



# Bistatic laser monitor for imaging objects and processes

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## Abstract

The laboratory model of a bistatic laser monitor which images objects and processes with amplified brightness is presented. The bistatic laser monitor is a laser active optical system, which includes two active elements. There are illumination source and optical signal converter (brightness amplifier) with pumping sources and a high-voltage modulator for synchronization of their operating modes. The illumination source and the brightness amplifier are based on active media in copper bromide vapors. The dependence of the image quality on the time lag between amplification and illumination pulses is determined. The parameters of images formed in monostatic and bistatic laser monitors are compared. The results of process imaging under background radiation conditions with the laboratory model developed are presented.

## 1 Introduction

The development of modern imaging methods and visual optical diagnostic equipment is among topical problems of photonics. They allow the study of burning processes, discharge generation and evolution, interaction of the powerful energy flows with matter, etc. Modern high-speed digital recording devices (video cameras) provide a high-time resolution and a possibility of processing and saving big data volume and make it possible to study such processes. Powerful background radiation obstructs process imaging, which is one of the features of these processes. It is necessary to suppress this radiation, for example, by means of laser illumination with an optical signal (image) filtration (spectral and temporal) [1]. Narrowband radiation sources (lasers) are used for illumination; high-speed video camera with a small exposure time provides a temporal filtration. This method is passive since the optical signal energy decreases while passing through optical components. This imposes limitations and requirements to the components of diagnostic equipment. In addition, the intensity of background light, its spectral composition, and the distance to

object under observation determine the possibility of using laser illumination.

There is another approach to investigation of such processes. It is based on application of active optical systems with the metal-vapor brightness amplifiers, which are used for optical imaging [2, 3]. The device is called a laser monitor [4–6]. CuBr-vapor laser monitors were shown to image processes hidden by a background light with a brightness temperature of up to  $45 \cdot 10^3$  K and temporal resolution up to  $10^{-5}$  s [7–9]. Such systems allow one to study manufacturing processes of new nanomaterials, surface modifying, etc. It is shown [10] that laser monitors allow imaging processes running on the surface of carbon electrodes at a temperature of about 4000 K. The study of laser metal welding, self-propagation high-temperature synthesis, nanopowder production with active optical systems (laser monitors) is described in [11–14]. The imaging systems used in these works have a feature, that is, the illumination and amplification functions are performed by a brightness amplifier. This makes impossible independent adjustment of illumination and amplification parameters and an increase in the distance between an object under study and a laser monitor [15, 16]. This disadvantage can be overcome by separation of illumination and amplification functions between two active elements [17]. Such an approach allows one to vary the illumination energy and the gain factor and image an object at a large distance. A possibility of imaging with the use of two CuBr active media is shown in [18]. Moreover, the separation of illumination and amplification functions between two active elements allows to build the imaging systems (laser monitors)

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with the absence of restrictions on the distance to a studied object. The maximum distance to the object which can be imaged in the monostatic laser monitor is determined by the super radiance (amplifies spontaneous emission—ASE) pulse duration. During this time, light from the active media should illuminate the object and the reflected signal should come into the active zone, i.e., ASE pulse duration should be more than the doubled time of light movement from the active media to the object.

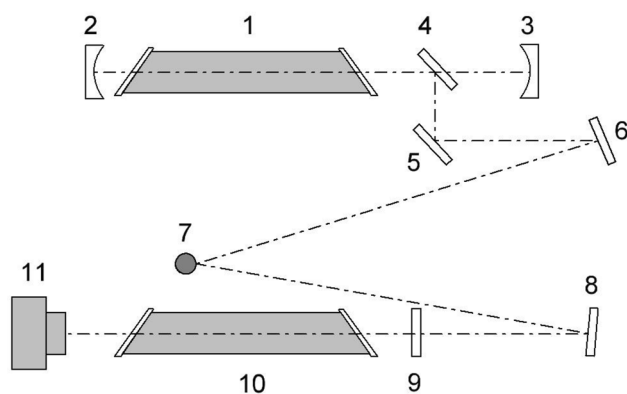
This paper represents the results of design and test of a laboratory model of laser active optical system (LAOS) with an independent illumination source—a bistatic laser monitor. The influence of its operating mode on the image quality is analyzed.

