High PRF Metal Vapor Brightness Amplifiers: Research and Applications

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Abstract: The paper presents the experimental and modeling results on obtaining high pulse repetition frequencies (PRF) (more than 100 kHz) of copper bromide vapor brightness amplifiers operating in a low input energy mode. The use of metal vapor brightness amplifiers for visual non-destructive testing of objects and fast processes blocked from observation by the intense background light is also discussed. It has been shown that the imaging method proposed in this paper proves to be the most reliable one for obtaining information about objects or processes in a real time mode using high PRF CuBr active media.

Keywords: active media, laser, pulse repetition frequency (PRF), brightness amplifier, laser monitor, background radiation, imaging.

1 Introduction

At the end of the last century several scientific groups 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 at a pulse repetition frequency (PRF) of about 10 kHz [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 nanostructured ones, 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 as brightness amplifiers 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 important results concerning the imaging 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 studying high PRF metal vapor lasers, designing and using high speed brightness amplifiers based on 100 kHz CuBr-active media for the diagnostics of fast processes through the intense background radiation. Among those are the imaging of the SHS process, the corona discharge in the air, the nanoparticles production process using a high-power fiber laser and etc. [9-11]. The typical duration of such processes ranges from tens of microseconds to tens of seconds. Thus, for imaging of fast processes in a real time mode it is necessary to obtain the PRF of the radiation (amplification) of 100 kHz and more. For the lasers on self-terminating transitions such PRF is not typical [12].

2 High PRF CuBr-vapor laser active medium. Experimental and modeling results.

In [13] the results of modeling of processes in the active medium of the high-frequency copper bromide vapor laser are discussed. The generation for the frequencies of 606 kHz and 513 kHz was obtained, the energy input into the GDT was 90 and 100 uJ/cm^{-3}, respectively. In this case, a low input energy mode is implemented. As the PRF increases up to 1 MHz the accumulation of the basic plasma components (concentrations of electrons and metastable copper atoms) does not disrupt the generation.

For obtaining high PRFs of copper (copper bromide) vapor brightness amplifiers, similarly as in [14], the high-frequency pumping source was designed. The pumping source was designed based on GMI-27B modulator lamp. The lamp was controlled by 12N60NZ high-frequency transistor. The optimal operation mode of the modulator lamp was obtained by adjusting the nets voltages and the heater voltage.

In the circuit, the low input energy mode was implemented by means of decreasing the duration of pumping pulses. In particular, the designed generator formed the pumping pulses with the duration of 20-40 ns (FWHM).

The GDT with a bore diameter of 0.7 cm and an active length of 28 cm was used in this work. The buffer gas pressure was varied from 10 to 100 Torr. Voltage, current and radiation pulses were registered by Tektronix P6015A voltage probe, Pearson Current Monitor 8450 current sensor and FK-22 coaxial photoelement, respectively.

Fig. 1 shows the waveforms of the GDT current, the modulator lamp anode voltage, the drain-source transistor voltage and the brightness amplifier radiation pulse at the PRFs of 357 kHz and 420 kHz.

