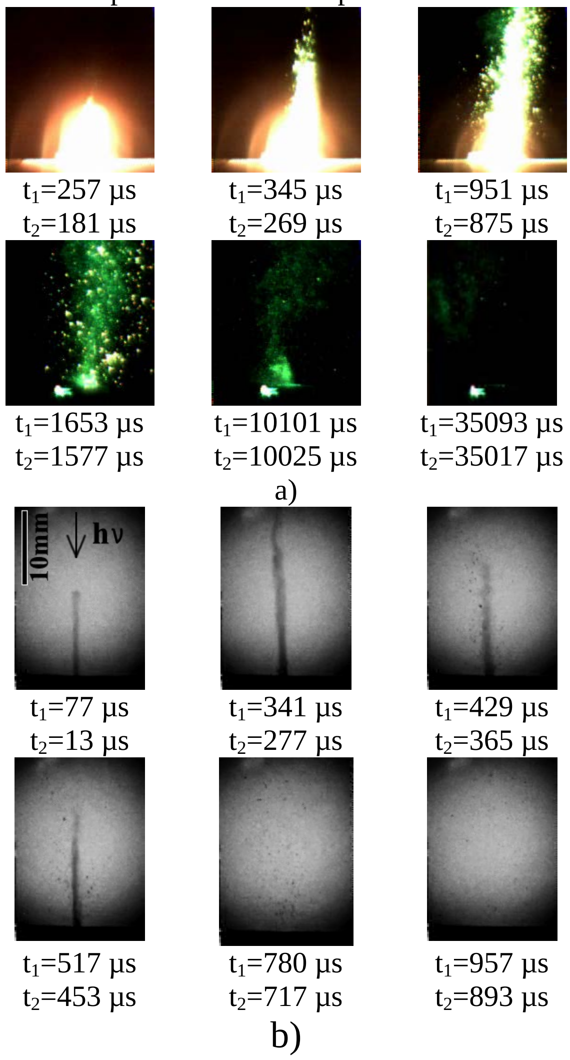

Fig. 8. The laser torch dynamics: t_1 – beginning of laser pulse, t_2 – beginning of the torch; a – in scattering light, b – laser monitor.

Thus, the use of the laser monitor with a high-speed copper bromide vapor brightness amplifier allows to completely filter laser torch glare and to study its dynamics.

6 Remote object visualization

In typical conditions the half-amplitude pulse duration of a copper vapor laser is (15 - 20) ns and for a halide copper vapor laser it is (30 - 40) ns. When the medium amplifies the input signal and its level is sufficient for obtaining the contrast image, the maximum distance to the object of observation is 7 - 8 m. In practice this distance is shorter as the

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gain decreases by the end of the pulse and the level of the input signal in the optical scheme reduces.

In the paper [16], we analyzed the use of a monostatic laser monitor scheme based on CuBr-amplifier with a typical pulse duration (and thereby the gain) for imaging remote objects. The increase in the distance between the object and the brightness amplifier in the scheme of the laser projection microscope leads to the increase in the time delay between the beginning of the ASE pulse and the moment of the arrival of the signal reflected from the object. It is obvious that when the time of the input signal arrival onto the amplifier changes the image energy reduces and the background energy (amplified spontaneous emission) increases. As a result, the image contrast also reduces.

In this work, as an object we used a mirror with a slit, which size was regulated by a micro-screw. Fig. 9 shows the results of imaging the object placed at a different distance from the amplifier and the laser pulse waveforms. The dotted line indicates ASE pulses without the object, whereas the solid line shows the ASE pulse with the object placed in the optical scheme.

For Fig. 9 the time delay between the beginning of the pulse and the input signal of the brightness amplifier is 2.6 ns. In this case, the obtained image has its maximum contrast. The radiation energy with an object located in the scheme is two times higher than the ASE energy. At a distance of 3.3 m (Fig. 9,b) the temporary misalignment between the beginning of the ASE pulse and the signal reflected from the object is 22 ns. Less than half of the reflected signal is brought to the active medium at the time when it is amplifying because of this time delay. Thus, the object is hardly distinguishable from the background, the spontaneous emission of the amplifier.

