

High Prf Metal Vapor Laser Active Media For Visual And Optical Monitoring

S N Torgaev^{1,2,3}, M V Trigub^{4,5}, G S Evtushenko⁶ and T G Evtushenko⁷

¹Assistant of professor, Tomsk polytechnic university, Tomsk, Russia

²Research assistant, V.E. Zuev Institute of Atmospheric Optics SB RAS, Tomsk, Russia

³Assistant of professor, Tomsk State University, Tomsk, Russia

⁴Assistant of professor, Tomsk polytechnic university, Tomsk, Russia

⁵Research assistant, V.E. Zuev Institute of Atmospheric Optics SB RAS, Tomsk, Russia

⁶Professor, Tomsk polytechnic university, Tomsk, Russia

⁷Assistant of professor, Tomsk State University, Tomsk, Russia

E-mail:torgaev@tpu.ru

Abstract. In this paper the feasibility of using metal vapor lasers for visual and optical monitoring of fast processes is discussed. The theoretical calculations consistent with the experimental study have been performed. The possibility of visualizing objects with pulse repetition frequency of the brightness amplifier up to 60 kHz has been demonstrated. The visualization results of the corona discharge are also given.

1. Introduction

Today many scientific and technical problems are related to the necessity of real-time visual monitoring of different objects and processes shielded by the intense broadband background illumination. The examples of such processes are self-propagating high-temperature synthesis, the processes of interaction of intense energy fluxes with the surface, welding, plasma discharge, etc. Visualization of such processes is possible using active optical systems with brightness amplifiers, for example, a laser monitor [1–3].

Active optical systems based on metal vapor brightness amplifiers have a number of advantages such as high spectral brightness of radiation, high gain in a narrow spectral range (2–5 pm), operation in a pulse-periodic mode. For the visualization of fast processes it is necessary to use a high-frequency brightness amplifier. The typical pulse repetition frequency (PRF) of metal vapor amplifiers, such as copper bromide vapor amplifier, is about 10–30 kHz. The pulse repetition frequency is limited by a number of plasma-chemical processes within the active medium of the amplifier. In [4,5] the authors showed that obtaining high pulse repetition rate is possible with brightness amplifiers operating with a low input energy into the discharge. In this case, the negative impact of cumulative effects in a plasma discharge are partially leveled. Such a mode can be obtained when the amplifier is pumped by high frequency pulses of short duration (20–50 ns, with typical duration of 200–300 ns), as well as it operates in a low-current mode, i.e. when the current going through the gas discharge tube (GDT) is lower than its typical values and equals a few amperes [6].



2. Optical schemes. Calculation and experimental data

One of the features of metal vapor active media on self-terminating transitions is that they can operate effectively both as a generator and an amplifier. Moreover, operating as a brightness amplifier, along with the high gain of the active medium up to 100 dB/m, the metal vapor active media emit intense superradiance, that is 20–30% of the power of the laser.

These advantages of metal vapor active media inspired engineers to design a laser projection microscope, and later, a laser monitor [1,3,7,8]. Laser monitors can be built using two schemes: monostatic [7] and bistatic [9]. In the first one, the active medium is both a radiation source and a brightness amplifier (figure 1a). In the bistatic scheme the object is illuminated by the active medium that operates as a generator (laser), and the reflected signal is amplified by the other similar active medium (figure 1b).

