A copper vapor laser with 2.6 W/cm^3 specific average output power

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Abstract

An average laser power of 0.975 W is obtained from a small-bore copper vapor laser with an active volume of 0.377 cm^3, i.e. a record specific average power of 2.6 W.cm^{-3} is achieved for copper lasers of any type.

1 Introduction

Though the low-temperature variants of the copper vapor laser (CVL), such as copper bromide (CuBr) vapor laser (Sabotinov et al. 1975) and copper (Cu) HyBrID (Hydrogen Bromide In Discharge) laser (Livingstone et al. 1992), have three-time higher efficiency, incomparably less production and operation difficulties, significantly shorter warm-up time, they still can not reach the average output power of 550 W (Hackel and Warner 1993) achieved by single-tube CVL. The record-high average laser powers of 150 W and 201 W obtained through CuBr vapor laser (Kostadinov et al. 2023) and Cu HyBrID laser (Jones et al. 1994), respectively, are even lower than 250 W delivered via single power amplifier, which together with several other power amplifiers have produced an average output power higher than 10 kW (Hackel and Warner 1993). Moreover, CVLs possess higher laser pulse energy at the same average output power, due to the

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lower pulse repetition frequency (*prf*), higher peak pulsed power, shorter laser pulse duration, higher lasing stability, etc.

Exactly the opposite, when the average laser power extracted from unit volume, so called specific average output power, has been investigated, the CVL, CuBr vapor laser and Cu HyBrID laser with the same diameters of 4.5 mm, lengths of 30 cm and volumes of 4.77 cm^3 of the active zones have generated average laser powers of 3.1 W (Vorob'ev et al. 1991), 6.7 W (Astadjov et al. 1994) and 9.5 W (Sabotinov et al. 1995), respectively. The authors have calculated that the corresponding specific average laser powers have been 1.3 $W.cm^{-3}$ for CVL with corrections made for copper pieces aperturing and window losses, 1.4 $W.cm^{-3}$ for CuBr vapor laser and 2 $W.cm^{-3}$ for Cu HyBrID laser. Further reduction in the active volume through reducing the active length to 7.5 cm and 2.54 cm (an inch) keeping the same active diameter of 4.5 mm (Sabotinov et al. 1995) has resulted in unsatisfactorily low average output powers of 1.67 W and several tens of mW, respectively. The specific average laser powers have been 1.4 $W.cm^{-3}$ and less than 0.1 $W.cm^{-3}$, respectively. Unfortunately, a decrease in the active zone diameter of the CuBr vapor laser and the Cu HyBrID laser below 4.5 mm will lead to growth of copper dendrites, which will partially obscure the laser beam. Fortunately, the CVLs suffer no such limitations. Furthermore, reduction in the active diameter keeping the active or cavity length high enough will result in a decrease in laser beam divergence down to the diffraction limit even with a flat-flat stable cavity. In our previous not yet published experiments a high-temperature CVL with a 4-mm bore and an active length of 30 cm, i.e. the active volume is 3.77 cm^3, was studied. An average output power of 1.50 W was obtained, i.e. the specific average laser power was 0.4 $W.cm^{-3}$. In addition to the relatively low average output power, the diffraction-limited laser radiation was obtained only with a negative branch unstable cavity.

In this paper a high-temperature CVL with a 2-mm bore and an active length of 12 cm, which produces a maximum average output power of 0.975 W, is described, i.e. a record-high specific average laser power of 2.6 $W.cm^{-3}$ is achieved for lasers oscillating on the atomic copper self-terminating transitions of any type. Though laser pulse energy is relatively low in comparison with other lasers, such as CVL (Knowles and Brown 1995), CuBr vapor laser (Astadjov et al. 1994) and Cu HyBrID laser (Sabotinov et al. 1995), the specific laser pulse energy is from 4 to 6 times higher than the cited values. The laser tube is also investigated with a standard flat-flat stable resonator at three different cavity lengths. Experimentally determined laser beam divergence is near the diffraction-limited divergence of a Gaussian TEM_{00} beam.

