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Copper bromide vapor brightness amplifiers with 100 kHz pulse repetition frequency

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ABSTRACT

The paper presents a laser monitor with 10 μs time-resolution based on a high-frequency copper bromide vapor brightness amplifier. A sync circuit has been designed for single-pulse imaging. The analysis of amplifying characteristics of the active elements and active optical system (laser monitor) parameters allowed to determine the optimal concentration of HBr at which the images can be obtained with minimum distortions. For the active element operating at high frequencies (more than 50 kHz) as a brightness amplifier, the concentration of HBr must be lower than that needed for obtaining the maximum output power. The limiting brightness temperature of the background radiation which does not affect the image quality is determined. The potential feasibility of using a proposed brightness amplifier for visualizing processes blocked from viewing by the background radiation with the brightness temperature up to 8000 K is demonstrated.

1. Introduction

Laser and plasma methods are actively used in the production of new materials, including nanostructured materials, and the modification of materials properties [1]. The cost-effectiveness of these technologies is of great importance. In most cases the methods are based on the interaction of intense energy fluxes with matter. In this case visual and optical monitoring of energy-matter interaction is often blocked by the background radiation, or glare. This radiation can be of different origin, for example, equilibrium and non-equilibrium plasma, intense magnetic field, ionizing field, etc. For visualizing processes through the glare it is necessary to use laser diagnostic methods that allow to reduce its effect on the obtained images [2].

One of the best examples of optical systems used for visual and optical monitoring of processes and objects are active optical systems (AOS) with metal vapor brightness amplifiers - laser projection microscopes and laser monitors [3–18]. These systems have a number of advantages that make them an ideal instrument for visualizing fast processes in a real-time mode [19,20]. In [3–7] the results of the use of systems with brightness amplifiers for obtaining images of micro-objects on a big screen are discussed. In other works [8–18], the authors consider the possibility of using active optical systems for monitoring objects and processes blocked by the background radiation. In [11–12] the possibility of imaging of such processes at a speed record for that time is shown. All the results mentioned above refer to the time of the early stage of the development of high speed imaging equipment. When high speed cameras appeared it became possible to take advantage of all the benefits of active optical systems based on metal vapor brightness amplifiers. The use of them allows to perform high speed real-time imaging of the processes through the glare [10,13–16]. Prof. I. Klimovsky called this instrument 'laser monitor' [10]. A laser monitor is an active optical system intended for high speed imaging, whereas a laser projection microscope was utilized for obtaining images of micro-objects on a big screen. Contemporary research papers on the use of laser monitors mostly focus on the imaging of objects and processes obscured by the intense background radiation. In particular, in [16] the processes on the surface of graphite electrodes are visualized through the arc combustion. The use of a laser monitor made it possible to obtain new data, in particular those about a cathode spot, and determine the conditions for laser welding when the weld seam has the least number of defects [17]. There are also several theoretical works focused on the use of optical systems with brightness amplifiers for the diagnostics of processes in a thermonuclear reactor [18]. In all the works mentioned above the active medium of the metal vapor laser operating in a pulsed-periodic mode was used as a brightness amplifier [21,22]. In [16] the maximum frame rate was 16,000

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frames per second, which was limited by the maximum pulse repetition frequency (PRF) of a certain brightness amplifier.

In [23] active optical systems with copper bromide vapor brightness amplifiers are discussed, and the influence of HBr addition on amplifying characteristics of the active element is studied. One of the key ideas in [23–26] is that the copper bromide vapor medium can operate effectively at a relatively high PRF and thus the time resolution of a laser monitor based on such a brightness amplifier will be higher than that of a copper vapor laser monitor [20,27]. In spite of the fact that the maximum PRF of the copper bromide vapor laser is 700 kHz [28], there are no data in literature concerning the design of a brightness amplifier with a PRF of 50 kHz and higher.

The issues of development, research, optimization and use of high frequency brightness amplifiers a laser monitor is based on are discussed in this paper.

2. Experimental setup

In this work, a copper vapor bromide active element with the active length of 50 cm and bore diameter of 2.5 cm was used. The buffer gas (neon) pressure was 25 Torr. The construction of the active element was similar to that demonstrated in [29]. The tube wall, containers with copper bromide and HBr generator were heated by independent external heaters which stabilized the temperature as the pumping rate was varied. The laser was pumped using a direct discharge circuit on a storage capacitor. Tacitron TGU1-1000/25 was used as a commutator. Images were registered by the following photo- and video cameras: Casio EX-FH20 with the frame rate of 1000 frames per second, high-speed cameras MotionPro X3 with the frame rate of 40,000 frames per second and FastCam HiSpec1 with the frame rate up to 100,000 frames per second. The optical schemes were constructed using different objectives (standard micro-objectives of different magnification factors, objective Industar-51, etc.), the optical elements were positioned using optomechanical equipment made by Standa.