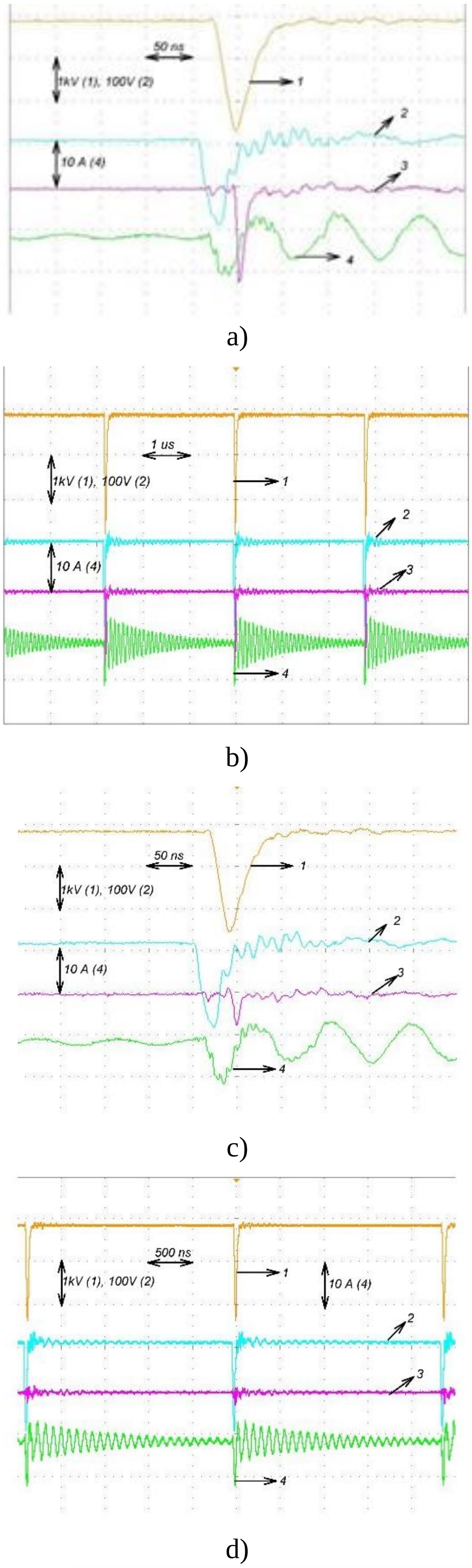


Fig. 1. Waveforms of the modulator lamp anode voltage (1), the drain-source transistor voltage (2) and the brightness amplifier radiation pulse (3) and the GDT current (4) at the PRFs of 357 kHz (a,b) and 420 kHz (c,d).

The results shown in Fig. 1 suggest that at high PRFs the pumping pulse duration (FWHM) does not exceed 50 ns, whereas the current amplitude through the GDT is not more than 15 A. In these experiments, the input energy into the GDT was 36 uJ/cm^{-3} at 357 kHz and 31 uJ/cm^{-3} at 420 kHz.

It should be noted that the low input energy mode can be also provided using low-current discharge mode. This mode requires the modification of the pumping circuit. In a low-current discharge mode, the amplitude current values are several amperes, the voltage falling edge after the breakdown is 10-15 V/ns, and the current slew rate does not exceed 0.01 A/ns, which distinguishes this type of pumping from conventional one used for lasers on self-terminating transitions [15].

The experimental and modeling results show the low input energy mode allows to increase the operating frequency of copper bromide vapor lasers and brightness amplifiers up to several hundreds of kHz.

It is planned to make experiments for obtaining high PRFs using hydrogen containing additives in the active medium of the brightness amplifier. The use of these additives allows to increase the effectiveness of plasma relaxation in the interpulse period. Fig. 2 shows the calculations of prepulse electron concentrations without HBr and with HBr addition of 0.2 Torr to the neon buffer gas at different pumping PRFs. The basis of the modeling is a zero-dimensional model of the active medium. This model includes differential equations describing changes in concentrations of reactants that are in plasma discharge and populations of different energy levels of atoms [16].

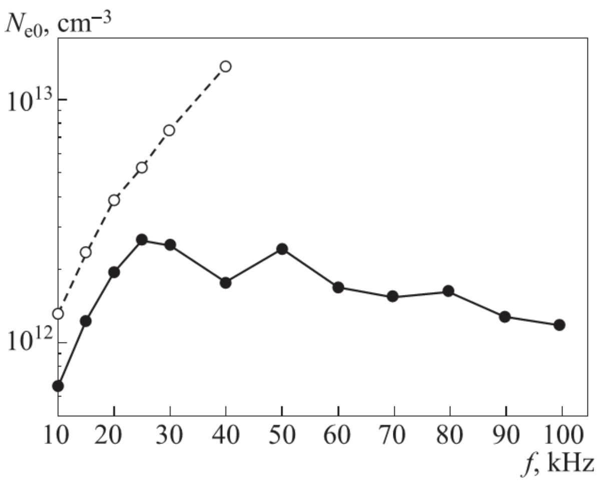


Fig. 2. Prepulse electron concentrations with HBr additives (solid curve) and without HBr additives (dashed curve).

The fast plasma relaxation allows to increase not only the radiation (amplification) PRFs, but also the GDT aperture, which is essential for using them as brightness amplifiers in active optical systems.

3 Laser monitor for visual diagnostics of fast processes in a real time mode.

A simplified optical scheme of the laser monitor is shown in Fig. 3. 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 sync circuit and optical elements.

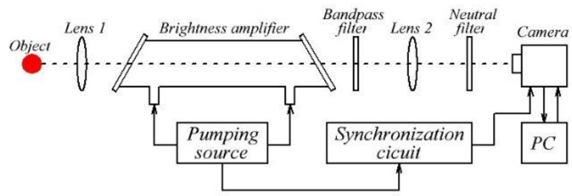


Fig. 3. A simplified optical scheme of the laser monitor

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 [17].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) [12] and capacitive pumping, when electrodes were placed outside the GDT [18].