2 Experimental setup

The construction of the new laser tube is schematically depicted in Fig. 1. The active zone is confined by six Al_2O_3 ceramic inserts, which have inside and outside diameters of 2 mm and 6 mm, respectively, and are coaxially mounted in a BeO ceramic tube with an inside diameter of 6 mm and a length of 14 cm. The two end inserts are 1.5 cm long, while the other inserts are 2 cm in length. The Cu pieces, which are not larger than 2 mm, are placed between the Al_2O_3 ceramic inserts. Hence the length of the active zone is 12 cm, i.e. the active volume is 0.377 cm^3. Compact thermal ZrO_2 powder insulation of the discharge zone is applied between the BeO ceramic insert and the basic tube made of fused quartz. Cylindrical copper electrode is used as the grounded electrode, while the high-voltage electrode is made of porous copper. The laser
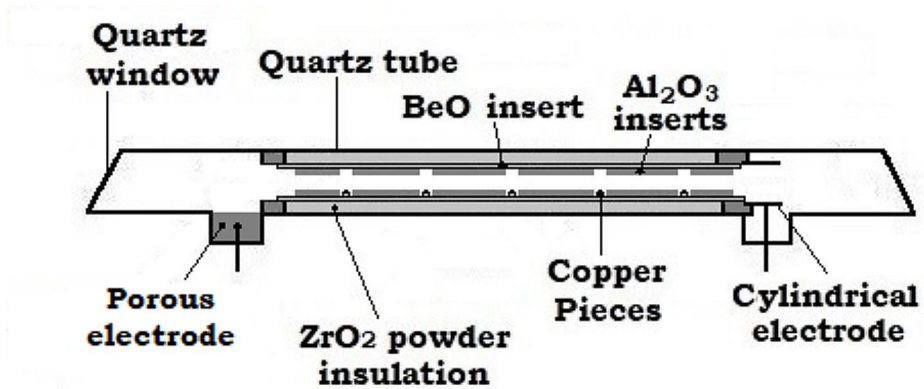
Fig. 1 Schematic diagram of laser tube studied

cavity consists of a flat high-reflectivity mirror for 510.6 nm and 578.2 nm, respectively, and a plane-parallel BK7 glass plate having one-side anti-reflection coating as an output coupler.

The investigated laser tube is excited via an electrical excitation scheme with peaking capacitor, so called capacitor charge transfer circuit. The average output power is measured through a calorimetric power–energy meter Scientech Inc. Vector S310 with a sensitivity range from 200 nm to 10 μm.

3 Results and discussion

Preliminary study on the laser tube showed that the average electrical power must be limited to no more than 1 kW, since the Al_2O_3 ceramic inserts were completely melted and the laser volume were fully apertured.

The average output power as a function of the average electrical power is shown in Fig. 2 with all the relevant input parameters listed on the graph. Specific average laser power is presented as a second vertical axis for convenience. A monotonic growth of the laser power with the increase in the input power is observed.

The dependence of the average laser power on the neon (Ne) buffer-gas pressure is presented in Fig. 3 as well as all the relevant input conditions. Specific average output power is presented as a second vertical axis for convenience. A monotonic growth of the laser power with the decrease in the Ne buffer-gas pressure is observed, as it has been reported for the CVL (Vorob'ev et al. 1991).

The obtained results given in bold are compared in Table 1 with the record-high results achieved so far with CVLs (Vorob'ev et al. 1991; Knowles and Brown 1995), CuBr vapor laser (Astadjov et al. 1994) and Cu HyBrID laser (Sabotinov et al. 1995).

Although the main goal is to achieve higher specific average laser power, which is undeniable accomplished, the specific laser pulse energy is 3.7-time higher than the highest value achieved so far (Sabotinov et al. 1995).