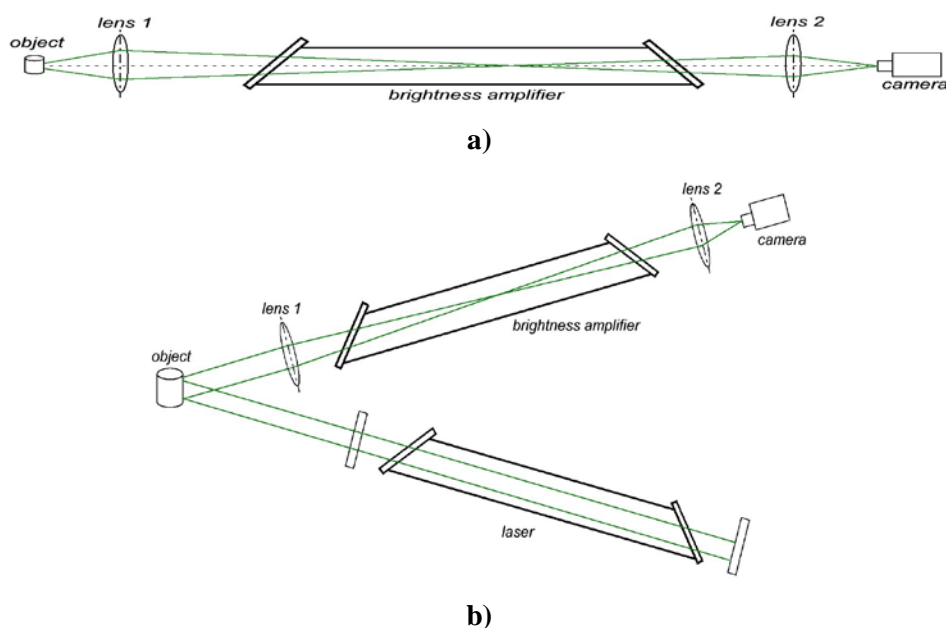


Figure 1. Laser monitor optical schemes: a) monostatic, b) bistatic.

The high repetition frequency (300 kHz, and then 400 kHz) in a copper bromide vapor laser was obtained in [10,11]. In [11] a GDT with a diameter of 0.5 cm and a length of 24 cm was utilized. Subsequently, in [12], using a GDT with a diameter of 0.7 cm and active medium length of 14 cm the pulse repetition frequency reached 700 kHz. In the works mentioned above the laser was operated at a low energy input into the discharge which was obtained when the laser active medium was pumped by high-voltage pulses of short duration. It was observed that the mode of high pulse repetition frequencies could be achieved in a GDT with a small diameter. In a GDT of a small diameter the interpulse plasma recombination is more effective due to diffusion processes. However, the use of lasers (brightness amplifiers) with a small diameter GDT in active optical systems is not effective because the field of view is reduced. Thus, the challenge was to obtain high pulse repetition frequencies (and gain), up to 100 kHz and above in GDTs with a diameter more than 1 cm [13].

In this paper the experimental data are analyzed and theoretical estimations of electrical characteristics for two GDTs are provided. The experimental conditions and the GDT parameters are given in table 1.

Table 1. Experiment and GDT parameters.

	GDT №1	GDT №2
GDT diameter, cm	2	0,7
Active medium length, cm	50	14
Pulse repetition rate, kHz	5–40	630
Neon pressure, torr	20	20-25
GDT wall temperature, K	650	550

As it was mentioned above, it is possible to obtain high pulse repetition frequency of metal vapor brightness amplifiers when they are operated at a low energy input into the discharge. However, when using such a mode the output energy decreases, which is confirmed by the modelling and experimental results. Figure 2 shows the dependence of the output energy of the copper bromide laser (at a green wavelength of 510.6 nm) on the pump pulse repetition rate in the range of 10 kHz to 40 kHz [5] for GDT № 1. These dependences were obtained both experimentally and by means of simulation.

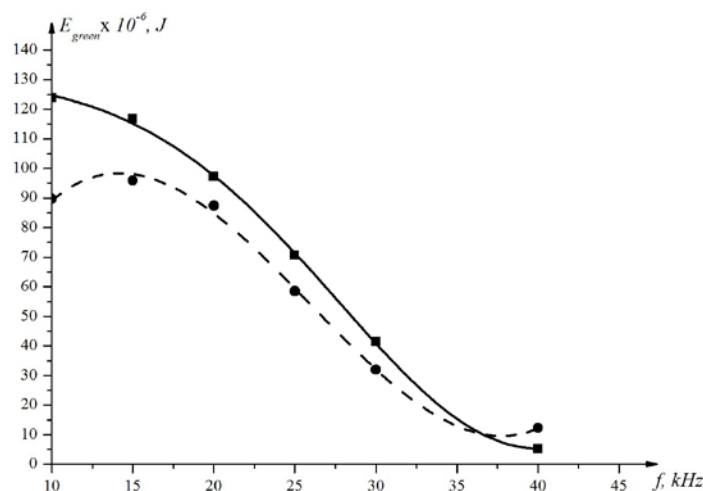


Figure 2. Dependence of the radiation energy (green wavelength of 510.6 nm) on the frequency: experimental (solid line) and calculation (dashed line) data.