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 the radiation spectra of the active element and a background light source was carried out with a spectrometer produced by Ocean Optics USB4000-VIS-NIR-ES in the spectral range of 350 nm to 1000 nm. 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 a 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. 4 shows the principle of operation of the synchronization circuit.

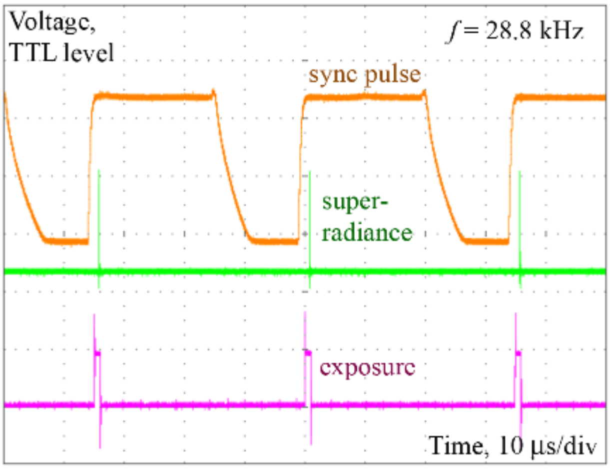
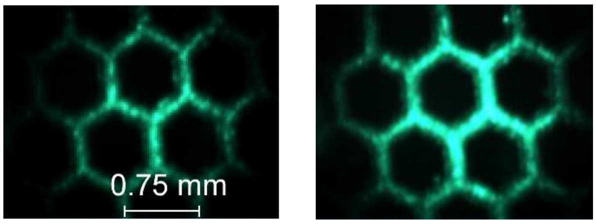


Fig. 4. The principle of operation of the synchronization circuit

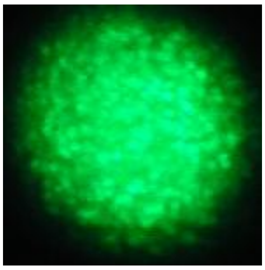
As test objects in the first experiments we used metal grids which were hidden from observation by the candle light with a brightness temperature of about 1000 K (Fig. 5) or by the radiation of d.c. arc with argon buffer gas (T=10000 K) passing through it. As it was expected, the background light between the object and brightness amplifier did not practically affect the image quality.



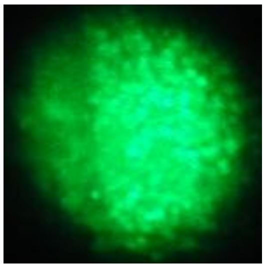
a) b)

Fig. 5. The image of the test object with different camera exposure: a) 2 µs, b) 40 µs.

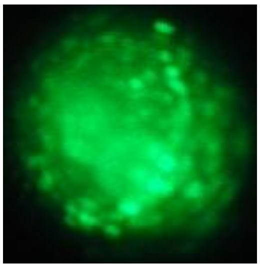
In addition to the visualization of static objects, the real time combustion process in the Bengal candle flame was also visualized. The results are shown in Fig. 6.



a)



b)



c)

Fig. 6. Imaging of Bengal candle combustion process: a) beginning of combustion, b) combustion, c) end of combustion.

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

4 Imaging 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 imaging of various SHS structures were made. As one of the structures, mixture (65%$FeTiO_3$+35%Al)+35% of kaolin was studied.

Fig. 7 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 imaging methods is impossible.

Using a laser monitor the dynamics of the process (Fig. 8) was observed. In the experiments, the frame rate was 2808 frames/sec., and the field of view was 1.5 mm. The dynamics of the process (Fig. 8) was observed with a laser monitor. In the experiments, the frame rate was 2808 frames/sec., and field of view was 1.5 mm.

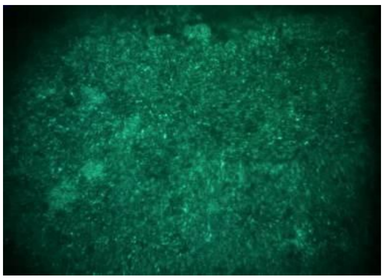
a)

b)

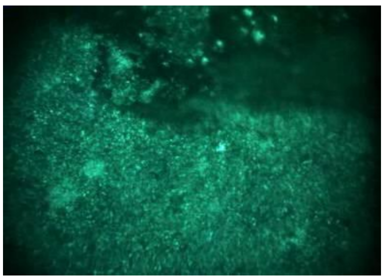
c)

Fig. 7. SHS-structure combustion: a) beginning of combustion, b) combustion, c) end of combustion.