The divergence of each pass (or double-pass) of the CVL radiation for any stable optical resonator is inversely proportional to the length (or the doubled length) of the optical cavity (Salimbeni 1996). A CVL (Brown and Coutts 1996) with an active volume of 4.8 cm^3 (5.5-mm
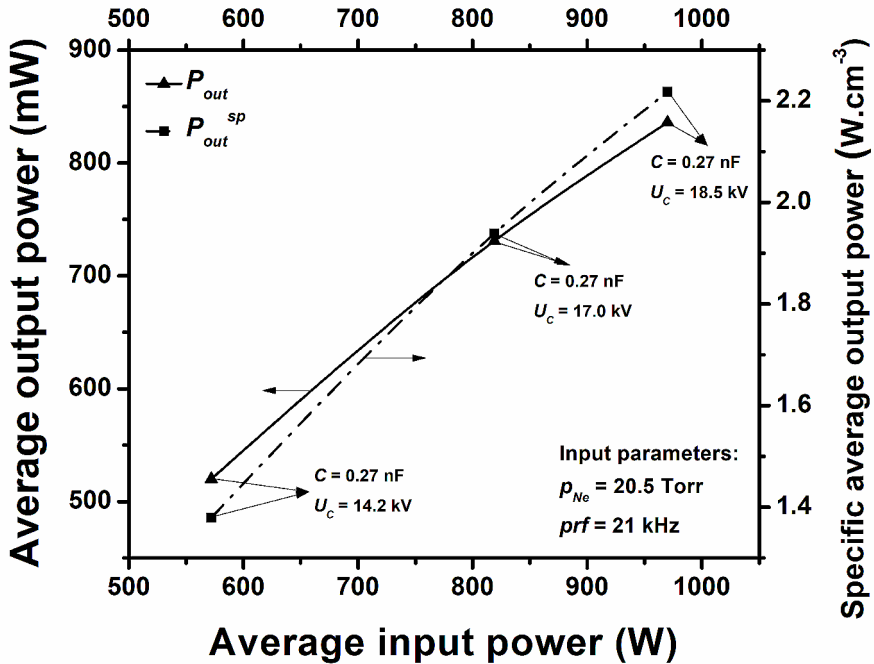
Fig. 2 Average output power as a function of average electrical power

bore and an active length of 20 cm) has produced as much power with diffraction-limited beam quality with a plane-plane resonator as when it has been configured with an unstable cavity. This result and the extremely low inside diameter of our laser tube inspires the investigation of the laser beam divergence with a plane-plane resonator. Laser beam divergence is experimentally determined through beam diameter measurement at different distances, namely 10 m, 25 m and 50 m, for three different cavity lengths, namely 40 cm, 100 cm and 180 cm. Average output power is also measured for each cavity length. The obtained results are summarized in Table 2. The lowest beam divergence is achieved for the resonator length of 180 cm and it is compared in Table 3 with the calculated divergences of a Gaussian TEM_{00} beam and a diffraction-limited flat-top beam.

Studying transverse beam distribution, a diffraction ring patterns are observed for each mirror separation. The minimums grow deeper with the increase in the cavity length and are zeros, as it is seen in Fig. 4, for the cavity length of 180 cm. Moreover, at the cavity length of 180 cm the same pattern is observed for single- and double-pass laser radiation, i.e. without output coupler. The alignment of the output coupler only increases the laser power. Such pattern has been also reported for a CVL with a beam propagation factor M^2 of 1.3 (Withfold et al. 2004).
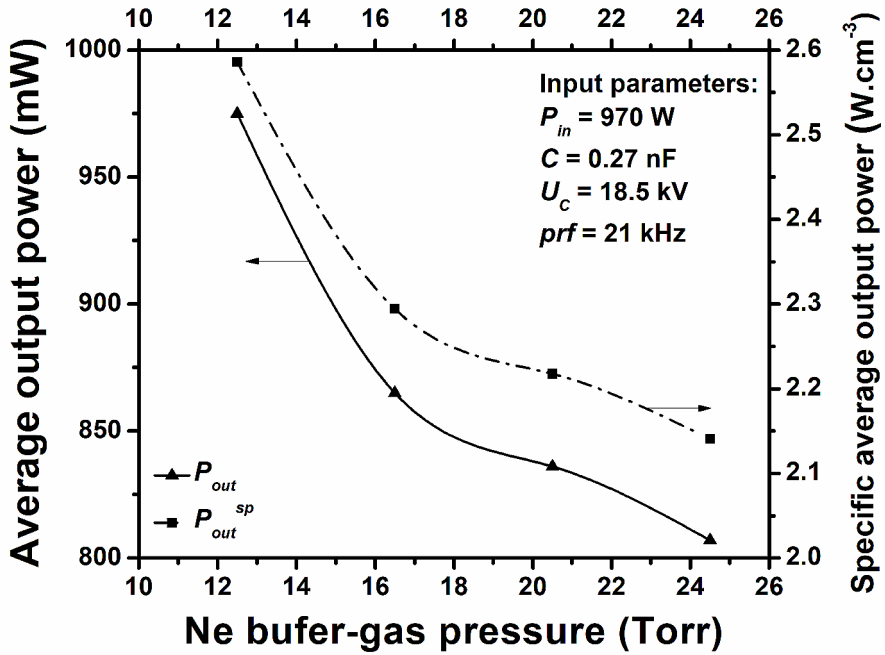
Fig. 3 Dependence of average output power on Ne buffer-gas pressure

