High-beam-quality sealed-off master oscillator – power amplifier system oscillating in the visible spectral range on atomic copper transitions for micromachining in research and technology

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Abstract. High-beam-quality sealed-off master oscillator – power amplifier system is developed and studied based on a copper bromide vapor laser and oscillating on atomic copper self-terminating transitions. A detailed study on the laser beam divergence is carried out demonstrating the capability of CuBr vapor laser systems to emit diffraction-limited laser beams. Precise microprocessing of various materials, such as optical grade fused quartz, Si, stainless steel, is also implemented.

1. Introduction

One standard application of lasers is in industry for cutting, welding, drilling, etc. of materials. The range of application of laser radiation is determined by the radiation properties, such as power, wavelength, beam geometry, divergence, etc. The precision of many operations implemented by lasers depends on the so called beam quality.

For quite a lot of manipulations, the beam quality is associated with the minimum size of the spot that is to be treated by laser radiation. In theory, light can be focused to the size determined by diffraction.

The simplest way of measuring precisely the laser beam divergence is focusing the laser radiation by a mirror or a lens. The laser beam divergence $\theta$ is calculated using the expression:

$$\theta = \frac{d}{f}$$

(1)

where $d$ is the diameter of the focal spot of a concave mirror or focusing lens with a focal distance $f$. Another parameter of characterizing a laser beam is $M^2$ (M-squared), the so called beam propagation factor (or times-diffraction-limited factor). It is defined as the ratio of the laser beam divergence $\theta$ and the diffraction-limited divergence $\theta_{00}$ of a perfect Gaussian TEM$_{00}$ beam. It is well known that the diffraction-limited divergence of an ideal Gaussian TEM$_{00}$ beam is defined as follows:

$$\theta_{00} = \frac{4 \lambda}{\pi D}$$

(2)
where $D$ is the diameter of the input beam and $\lambda$ is the wavelength of the laser radiation. From expressions (1) and (2) one could easily derive a formula for determination of the beam propagation factor $M^2$:

$$M^2 = \frac{\pi}{4\lambda f} D d$$  \hspace{1cm} (3)

For a circular laser beam of diameter $D$ having a flat-top (also known as top-hat) radial intensity distribution of the laser emission, the diffraction-limited divergence $DL$ is calculated as $DL=2.44 \lambda/D$, which is 1.9 times higher than the diffraction-limited divergence $\theta_0$ of a perfect Gaussian TEM$_{00}$ beam.

Most of the systems based on copper (Cu), copper bromide (CuBr) and Cu:HyBrID vapor lasers operating on self-terminating atomic copper laser transitions (as single oscillators or as master oscillator with power amplifier, MO–PA systems) have been reported to achieve a laser beam divergence in the range 1-2 times the $DL$ value [1-7]. The beam propagation factor $M^2$ of those laser systems is in the range of 2-4. We consider it unsatisfying. Recently announced second harmonic Nd:YAG laser systems produced by Spectra-Physics and Coherent emit single transverse mode TEM$_{00}$ laser oscillation at the wavelength of 532 nm with a beam propagation factor $M^2$ of about 1.1 – 1.3. A new subclass of Cu vapor lasers, termed kinetically enhanced Cu vapor lasers, has been developed to improve the gas discharge kinetics and hence the output laser parameters of the copper vapor lasers, namely average power, laser pulse energy, and beam quality. A beam divergence of about 22 µrad of a 38-mm laser beam with top-hat radial intensity profile has been measured in [8] that corresponds to $\theta=0.7DL$ and beam propagation factor $M^2=1.3$. In our previous studies on MO–PA system strontium vapor system oscillating on the 6.45-µm laser line, a beam propagation factor $M^2$ of 1.1 and 1 was reported, respectively [9, 10]. The technique of spatial filtering down to the diffraction limit by a hard diaphragm in the laser beam in the visible spectral range is dramatically more difficult to implement in the middle infrared spectral region, due to the fact that the wavelength of 6.45 µm is 12 and 11 times larger than the wavelengths of 510.6 nm and 578.2 nm.

In this paper, we present the development and investigation of a high-beam-quality (diffraction-limited) sealed-off MO–PA CuBr vapor system oscillating in the visible spectral range on atomic self-terminating Cu transitions for micromachining in research and technology. We demonstrate precise micro-drilling of grade fused quartz, micro-cutting of stainless steel and Si samples, which confirm the beam divergence measurements made via other techniques.

