High-power high-beam-quality sealed-off master oscillator – power amplifier system oscillating in the middle infrared spectral range on strontium atomic transitions

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Abstract. High-beam-quality sealed-off master oscillator – power amplifier system is developed and studied based on an atomic strontium vapor laser and delivering high-power laser radiation in the middle infrared spectral range. A diffraction self-filtering of the laser radiation is used to reduce the laser beam divergence to the ultimate diffraction limit. A new optical design is utilized for the master oscillator to visualize the optical path through the entire optical scheme. A large-bore sealed-off laser tube is developed and studied with a stable cavity and is applied as a power amplifier as well. Precise microprocessing of optical grade fused quartz is also performed.

1. Introduction

The laser radiation with the wavelength 6.45 µm delivered by tunable free-electron lasers (FELs) has provided efficient and precise laser ablation of soft and hard tissues with minimal thermal collateral damage [1]. This discovery has inspired investigations on strontium and strontium halide vapor lasers [2, 3]. The importance of the wavelength has been proved with a ZnGeP₂ optical parametric oscillator (ZGP-OPO) tunable between 6 µm and 8 µm and pumped by a Q-switched Er:YAG laser [4]. As concerns the ablation parameters, it has been also demonstrated that the ZGP-OPO has outperformed the FEL regardless of 400-time lower laser pulse energy (250 µJ and 0.1 J for the ZGP-OPO and FEL lasers, respectively). This has been attributed to the 50-time shorter laser pulse (100 ns and 5 µs for the ZGP-OPO and FEL lasers, respectively) [4]. The Sr atom laser has the advantage over the FEL with its shorter laser pulse of 60 ns [3] and hence a higher peak pulse power, and also over the OPO with a better operation stability at a laser pulse energy in 1 mJ range and a two-order of magnitude higher pulse repetition rate.

Although the applications of the tunable laser sources delivering laser radiation at the wavelength 6.45 µm justify the great efforts spent to improving the Sr vapor laser performance, several advanced laser applications, such as precise laser ablation of organic materials, glass and quartz processing, thermal glass cracking, remote sensing of the atmosphere, determination of the linear optical properties of newly-developed materials, etc., have been also implemented by using the Sr vapor systems [3].

Except on the laser energy characteristics, the efficiency and accuracy of high-precision microprocessing of various materials, including biological tissues, via laser ablation crucially depend on the laser beam quality. It is quantitatively determined by $M^2$, so called beam propagation factor (or
times-diffraction-limited factor). The beam propagation factor is defined by the ratio of the laser beam divergence and the diffraction-limited divergence of a perfect Gaussian TEM$_{00}$ beam with the same beam diameter.

A master oscillator – power amplifier (MO–PA) strontium (Sr) vapor system delivering diffraction-limited laser radiation ($M^2 = 1$) at the 6.45-μm laser line was developed in our previous investigation [5]. The average output power of 3 W obtained in [5] is five times lower than that achieved with a single-tube Sr vapor laser [2]. The precise alignment of the extremely complicated optical schemes in the middle infrared (MIR) spectral region raises great difficulties in comparison with the ultraviolet, visible and near infrared lasers.

In this work, a diffraction-limited sealed-off MO–PA Sr vapor system oscillating in the MIR spectral range is developed and investigated. A new optical arrangement is utilized for the MO to visualize the optical path through the entire optical scheme. A large-bore sealed-off power amplifier is also used to increase the average laser power. Precise micro-welding, micro-cutting and micro-drilling of optical grade silica is also implemented.

### 2. Experimental setup

A schematic diagram of the MO–PA system is shown in figure 1. The parameters of the optical elements of the experimental scheme are presented in table 1. A new optical arrangement of the MO is developed, as follows: two laser tubes are placed in a negative-branch unstable resonator with magnification $M = 17$, 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. For spatial adjustment of the MO beam and the aperture of PA, a reflection telescope with magnification $M = 1.8$ is formed by the concave mirrors M5 and M7. A 0.5-mm diaphragm M6 is also placed in its confocal plane for diffraction spatial filtering. For precise material microprocessing, the laser beam is focused by a CaF$_2$ objective with a focal length of 15 cm. The samples are placed on an Aerotech X-Y stage controlled by a computer and a suitable software. 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.

![Figure 1. Schematic diagram of the investigated MO–PA system.](image)

| Optics | M1 | M2 | M3 | M4 | M5 | M6 | M7 | M8 | Objective |
|--------|----|----|----|----|----|----|----|----|-----------|
| Focal length (cm) | 200 | 12 | $\infty$ | 86 | $\infty$ | 159 | $\infty$ | 15 |           |
The first laser tube (LT1) is with copper bromide (CuBr) and windows made of CaF₂. Laser oscillation at the 510.6-nm and 578.2-nm copper atomic lines is used to visualize the optical path through the entire optical scheme. The LT1 is a 90-cm-long silica tube 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. Therefore, the gain medium is 50-cm long and 2 cm in diameter. Cylindrical Cu electrodes are used. CuBr is placed between the diaphragms. The second laser tube (LT2) is the actual MO with strontium and has the following features: a BeO ceramic insert confining the active zone with an inside diameter of 20 mm and a length of 50 cm is coaxially sleeved in the basic tube made of fused quartz. The third laser tube (LT3) used as PA consists of an Al₂O₃ ceramic insert, confining the active zone and having an inside diameter of 25 mm and a length of 100 cm, coaxially sleeved in the basic silica tube. Cylindrical electrodes made of molybdenum (Mo) are used in both tubes LT2 and LT3. The MO and PA are with additional thermal insulation of the discharge zone, i.e. the zones between the ceramic insert and the basic quartz tube are compactly filled with Al₂O₃ powder insulation and Al₂O₃:ZrO₂ fibrous insulation for the MO and PA, respectively. The Sr pieces are spread inside the ceramic tubes along their length. The CaF₂ windows are sealed to the ends of the three tubes. The necessary vapor pressure for laser oscillation in the three tubes is obtained by discharge heating, i.e. LT1, LT2 and LT3 operate in a self-heating regime. The active zones of the laser tubes are placed in stainless steel enclosures to ensure a uniform axial temperature distribution. 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, given in figure 2, based on a command-charged symmetrical Blumlein scheme with a peaking capacitor and magnetic pulse-compression circuits. A master timing system (MTS) is used for precise synchronization of the MO–PA power supplies. A separate power supply is used for the LT1.