### 1.1 Experimental technique

The laboratory model of bistatic laser monitor is shown in Fig. 1.

A CuBr-laser is used as illumination source 1. Spherical mirrors 2 and 3 form an unstable telescopic cavity with lateral radiation output by means of apertured mirror 4. The radiation is guided to object 7 by mirrors 5 and 6. A reflected beam is guided by mirror 8 to lens 9, which forms an optical image. Next, the signal propagates through the active media of CuBr brightness amplifier 10. The image with enhanced brightness is projected to camera 11, which allows recording it with a digital video camera.

Both active elements of the bistatic laser monitor (illumination source and brightness amplifier) are CuBr-vapor active media with independent heaters of the GDT active zones, HBr generator, and containers with CuBr [19]. Each active element has its own pump source with pulse charging of the storage capacity and following discharging through a thyatron (gas triode with a hot cathode) [20]. The length and diameter of the active zone of the illumination source



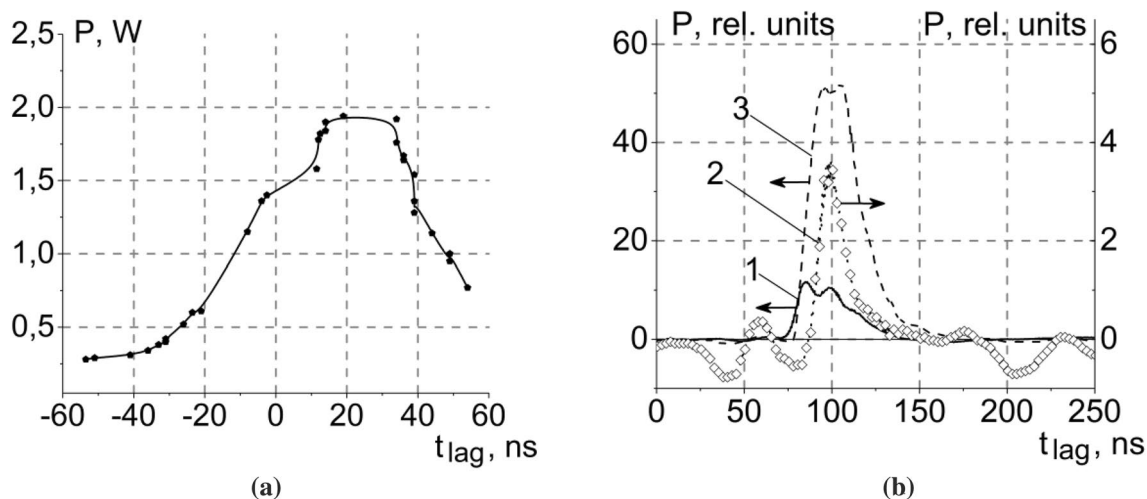
**Fig. 1** Diagram of the bistatic laser monitor: illumination source (1); spherical mirrors (2 and 3); apertured mirror (4); mirrors (5, 6, and 8); object (7); lens (9); brightness amplifier (10); camera (11)