2. Experimental setup

A schematic diagram of the simplified MO–PA system is shown in figure 1. It is characterized by the absence of a matching reflection telescope between the master oscillator (MO) and the high-power amplifier (PA) and was used in preliminary microprocessing of various materials. The laser silica tubes used for MO and PA are 90-cm-long with two electrodes separated at 50 cm from each other. Several discharge confining diaphragms with an inside diameter of 2 cm are equidistantly placed between the electrodes. Thus, the gain media of MO and PA are 50 cm in length and 2 cm in diameter. Cylindrical copper electrodes are used. CuBr is placed between the diaphragms. The active zones of both laser tubes are placed in stainless steel enclosures. The vapor pressure necessary for laser oscillation is obtained by discharge heating, i.e. the MO and PA operate in a self-heating regime. Quartz windows are sealed to the ends of the laser tubes. The temperature on the quartz tube surface is measured by a thermocouple. The laser tubes investigated are excited by an innovative electrical pulsed excitation scheme, which is described in detail in [10]. The average output power is measured by a calorimetric Scientech Vector S310 power-energy meter with a sensitivity range from 200 nm to 10 µm.

The MO operates with a negative branch unstable resonator with magnification $M = 50$, which consists of two concave mirrors M1 and M2. A flat scraper mirror M3 placed on the confocal plane provides energy extraction and self-filtering of the radiation. Flat mirrors M4 and M5 guide the laser beam. A master timing system (MTS) is used for precise synchronization of the MO–PA power supplies. For precise material microprocessing, the laser beam could be focused by an achronical objective with
a variable focal length, such as 100 cm, 40 cm, 12 cm, and 6 cm. The samples are placed on an Aerotech X-Y stage, which is controlled by a computer with suitable software.

### Table 1. Parameters of optical elements, namely mirrors, lenses, diaphragms.

| Optics | M1 | M2 | M3 | M4 | M5 | D6 | M7 | D8 | M9 | M10 |
|--------|----|----|----|----|----|----|----|----|----|-----|
| Focal length (cm) | 100 | 2 | $\infty$ | 0.5-mm orifice | $\infty$ | $\infty$ | 4-mm orifice | 25 | Variable aperture | 250 | $\infty$ |

3. Results and discussion

The simplified MO–PA system was preliminarily used for micro-scribing of Si samples and microchips in microelectronics. The successful application to this precise material processing prompted the system’s further use for micro-drilling in laser grade fused quartz with an extremely high aspect ratio. Cubic silica samples were used to facilitate the material characterization by optical microscopy. Laser radiation with an average output power of 5 W was focused by an achromatic lens with a focal length of 12 cm on the
silica sample surface. We varied the pulse repetition rate (prr), while keeping the laser pulse energy constant (263 µJ for maximal prr and average laser power). In figure 3, image of the micro-holes is shown for several different prrs, namely 10 Hz, 20 Hz, 30 Hz, 50 Hz, 100 Hz, 500 Hz, 1 kHz, 2 kHz, 5 kHz, 9.5 kHz and 19 kHz (from the bottom to the top of the image), at two different magnifications (a) and (b), respectively. It should be noted that the scale subdivisions and divisions are equal to 10 µm and 100 µm, respectively. The maximal hole diameter was measured at the sample surface and varied between 23 µm and 34 µm, while a maximal hole depth of 28 mm was achieved at a prr of 19 kHz. The maximal aspect ratio (defined as the ratio of the hole depth and the hole diameter) was 97 at a prr of 2 kHz. Earlier, a Cu vapor laser with an average power of 1.5 W and a beam divergence of 110 µrad (1.1DL, where DL is calculated for a 12.5-mm diameter beam) operating at a prr of 4 kHz was used to drill micro-holes in fused silica achieving comparable hole diameter, hole depth, and aspect ratio [5]. The enhancement of the hole length was explained by a guiding effect produced by the high-quality hole walls, along which the radiation propagates with low losses [5].

![Figure 3. Micro-holes drilled in silica sample at two different magnifications.](image)

Despite the results obtained, the laser beam divergence was further reduced by a reflection telescope with magnification $M = 10$, as shown in figure 2. Varying the orifice diameter of the diaphragm D8, the beam divergence was measured for different beam diameters $D$. In table 2, the laser beam divergence is cited as measured by the two different methods and compared with the beam divergence of an ideal Gaussian beams having the same diameters.

It must be noted that all values of the beam propagation factor $M^2$ are lower than 1.9, which means that the beam divergence is well below the diffraction limit $DL$ for the flat-top beam distribution.