![Figure 2. Schematic diagram of the electrical pulsed excitation scheme.](image)

## 3. Results and discussion

The laser tube LT3 was preliminarily investigated with a flat-flat stable laser cavity to optimize the discharge conditions for both maximal energy characteristics and steady-state temperature regime. The results obtained concerning the optimal gas-discharge conditions and maximal steady-state laser characteristics are summarized in table 2. The increase in the charging capacitance ($C_1 + C_2$) is necessary not only for the sake of laser optimization, but also to reduce the charging voltage $U_A$ and hence the unavoidable noise.

The microprocessing experiments were carried out at the following MO–PA characteristics: average laser power of the MO $P_{MO}$ of 0.27 W; average laser power of the PA $P_{PA}$ of 3.35 W; average laser power incident on the target $P_{out}$ of 1.78 W, which correspond to a laser pulse energy of 94 µJ at the prr of 19 kHz. For the 6.45-µm laser, line diaphragm M6 with an 0.5-mm aperture provides diffraction
spatial filtering of the laser beam focused by the mirror M5. Hence, the diffraction-limited beam divergence is 411 µrad. For an objective with a 15-cm focal distance, a focal spot diameter and energy fluence of 61.6 µm and 3.1 J cm⁻², respectively, were calculated.

Table 2. Gas-discharge and laser parameters: \(p_{\text{He-Ne}}\) – pressure of the buffer gas mixture; \(C_i\) – nominal value of the capacitors; \(U_A\) – charging voltage; \(prr\) – pulse repetition rate; \(P_{\text{in}}\) – average input power; \(P_{\text{out}}\) – average output power; \(E_p\) – laser pulse energy; \(\tau_p = 60\) ns – laser pulse duration.

| Laser tube | \(p_{\text{He-Ne}}\) (Torr) | \(C_1\) (nF) | \(C_2\) (nF) | \(C_P\) (nF) | \(U_A\) (kV) | \(prr\) (kHz) | \(P_{\text{in}}\) (W) | \(P_{\text{out}}\) (W) | \(E_p\) (µJ) |
|------------|------------------|--------------|--------------|-------------|-------------|--------------|----------------|----------------|-------------|
| PA         | 42.5-2.5         | 0.75         | 0.82         | 0.26        | 8           | 19           | 955            | 3.5            | 184         |
| PA         | 42.5-2.5         | 0.75         | 0.82         | 0.26        | 9           | 19           | 1210           | 4.6            | 242         |
| PA         | 42.5-2.5         | 0.75         | 0.82         | 0.26        | 10          | 17           | 1335           | 4.8            | 282         |
| PA         | 42.5-2.5         | 0.75         | 0.82         | 0.26        | 10          | 19           | 1490           | 5.8            | 305         |
| PA         | 42.5-2.5         | 1            | 1.1          | 0.26        | 8           | 17           | 1140           | 4.4            | 259         |
| PA         | 42.5-2.5         | 1            | 1.1          | 0.26        | 9           | 17           | 1450           | 5.5            | 324         |
| MO         | 42.5-2.5         | 0.75         | 0.9          | 0.11        | 8           | 17           | 900            | 0.27           | 16          |

In the microprocessing experiments, the laser spot diameter, and hence the energy fluence, were varied through introducing a small inclination angle of the silica samples and moving the samples by the X-Y stage. In figure 3, images of the micro-melting and micro-cutting at an X-Y stage speed of 100 mm/min are shown for the two \(prrs\) of 2 kHz (upper channel) and 19 kHz (lower channel). It should be noted that the scale subdivisions and divisions are equal to 10 µm and 100 µm, respectively. The channel width (light area in the channel center) varied between 15 – 50 µm without the heat-affected zone (dark area in the channel and secondary light areas in the lower channel).

![Figure 3. Micro-channels melted and cut in silica sample.](image)

Images of the micro-melting and micro-drilling are presented in figure 4. The hole diameter is around 180 µm without the heat-affected zone. The crater diameter is larger in comparison with the channel width, due to the fact that the holes are made when the X-Y table was stopped and the sample surface was out of focus as well. Though this is a side effect, it gives evidence that the output laser characteristics are sufficient for material microprocessing.
4. Conclusions
A sealed-off MO–PA system based on a strontium vapor laser and delivering high-power laser radiation at the 6.45-µm laser line with a diffraction-limited beam divergence is developed and applied to precise microprocessing of a silica sample. An average output power of 5.8 W is achieved with the large-bore sealed-off strontium vapor laser with a stable cavity.

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