gas-discharge tube (GDT) were 90 cm and 5 cm, respectively. The pumping power was 1.85 kW with the use of the storage capacitor with capacitance of 1100 pF. The laser provided the maximum radiation power of 8.2 W (with the plane-parallel cavity) at a PRF of 16.7 kHz. The length of the brightness amplifier active zone was 30 cm and the diameter 4 cm. The pumping power did not exceed 1 kW, the capacitance of the storage capacitor was also 1100 pF. The element with the plane-parallel cavity provided the maximum power of 2 W. The operating modes of the brightness amplifier and the illumination source are synchronized by a high-voltage modulator. The modulator produces control signals for thyratrons of the illumination source and brightness amplifier with an adjustable time lag between them. The adjustment of the time lag is discrete. To determine the value of the time lag, it is necessary to modify the optical system: object under observation 7 should be changed to a mirror and lens 9 should be removed. This scheme is a MOPA system [21], which consists of a master oscillator (MO) and a power amplifier (PA). The dependence of the output power on the time lag between the oscillator and amplifier pulses is shown in Fig. 2a. The light pulses are recorded by coaxial photocells (FEC-22SPU-M); one of them is located on the place of object 7 and the second replaces video camera 11. In addition, a plane-parallel plate is mounted before the first coaxial photocell; as a result, a part of radiation passes through it and is recorded by coaxial photocell, and another part is reflected to mirror 8, as shown in Fig. 1. Both coaxial photocells are connected to an oscilloscope to record the oscillator and amplification signals. The time lag between pulses should obviously be determined from the waveforms, but the distance between object 7 and amplifier 10 is to be taken into account. Besides, there is hardware delay due to the equipment used. The object under observation and one of the coaxial photocells are distant 2 m apart from the amplifier. This means that a signal from the oscillator is 6 ns late. The use of another recording device and electrical cables can change the hardware delay; therefore, it is unnecessary to find the equivalent time delay for each specific case.

Figure 2a shows that the maximal output power of the bistatic laser monitor attains 1.92 W at a time lag from 12 to 34 ns. The waveforms of the optical signals are shown in Fig. 2b. It is known that there is an optimal time lag, which ensures the maximal output power of a MOPA system. It is important to determine the influence of the time lag on the image quality in the LAOS.

### 1.2 Experimental study of the laser active optical system

The bistatic laser monitor was used for imaging test objects and processes hidden by background radiation. A metal ruler was used as a test object. The optical scheme is shown in



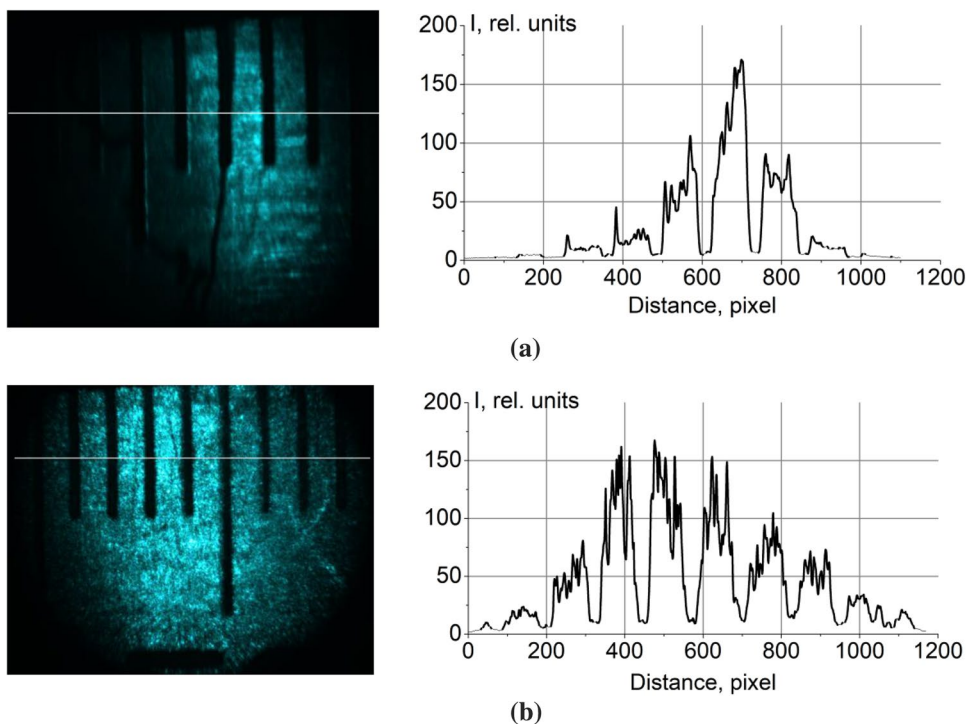
**Fig. 2** **a** Dependence of output power on the time lag; **b** waveforms of master oscillator (1) and amplifier superradiance pulses (2) and amplified signal (3) at a time lag of 19 ns