In a number of practical tasks the decrease in the generation energy (superradiance) can be quite critical, for example, when visualizing objects with a high absorption coefficient at amplifier wavelengths. At the same time the energy of the radiation reflected from the object brought to the amplifier may be insufficient for the amplification, i.e. the energy of the input signal can be lower than the noise energy of the amplifier. And in this case the input signal carrying the image will not be amplified. For example, in GDT № 1 at a pulse repetition rate of 40 kHz the noise energy of the amplifier is $E_{N_GDT\ №1} = P_{N_GDT\ №1} \cdot \tau = 2.8 \cdot 10^{-12} J$. And the energy of the radiation (for the green line) is $E_{GDT\ №1} = 5 \cdot 10^{-6} J$. And when the amplifier operates at a frequency of 630 kHz (GDT №2) the noise energy of the amplifier is $E_{N_GDT\ №2} = 8.7 \cdot 10^{-12} J$, and the energy of the radiation (for the green line) is $E_{GDT\ №2} = 0.12 \cdot 10^{-6} J$. In this case, the experimental data are given for the copper bromide vapor active element that operates in a generator mode. When it is used as a brightness amplifier it is

operated in a superradiance mode (without a resonator). In this case the energy of the radiation is 5 times less approximately. Consequently, when the active medium is operated in a brightness amplifier mode the radiation energy for GDTs presented above will be approximately $E_{GDT.N\#1} = 1 \cdot 10^{-6} J$ and $E_{GDT.N\#2} = 6.8 \cdot 10^{-9} J$ for GDTs №1 and №2, respectively.

The presented estimates show that when the pulse repetition frequency increases the radiation energy decreases much faster than the energy of the noise of the amplifier but remains higher than the last one. This allows to visualize objects though the image quality will decrease. The pulse energy of the brightness amplifier noise is determined by the following equation [14]:

$$E_N = h \cdot \nu \cdot \Delta \nu \cdot \tau_{INV} \cdot \left(\frac{d^2}{\lambda \cdot L} \right)^2,$$

where τ_{INV} is the radiation pulse width, $\Delta \nu$ is the radiation bandwidth due to the Doppler broadening, ν is the frequency of the green radiation wavelength, d is a GDT diameter, L is a GDT active medium length. This ratio shows that the amplifier noise energy is not directly dependent on the pulse repetition rate. The increase in the pulse repetition rate reduces the duration of inversion (the duration of the laser pulse, τ_{INV}). However, the experimental data show that when the pump frequency varies from 10 to 40 kHz, the laser pulse duration (FWHM) is reduced by a factor of 1.5, while the radiation energy is reduced by a factor of more than 20 (figure 2). When obtaining generation in a GDT with a diameter of more than 1 cm, which is necessary for its application as an amplifier, it will be necessary to reduce the input energy which will also reduce the energy of the radiation.

Thus, as the pulse repetition frequency increases the radiation energy significantly decreases. When the active element is used as a brightness amplifier in a monostatic scheme of the laser monitor (figure 1a) for visualizing objects with a small reflectance coefficient of the corresponding wavelength, the energy of the signal brought to the amplifier can be of the same order as the noise energy. This effect leads to a considerable deterioration of the quality of the image formed by the laser monitor. For the visualization of such objects it is necessary to use a brightness amplifier with active additives, which will increase the generation energy. For the visualization of distant objects and objects with a low reflectance coefficient it is necessary to use a bistatic laser monitor scheme (figure 1b). In this scheme it is possible to significantly increase the energy of the illumination using an independent source that operates as a generator and a brightness amplifier synchronized with the latter in time.

The analysis suggests the possibility of designing a brightness amplifier with the pulse repetition rate up to 100 kHz when it is operated in a low energy input mode. At the same time the time resolution of the laser monitor will be 10^{-5} s. And the use of active additives (e.g., HBr) will increase the efficiency of laser plasma recombination during the interpulse period. This will increase the aperture of the brightness amplifier active medium and pulse repetition frequency.