Table 1 Features of discharge tubes, electrical input parameters and output laser characteristics: V_a – active zone volume; prf – pulse repetition frequency; P_{in} – average electrical power; P_{out} – average output power; $P_{out}{}^{sp}$ – specific average laser power; E_p – laser pulse energy; $E_p{}^{sp}$ – specific laser pulse energy

Laser tube	V_a (cm³)	prf (kHz)	P_{in} (W)	P_{out} (W)	$P_{out}{}^{sp}$ (W/cm³)	E_p (µJ)	$E_p{}^{sp}$ (µJ /cm³)	Reference
CVL	**0.377**	**21**	**970**	**0.975**	**2.6**	**46**	**123**	
CVL	2.385	70	989	3.1	1.3	44	19	(Vorob'ev et al. 1991)
CVL	5.227	4	–	0.5	0.1	125	24	(Knowles and Brown
		16	–	2.1	0.4	131	25	1995)
		24	–	3.0	0.6	125	24	
CuBr vapor laser	4.771	52	1000	6.7	1.4	129	27	(Astadjov et al. 1994)
Cu HyBrID laser	4.771	53.5	1380	5.4	1.1	101	21	(Sabotinov et al. 1995)
Cu HyBrID laser	4.771	60	1781	9.5	2.0	158	33	(Sabotinov et al. 1995)
Cu HyBrID laser	1.193	60	1080	1.67	1.4	28	23	(Sabotinov et al. 1995)
Cu HyBrID laser	0.404	–	–	<0.05	<0.1	–	–	(Sabotinov et al. 1995)

Table 2 Cavity length alteration: l_c – cavity length; P_{out} – average laser power

l_c (cm)	40	100	180
P_{out} (W)	350	250	60

Table 3 Beam divergence measurements: DL^G and DL^Y – Beam divergence of a diffraction-limited flat-top beam for 510.6 nm and 578.2 nm, respectively; $\theta_{exp}{}^G$ and $\theta_{exp}{}^Y$ – beam divergence experimentally determined for 510.6 nm and 578.2 nm, respectively; $\theta_{00}{}^G$ and $\theta_{00}{}^Y$ – beam divergence of a gaussian TEM_{00} beam for 510.6 nm and 578.2 nm, respectively; $M^2{}_G$ and $M^2{}_Y$ – beam propagation factor for 510.6 nm and 578.2 nm, respectively