Fig. 1. The imaging results in monostatic (a) and bistatic laser monitor (b) are shown in Fig. 3, along with the intensity distribution along a horizontal line. In this case, the time lag in the bistatic laser monitor equals 19 ns. The ImageJ software package was used for the mathematical processing of images [22].

Each frame was formed by one brightness amplifier pulse [7]. It should be noted that the optical scheme was not modified while imaging in the both schemes of the laser monitor.

The illumination source radiation was overlapped for imaging in the monostatic laser monitor. The image quality is obviously better in the bistatic laser monitor at the same distance between the object and the brightness amplifier. The analysis of the intensity distribution along the horizontal line shown in Fig. 3 shows approximately 40% increase in the field of view. It is possible to observe five marks of the ruler without the illumination source and eight lines with it. The local contrast increases by 40%. The background intensity

**Fig. 3** Imaging results for the object under observation in **a** monostatic and **b** bistatic laser monitor



remains unchanged, i.e., about 10% black (grayscale). The brightness of the polished ruler surface image almost doubles. Despite all the advantages, the image obtained in the bistatic laser monitor has a pronounced speckle structure, which can adversely affect the image processing. It is caused by a high monochromaticity of the illumination in this case.

Then, the ruler was imaged at different time lags between illumination and amplification pulses. The results are shown in Fig. 4.

The image quality is very similar at time lags of 12 and 34 ns. This is consistent with the fact that the output power of the brightness amplifier remains almost unchanged at time lags of 12 and 34 ns (Fig. 2a). The local contrast (Weber) varies from 7.6 to 8.3 in the 250–400 pixel range for these images. The contrast is 2.8 for the image formed with a time lag of  $-8$  ns. It should be noted that the background intensity (250–275 pixel range on the intensity distribution plots) increases from 8% ( $t_{\text{lag}} = -8$  ns) to 11% black ( $t_{\text{lag}} = 12$  and 34 ns). The increase in the background is, in our opinion, due to the growth of the gain factor (Fig. 2a), which affects the amplification of a weak signal from the dark object region. Thus, the image quality is identical at time lags of 12 and 34 ns between the illumination and amplification pulses. But it is necessary to study the dependence of image quality on the time lag in the range from 12 to 34 ns. It requires the development of a high-voltage modulator with a slow adjustment of the time lag.

As is noticed before, active optical systems with brightness amplifiers allow imaging objects and high-speed processes under background radiation conditions. As a part of the work, the process of self-propagating high-temperature synthesis of FeO–Al–Al<sub>2</sub>O<sub>3</sub> structure was imaged [23]. The mixture was previously studied with the use of monostatic laser monitor [7]. The synthesis was recorded with an AOS Q-PRI video camera, with a sync rate of 4000 frames/sec and a field of view of 3 × 3 mm; the camera exposure was minimal and equaled 2 μs. The imaging results are shown in Fig. 5.

The recorded frames allow us to estimate the qualitative and quantitative parameters of the combustion process. The burning rate has been estimated; it agrees with the studies of the synthesis processes of porous composite materials [23]. The width of the combustion front is also determined. The resulted images are to be used for estimation of processes of structural transformations during the reaction.