**Table 2.** Laser beam parameters: $D$ – laser beam diameter; $\theta_1$ – beam divergence measured by optical microscope; $\theta_2$ – beam divergence measured by CCD camera; $\theta_00$ – beam divergence of an ideal Gaussian beam; $M^2_1 = \theta_1/\theta_00$; $M^2_2 = \theta_2/\theta_00$.

| $D$ (mm) | $\theta_1$ (µrad) | $\theta_2$ (µrad) | $\theta_00$ (µrad) | $M^2_1$ | $M^2_2$ |
|---------|------------------|------------------|------------------|---------|---------|
| 34      | 22.4±2.8         | 19.1             | 1.17±0.15        | –       | –       |
| 20      | 39.2±2.8         | 50±5             | 32.5             | 1.21±0.10| 1.54±0.15|
| 10      | 78.4±5.6         | 90±10            | 65.0             | 1.21±0.10| 1.38±0.15|
| 6       | 168.0±5.6        | 186±10           | 108.4            | 1.55±0.05| 1.71±0.9 |
| 4       | 235.2±5.6        | 242±34           | 162.5            | 1.45±0.04| 1.49±0.21|

These results encouraged us to assess the lowest laser pulse energy for ablation produced by CuBr laser radiation and to verify our beam divergence measurements once again. For this purpose, we used the MO beam magnified by the telescope and focused it by an achromatic lens with a focal length of 6 cm for micro-cutting Si and stainless steel samples. With MO operating at a prr of 19 kHz, we reduced the laser power by decreasing slightly the operating temperature. Micro-cutting in both Si and stainless steel samples was achieved at an average laser power of 0.7 mW, which corresponds to a laser pulse...
energy of 37 nJ. Figure 4 shows images of the micro-channels cut in Si (a) and stainless steel (b) samples at the following speed of the X-Y stage: 10, 20, 50, 100, 200, 400 and 800 mm/min (from the left-hand to the right-hand side of the image and the focus at the image bottom). The channels width at the focus decreased from 15 µm to less than 5 µm with the increase in the X-Y stage speed.

![Micro-channels cut in Si (a) and stainless steel (b) samples.](image)

**Figure 4.** Micro-channels cut in Si (a) and stainless steel (b) samples.

### 4. Conclusions

High-beam-quality sealed-off master oscillator – power amplifier system based on a CuBr vapor laser and oscillating on atomic self-terminating Cu transitions is developed and studied. A detailed study on the laser beam divergence is carried out confirming the feasibility of producing diffraction-limited laser beams by CuBr vapor laser systems. Precise microprocessing of various materials, such as optical grade fused quartz, Si, stainless steel, is also realized. Micro-scribing in both Si and stainless steel samples is achieved with a laser pulse energy as low as 37 nJ.

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### References

[1] Stoilov V M, Astadjov D N and Vuchkov N K 2000 *Optical and Quantum Electronics* **32** 1209–17

[2] Astadjov D N, Stoychev L I, Dixid S K, Nakhe S V and Sabotinov N V 2005 *IEEE Journal of Quantum Electronics* **4018** 1097–101

[3] Astadjov D N, Stoychev L I and Sabotinov N V 2007 *Optical and Quantum Electronics* **39** 603–10

[4] Bhatnagar R, Dixid S K, Shukla P K, Singh B and Mittal J K 1996 *Pulsed Metal Vapour Lasers* ed C E Little and N V Sabotinov (Dordrecht: Kluwer Academic Publishers)

[5] Salimbeni R 1996 *Pulsed Metal Vapour Lasers* ed C E Little and N V Sabotinov (Dordrecht: Kluwer Academic Publishers)

[6] Walter W T 1996 *Pulsed Metal Vapour Lasers* ed C E Little and N V Sabotinov (Dordrecht: Kluwer Academic Publishers)

[7] Bergmann H W, Körner C, Hartmann M and Mayrhofer R 1996 *Pulsed Metal Vapour Lasers* ed C E Little and N V Sabotinov (Dordrecht: Kluwer Academic Publishers)

[8] Withfold M J, Brown D J W, Mildren R P, Carman R J, Marshal G D and Paper J A 2004 *Progress in Quantum Electronics* **28** 165–96

[9] Kostadinov I K, Slaveeva S I and Temelkov K A 2019 *Proceedings of SPIE* **11047** 110471K

[10] Kostadinov I K Temelkov K A, Yankov G P and Ivanov B L 2020 *Optical and Quantum Electronics* **52** 94