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Amplifying characteristics of small-bore copper bromide lasers

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Abstract

A pair of copper bromide lasers in an oscillator–amplifier configuration was operated to measure and compare the small-signal gains and saturation intensities, as amplifying parameters of different laser tube lengths. The independencies of these amplifying parameters on the different amplifier tubes length with identical diameter were investigated, individually. Therefore, the output powers of the system were measured in different tubes lengths of amplifier and the optimum conditions were obtained. It was shown that, by changing the amplifier tube length, the amplifying parameters remain nearly constant without any remarkably changing, but the output power of the system was increased linearly due to increase of tube length. The experimental results were in good agreement with the theory. Moreover, the radial gain distribution was studied.

1 Introduction

Considerable attention has been given recently to lasers using the vapors of different compounds of copper. A technique for using copper halide as the source of copper atoms in a copper vapor laser (CVL) was first reported in 1973 [1, 2]. The operating temperature depends on the vapor pressure of the compounds and is about 510 °C for copper bromide laser (CBL), which is much lower than that of the CVL. Since a CBL can produce the wavelengths of 510.6- (green) and 578.2 nm (yellow) in visible region, similar to CVL one, then, the CBL has the same attractive applications of CVL in different areas of science and technology. The important advantage of a CBL compared with the CVL is having higher beam quality, which is better suited to many applications. The popular application of CBLs' brightness amplifiers is in visualization systems—laser monitors [3]. Such systems have been used to study the high-temperature processes and modification of materials, and gain plays as a key role in this manner [4, 5]. In addition, some works have been studied on spatial–temporal gain distribution on CBL [6, 7]. The other advantages of the CBL are simpler construction of tube, reduction of start-up time for laser oscillation from a cold start, higher pulse repetition frequency, higher wall-plug efficiency, and a pseudo-Gaussian beam intensity profile which is better suited to many applications than the top-hat profile of the CVL [8, 9]. On the other hand, the amplifying parameters of small-signal gain, g_0, and saturation intensity, $E_{s,}$ are important parameters to design and scale the lasers. In general, the master oscillator–power amplifier (MOPA) has been used for determining of these parameters. The CBL MOPA systems have been used to different technological applications, and also the development of the MOPA system in a CBL operating at 110 W average power has been reported [10, 11]. In our previous works, we used an MOPA system in the CVL, gold vapor laser (GVL), and CBL, to satisfy higher output power and beam quality simultaneously [12–17]. The gain characteristics and temperature profile have been achieved for CVLs and CBLs [6, 18–21]. In this work, the MOPA system of the CBL has been employed to investigate the behaviors of g_0, E_s and laser output power, P_{out}, versus the active gain length. There is an optimum delay time between the oscillator and its amplifier which the system produces its maximum output power. It was shown that by changing the amplifier tube length, the amplifying parameters remain nearly constant without any remarkable changing, but P_{out} of the system was increased linearly due to increasing of the laser volume through tube length. The experimental results were in good agreement with the theoretical relations. Moreover, the radial gain distributions of CBLs with different bore tubes have been studied.

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2 Experimental setup

In this work, five cylindrical tubes with the same inner diameter of 20 mm, but different active gain lengths of 28 (2 tubes), 38, 48, and 58 cm have been designed and constructed to investigate the effect of the active length on the amplifying parameters and output power of CBL. For measuring of the amplifying parameters, we used the Hargrove's model instead of the Frantz–Nodvik formula which has been used by other researchers, previously [22, 23]. The setup of experiments is similar to our previous works for CVL, GVL, and CBL MOPAs [12–17]. One heated side-arm reservoir of CuBr, which is located at the middle of the length of the tubes, is used to seed the discharge zone with the CuBr vapor. The laser tubes operated in self-heated mode. Hollow cylindrical water-cooled copper electrodes have been used. An independent electrical power source and its corresponding pulse generator have driven to each laser head. Two subsequent electrical discharges are produced which related delay time can be controlled manually by trigger. The entrance time of the laser pulse must be synchronized with the maximum inversion population of the amplifying medium. There is an optimum delay time between the lasers which the amplifier produces its maximum output power. Figure 1 illustrates schematic representation of the CBL MOPA which has been arranged for our main experiments. The master oscillator has been operated with a critical resonator constructed by a flat dielectric coated with high reflection coefficient of 98% as back mirror and uncoated flat quartz with reflectance coefficient of reflectivity ~ 4% as the output coupler. The input and output powers of the amplifier are measured by two Molectron™ PM500D power meters. The actual measured input energy has been corrected by consideration of losses due to the amplifier entrance window. Two high-voltage probes P6015 and an oscilloscope Tektronix™ model TDS1250 have been used for controlling of the delay time.