In the experiment, the distance from the object to the amplifier was varied from 1 m to 3 m. In all cases, the image quality was the same, which is impossible to get in the monostatic laser monitor [16]. As it was noted, the monostatic laser monitor has the restriction on the distance to the registered object. The theoretical maximum distance for the typical CuBr amplifier with the ASE pulse duration of 40 ns is about 6 m. According to our experimental work [24],

increasing of the distance leads to the decrease of the image quality, and losing in contrast. In the presented monitor, the decreasing of the image quality with the increasing of the distance is not observed. Actually, the maximum distance for imaging in the bistatic laser monitor determines by the maximum time delay between illumination and amplification. This restriction is the technical one and can be solved by the use of the synchronization circuit with the unlimited delay time.

## 2 Conclusions

A laser active optical system (LAOS), a bistatic laser monitor, is presented. The system consists of an illumination source and a brightness amplifier. Its feature is a possibility of imaging objects with enhanced brightness under background radiation conditions. This is achieved due to a high spectral brightness of the amplifier. The bistatic laser monitor has a number of advantages over a monostatic laser monitor and can be used for imaging objects and processes hidden by a background light. The illumination and amplification functions are separated between two active elements, which allows us to independently change the parameters of input signals and the amplification.

The field of view of the bistatic laser monitor is 40% higher than of a monostatic monitor with a constant optical scheme for imaging. The pronounced speckle structure of the images formed is one of the drawbacks of the bistatic laser monitor. It has been experimentally found that the image quality is the highest at time lags of 12 and 34 ns. This range allows us to gain the maximum output power in the MOPA system. The laboratory model of the bistatic laser monitor was used for imaging self-propagation high-temperature synthesis. The background radiation with a brightness temperature of about 2000 K did not distort the images.

One of the important features of the bistatic laser active optical system for imaging (bistatic laser monitor) is the absence of the restriction in the maximum distance between the observing object and the amplifier. The technical limitation is the time delay between illumination and amplification pulses. It provides by the illumination and amplifications functions separation. The use of the synchronization circuit allows to obtain the images with high quality by the optimization in the time of input signal coming and the amplification of the amplifier.

It should be noted that the use of a modulator allows us to choose only four discreet values of the time lag in the range specified: 12, 14, 19, and 34 ns. The absence of fine time lag adjustment does not allow a detailed study of the amplifying characteristic of the system. Hence, it is necessary to design a high-voltage modulator with a possibility of adjusting time