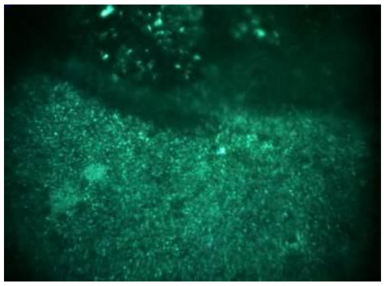
The visual analysis of the results allowed us to determine the characteristics of the combustion process of such a structure. It is seen that the burning takes place unevenly. At the initial stage, the surface material is absorbed (upward movement) and pores are being formed. Then the next part of the 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.



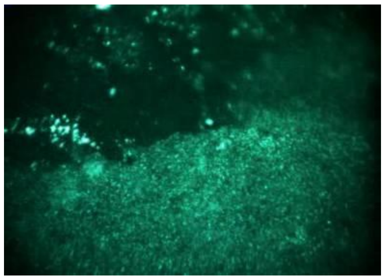
0 ms



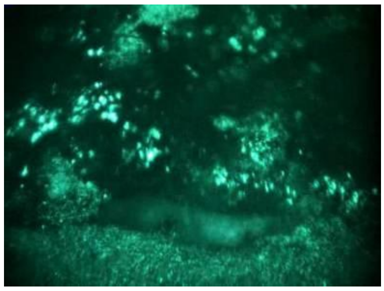
210 ms



250 ms



470 ms



550 ms

Fig. 8. Visualization of SHS-structure combustion process.

The results agree with those obtained by other methods and allow to analyze the structural transformations in different phases of the process and estimate the rate of the SHS process [9].

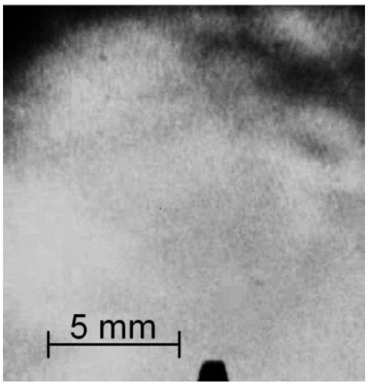
5 Visualization of corona discharge in air at atmospheric pressure

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

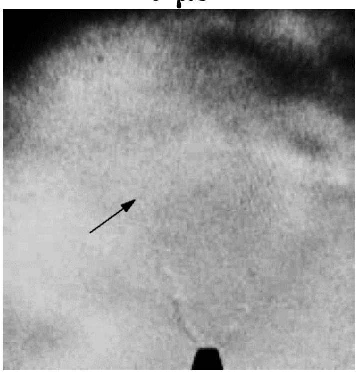
The corona discharge in air at atmospheric pressure was studied. The discharge was formed by a high-voltage pulse generator. The generator formed voltage pulses which consisted of separate trains with the duration of 10 ms and the frequency of 50 Hz. Each train consisted of a sinusoidal signal with an oscillation frequency of 290 kHz. A high voltage electrode was made of copper. When the ground electrode was placed 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. 9. 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.

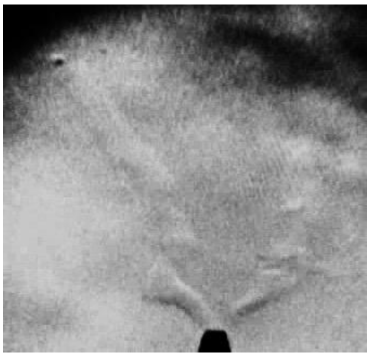
The data obtained with a laser monitor extend the knowledge of the development of the corona discharge. In particular, it is possible to estimate the speed of propagation of a diffuse discharge, which is equal to 16.3 m/s. It appeared to be much higher than the speed of the thermal expansion of the channel,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



0 μs



375 μs



750 μs

Fig. 9. The visualization of corona discharge using the laser monitor [10].

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.

Some our results are presented at the 7-th International Conference on Sensors and Signals SENSIG'15 and 12-th International Conference on Atomic and Molecular Pulsed Lasers (AMPL-2015) [19, 20].

6 Conclusion

We have shown that the metal vapor laser active media can operate at high PRF up to 0.5 - 1 MHz using low energy deposition in the discharge mode. The visualization methods and equipment based on high speed brightness amplifiers (laser monitor) allow to perform non-destructive testing of fast processes through the strong background radiation. The spatial resolution of the monitor of 1 μm and time resolution of 10^{-5} s have been obtained and can be improved in the near future.

In our experiments we used the so-called monostatic scheme of the laser monitor. It can be used for the diagnostics of objects placed at a distance less then 3 m [21]. 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.

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