3. Results of visualization

Based on the estimates, the scheme of a monostatic laser monitor that allows to obtain an image formed by a single superradiance pulse was designed. In this experiment the brightness amplifier operated at frequencies of up to 60 kHz, i.e with the time resolution $\approx 16.7 \mu s$. For obtaining the sufficient spatial resolution, the GDT with a diameter of the active medium of 2 cm was used. A further increase in the pulse repetition frequency was limited by the power source being used. The results of visualization of the test object (metal grid) at different pulse repetition frequencies are shown in figure 3.

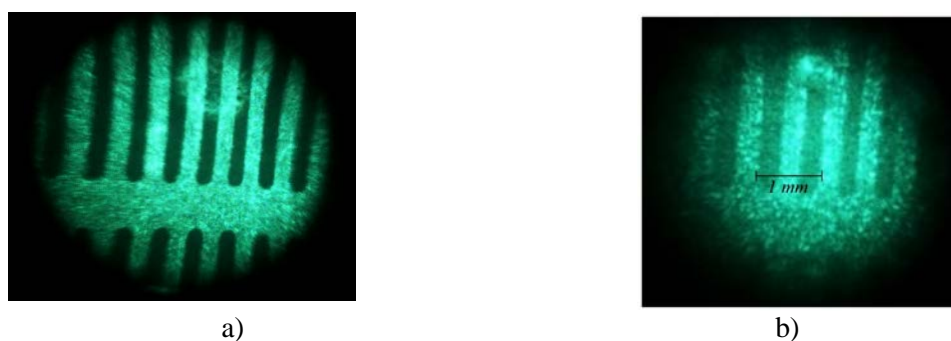


Figure 3. Visualization of the metal grid using a laser monitor with different PRF: 30 kHz (a) and 60 kHz (b).

In our experiment, as the frequency increased the superradiance beam diameter decreased from 1.2 cm at 30 kHz to 0.5 cm at 60 kHz. The visualization was performed in a scheme of the laser monitor with frame-by-frame image registration. In figure 3 it is shown that when the beam diameter, and hence the width of the gain profile decreased, the field of view was reduced.

Figure 4 shows the results of the visualization of the corona discharge obtained by the laser monitor [15] at different moments of time.

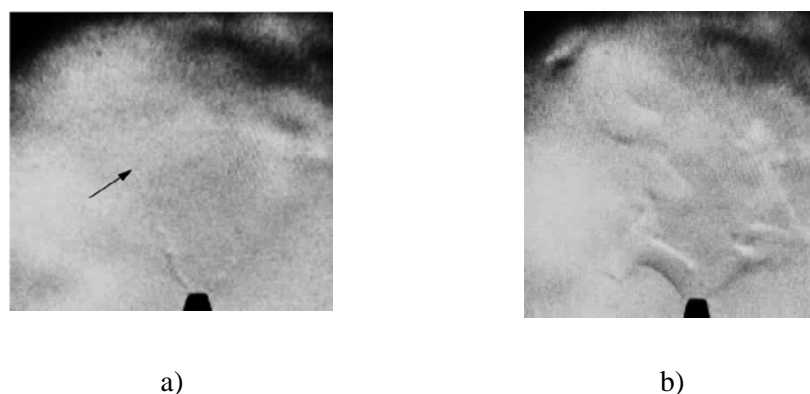


Figure 3. Visualization of the corona discharge process development at different moments of time: 375 μ s (a) и 1125 μ s (b).

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 the frame-by-frame registration mode it is possible to calculate the velocity of the discharge evolution, the movement of the thermal front, etc.

4. Conclusion

Thus, it has been shown that copper bromide vapor brightness amplifiers with high PRF can be used for designing high speed laser monitors. High pulse repetition frequencies are obtained using the mode of low energy input into the discharge. The current measurements suggest that for solving a number of problems it is advisable to use a bistatic laser monitor construction which will allow to monitor the objects, remote objects as well, with a low reflectance coefficient at the operating wavelength.