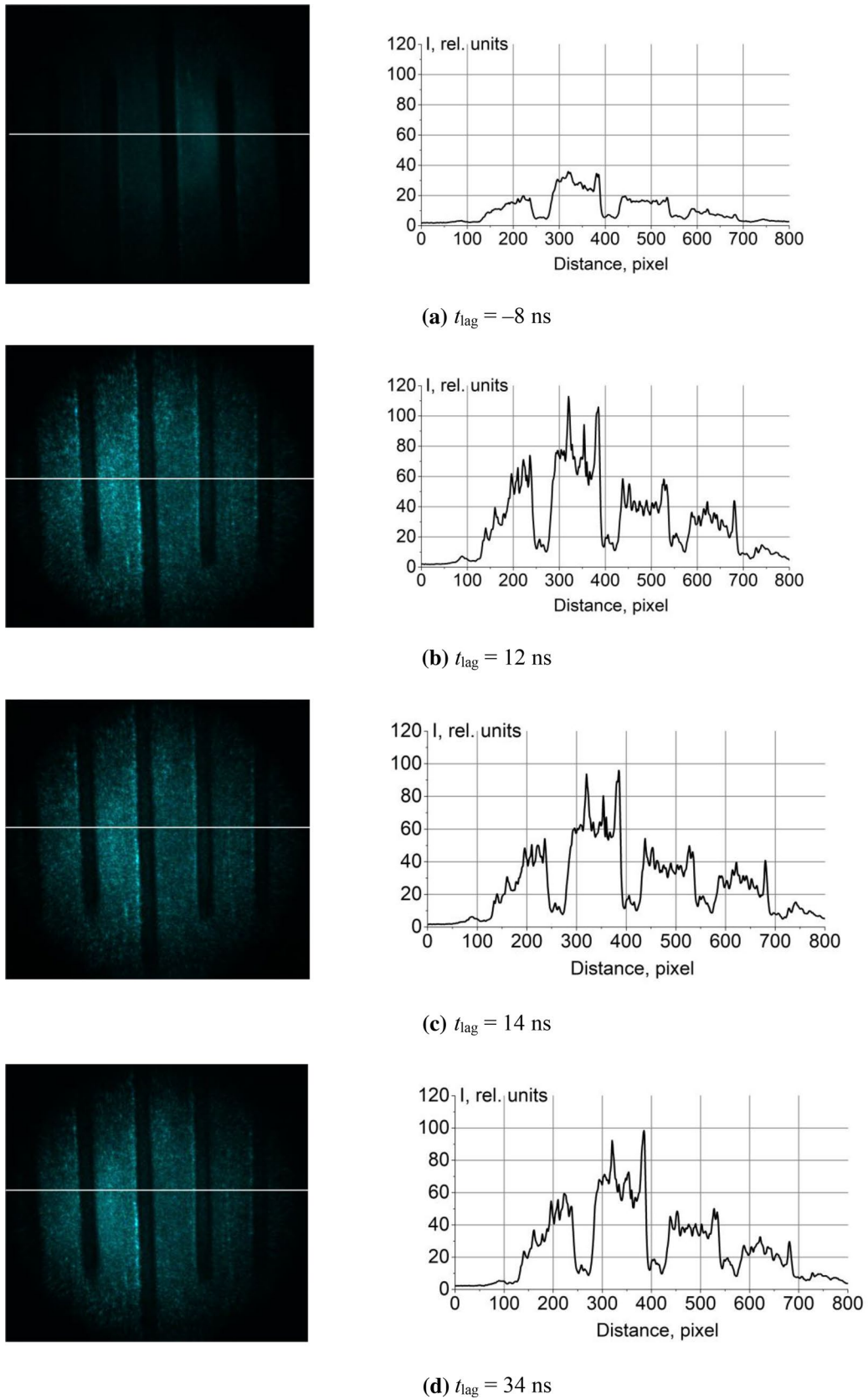
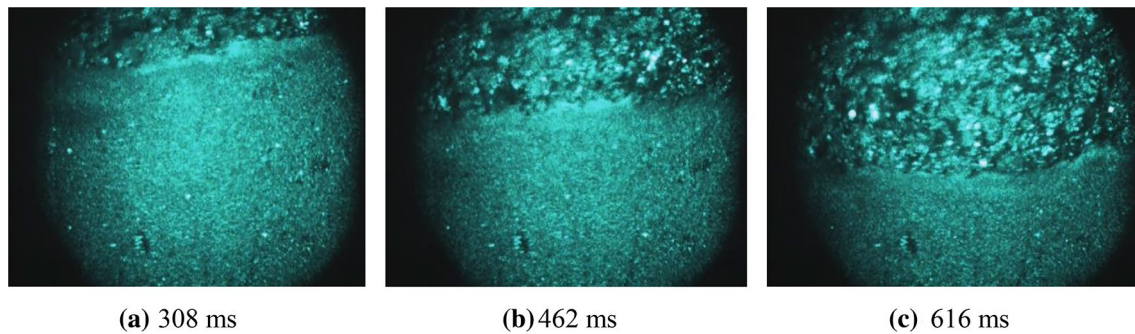


Fig. 4 Imaging of the test object in the bistatic laser monitor at different time lags between the illumination and amplification pulses



**Fig. 5** Images of self-propagating high-temperature synthesis

lag with a step of no more than 2 ns in a time interval on the order of a lasing pulse length (40 ns).

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