The placement of a quartz planar wafer into the optical scheme of the laser monitor allows to obtain lasing at the output of the brightness amplifier. This ensures the increase in the energy and decrease in the divergence of the radiation illuminating the object. As a consequence, the object is clearly visible at a distance of 3.3 m, and even discernible at a distance of 4.25 m, where the gain is insignificant, and the image contrast is low.

Thus, the monostatic scheme of the laser monitor based on a copper bromide amplifier can be used for the diagnostics of objects placed at a distance of 3 m. For the visualization of remote objects located at greater distances, it is necessary to either increase the pulse duration, or to design a bistatic laser monitor scheme consisting of an illumination laser and an amplifier.

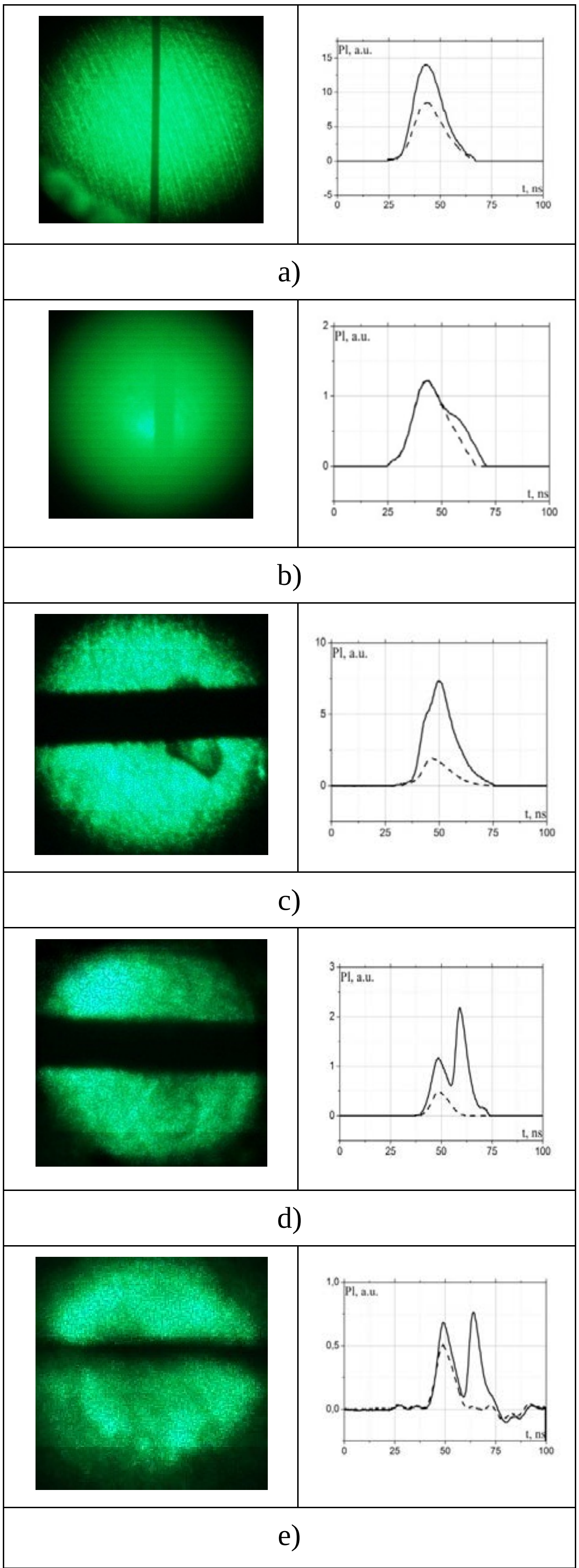

Fig. 9. Results of object visualization placed at different distances from brightness amplifier: a, c – 0.4 m, b, d – 3.3 m, e – 4.25 m; a, b – usual

scheme, c, d, e – with quartz planar wafer.

7 Conclusion

We have shown that the visualization method and instrument based on brightness amplifiers (laser monitor) allow to perform non-destructive testing of fast processes through the intense glare. It is also possible to monitor these processes even when the use of the laser illumination method proves to be inefficient. The spatial resolution of the monitor is 1 µm, with the time resolution being 10^{-5} s. The results obtained by different research groups suggest that high-speed brightness amplifiers (and laser monitors based on them) need further research in improving the instruments and methods for processing materials and widening the range of their applications as well.

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