A typical configuration of a laser monitor is given in Fig. 1. The algorithm presented in [30] was used to calculate the laser monitor optical scheme. A test object is illuminated by the ASE of the brightness amplifier, and the reflected radiation is amplified throughout the same radiation pulse of the amplifier. The gray filter was used for reducing the level of the output signal, which protected the camera from damage. To register the image at one of the wavelengths of the brightness amplifier it is necessary to use the band-pass filter. This is referred to as the monostatic imaging configuration. As test objects in this work we used metal grids, optical miras and others. In the experiments, the glare with the brightness temperature of the combustion process of 5 kK was produced using the DC arc [31]. Images formed by single ASE pulse were processed with the ImageJ program [32]. Radiation spectra were registered using USB spectrometer of the company Ocean Optics USB4000 – VIS – NIR – ES (it covers the 350–1000 nm range), the pulses were registered by Tektronix 3054C oscilloscope.

3. High frequency brightness amplifiers based on metal halide vapors. Laser monitor with 10 μs time resolution

For designing a laser monitor with the time resolution of up to 10 μs it is necessary to construct a brightness amplifier with a PRF of 100 kHz (high frequency amplifier) [33,34] and use the single-pulse imaging technique (referred to as 'frame-by-frame' imaging in a number of papers) [31,35]. For frame-by-frame imaging it is essential to make a sync circuit for a high speed camera. Previously in [35] the authors designed a circuit for single-pulse imaging with the maximum PRF of sync pulses of 50 kHz. In this work, the circuit synchronizing the operation of a high speed brightness amplifier and a high speed camera is built using STM32F1 microcontrollers. Fig. 2 shows the waveforms for the AOS operation at different maximum time resolutions that depend on the PRF of the brightness amplifier, where 1 is a sync pulse, 2 is a pulse of the camera exposition, and 3 is an ASE pulse of the brightness amplifier.

As can be seen from the oscillograms, the use of the designed system allows to obtain images in a laser monitor with the time resolution of up to 10 μs. The synchronizing system allows to vary the frequency of sync pulses for a high speed camera, which is multiple of the PRF of the brightness amplifier.

For the brightness amplifier used in this work in the case when HBr is not added, the increase in the PRF from 20 kHz to 60 kHz leads to the decrease in the laser output power from 2 W to 0.33 W. And the diameter of the radiation beam decreases from 1.2 cm to 0.7 cm. This will inevitably lead to the reduction of the field of view in the active optical system based on such a brightness amplifier. The results of the test object (metal grid with a step of 250 μm) imaging at different frequencies of the operation of the brightness amplifier are shown in Fig. 3.

Images were registered by a Fastec HiSpec1 camera. The laser monitor operated in a single-pulse imaging mode [32]. When the frequency was increased from 20 kHz to 60 kHz the field of view decreased by 40% due to the decrease of the gain profile width. The local contrast in the central region of the image reduced from 80% to 33%, which was the result of the decrease in the gain of the active medium. The obtained images had significant distortions, the inhomogeneity of the gain profile became more prominent as the frequency increased. Thus, the increase in the PRF of the brightness amplifier reduces the accuracy of the obtained data.

It is known that in order to increase the rate of plasma relaxation during the interpulse period it is necessary to increase the PRF of metal vapor lasers, which can be achieved using hydrogen-containing additives, in particular HBr [36]. It has been previously stated that the optimal concentration of the HBr-additive for the case when the active element is operated as a brightness amplifier is lower than when it is operated as a generator [37]. To determine the optimal concentration for the given experiment the single-pass gain profile at different HBr concentrations in the active medium has been analyzed. The results of the experiment are

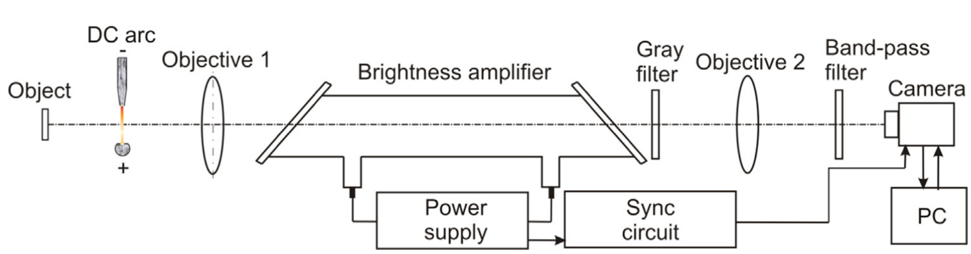

Fig. 1. Single-pulse imaging laser monitor with a sync circuit.