DL^G (μrad)	$\theta_{exp}{}^G$ (μrad)	$\theta_{00}{}^G$ (μrad)	$M^2{}_G$	DL^Y (μrad)	$\theta_{exp}{}^Y$ (μrad)	$\theta_{00}{}^Y$ (μrad)	$M^2{}_Y$
623	420	325	1.29	705	538	368	1.46
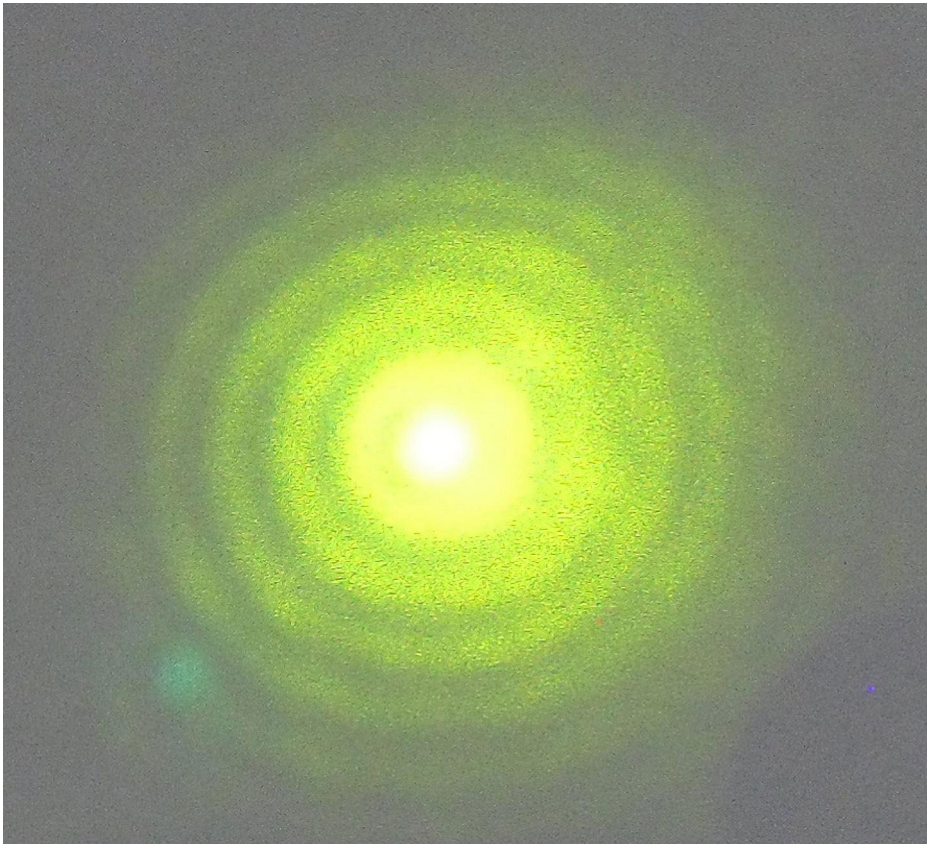
Fig. 4 Laser spot at cavity length of 180 cm

4 Conclusions

The small-bore copper vapor laser with an active volume of 0.377 cm^3 delivers an average laser power of 0.975 W, i.e. a record specific average power of 2.6 W.cm^{-3} is obtained for copper lasers of any type. Though the increase in comparison with the highest value of 2.0 W.cm^{-3}

achieved so far is 30%, the obtained specific laser pulse energy of 123 µJ.cm^{-3} is 3.7-fold higher than the highest value achieved to date. Experimentally determined laser beam divergence for flat-flat stable cavity is near the diffraction-limited divergence of a Gaussian TEM$_{00}$ beam and lower than the diffraction-limited divergence of a flat-top beam.

Author contributions I. K. designed and developed the laser tube, conducted the experiment and constructively reviewed the first draft of the manuscript.K. T. participated and assisted in the experiment, drew some of the figures, found the relevant references and wrote the manuscript.S. S. processed the data and drew some of the figures.G. Y. is the coordinator of the Project KP-06-H37/2 "Basic research and development of high-beam-quality high-power laser system oscillating in visible spectral range" of Bulgarian National Science Fund.All authors approved the scientific content of the manuscript prior to submission.

Data availability No datasets were generated or analysed during the current study.

Declarations

Conflict of interest The authors have no conflicts of interest to declare that are relevant to the content of this article. The authors also state that the results, which are presented in this paper, are new and original and do not exists in publicly archived datasets.

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