The experimental results show that the use of brightness amplifiers as an integral part of the laser monitor with frame-by-frame registration makes it possible to obtain images of high quality with the time resolution of up to 20 μ s.

The authors appreciate the help and comments of the senior researcher of V.E. Zuev Institute of Atmospheric Optics SB RAS D.V. Shiyanov

Acknowledgements

The work was supported by the Russian Science Foundation, Project № 14-19-00175.

References

- [1] Batenin V M, Klimovskij I I, Selezneva L A (1988) A study of coal arc electrode surface during the combustion process *Doklady Earth Sciences* **303** 857–860
- [2] Prokoshev V G (2009) Micro- and nanostructure and hydrodynamic instabilities induced by laser radiation on solid state surface and their diagnostic using laser and probe microscopy methods (Vladimir: dissertation on doctor habilitation degree of physical and mathematical sciences)
- [3] Evtushenko G S, Trigub M V, Gubarev F A, Evtushenko T G, Torgaev S N, Shiyarov D V (2014) Laser monitor for non-destructive testing of materials and processes shielded by intensive background lighting *Review of Scientific Instruments* **85**(3) 033111 doi: 10.1063/1.4869155
- [4] Torgaev S N, Boychenko A M, Evtushenko G S, Shiyarov D V (2013) Simulation of a CuBr–Ne–HBr laser with high pump pulse repetition frequencies *Russian Physics Journal* **55**(9) 1039–1045
- [5] Boichenko A M, Evtushenko G S, Nekhoroshev V O, Shiyarov D V, Torgaev S N (2015) CuBr-Ne-HBr laser with a high repetition frequency of the lasing pulses at a reduced energy deposition in the discharge *Physics of Wave Phenomena* **23**(1) 1–13
- [6] Fedorov V F, Fedorov K V, Shiyarov D V, Evtushenko G S (2014) Low-current discharge in a copper vapor laser *Proc. Conf. on Metal; Vapor Lasers* 84 [in Russian]
- [7] Zemskov K I, Isaev A A, Kazaryan M A, Petrash G G (1974) Laser projection microscope *Quantum Electronics* **1** 14–15
- [8] Kuznetsov A P, Buzhinskij R O, Gubskij K L, Savelov A S, Sarantsev S A, Terehin A N (2010) Visualization of plasma-induced processes by a projection system with a Cu-laser-based brightness amplifier *Plasma Physics Reports* **36**(5) 428–437
- [9] Buzhinskij O I, Vasiliev N N, Moshkunov A I, Slivitskaya I A, Slivitsky A A (2002) Copper vapor laser application for surface monitoring of divertor and first wall in ITER *Fusion Engineering and Design* **60**(2) 141–155
- [10] Evtushenko G S, Petrash G G, Sukhanov V B, Fedoev V F (1999) CuBr-laser with a 300 kHz pulse repetition rate *Quantum Electronics* **29** 775–777
- [11] Evtushenko G S, Gubarev F A, Fedoev V F, Sukhanov V B, Zaikin S S (2008) CuBr-laser operating at 400 kHz pulse repetition rate *Bulletin of the Tomsk Polytechnic University* **312** 106–107
- [12] Nekhoroshev V O, Fedorov V F, Evtushenko G S, Torgaev S N (2012) Copper bromide vapour laser with a pulse repetition rate up to 700 kHz *Quantum Electronics* **42**(10) 877–879
- [13] Trigub M V, Shiyarov D V, Vlasov V V (2014) Brightness Amplifiers with PRF up to 100 kHz *International Conference of Young Specialists on Micro/Nanotechnologies and Electron Devices, EDM* 301–304
- [14] Pasmanik G A, Zemskov K I, Kazaryan M A and others (1988) Optical systems with brightness amplifiers (Russia: Gorkij) [in Russian]
- [15] Rybka D V, Andronikov I V, Evtushenko G S, Kozyrev A V, Kozhevnikov V Yu, Kostyrya I D, Tarasenko V F, Trigub M V, Shut'ko V Yu (2013) Corona discharge in atmospheric pressure air under a modulated voltage pulse of 10 ms voltage pulse *Atmospheric and Oceanic Optics* **26** 85–90