3 Results and discussion

There is an optimum electrical input power: a key parameter that determines the population inversion, for each length of the amplifier tube, which gives maximum output power. Of course, these optimum electrical input powers are not the same for different lengths of tubes, but the specific electrical input powers of all tubes are nearly the same (~ 11.5 W/cm^3). The tube parameters with optimal pumping powers and specific input powers are inserted in Table 1.

The amplifier output power versus electrical input power and tube length for each of four lengths of the tubes are shown in Fig. 2.

In other electrical input power values except of the optimum one, the output power is decreased due to unsuitable

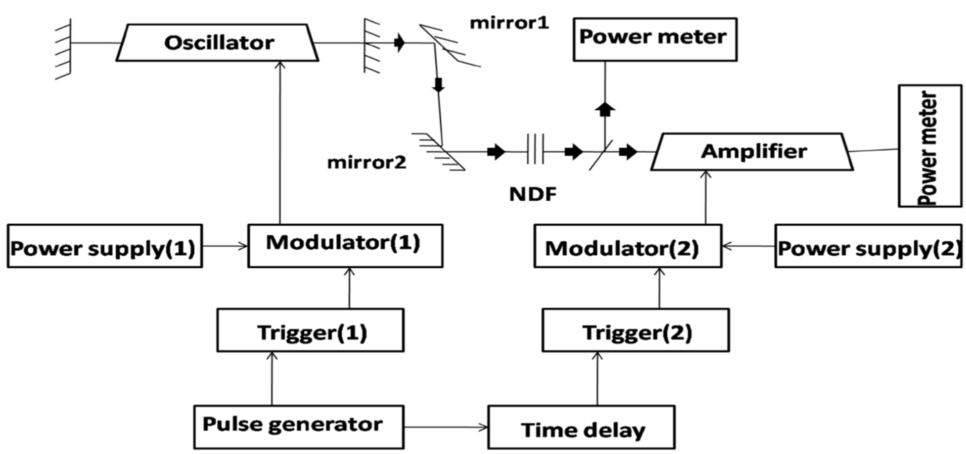


Fig. 1 Schematic representation of the CBL MOPA

Table 1 Amplifier tube parameters with optimal pumping parameters and specific input powers

L (cm)	*V* (cm^3)	Optimum electrical input power (kW)	Optical input power (W)	P_{out} (W)	Specific electrical input power (W/cm^3)	Specific optical input power (W/cm^3)
28	87.92	1.2	2	5.8	11.4	0.023
38	119.32	1.38	2	7.7	11.5	0.017
48	150.72	1.75	2	9.6	11.6	0.013
58	182.12	2.1	2	11.4	11.5	0.010

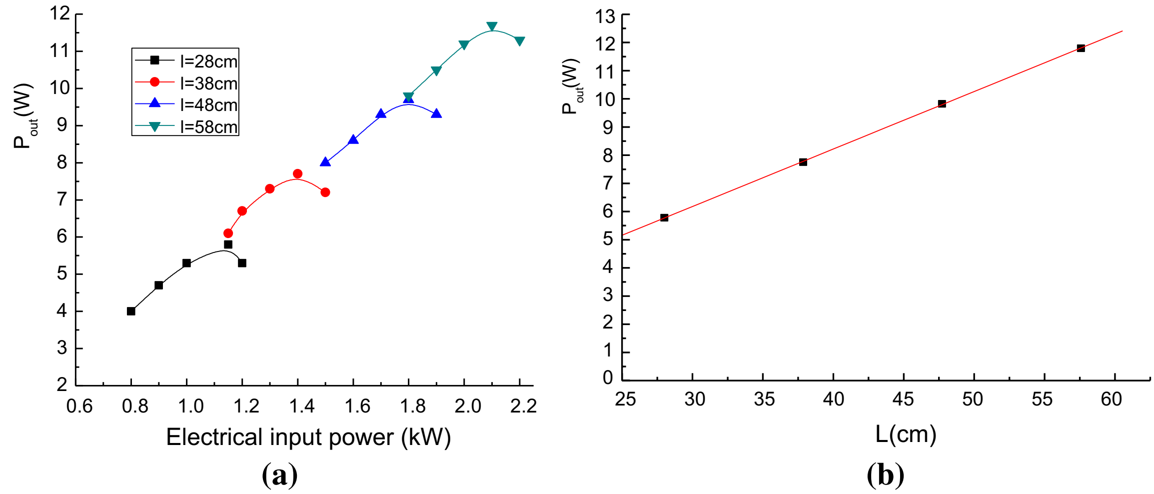


Fig. 2 Amplifier output power versus **a** electrical input power and **b** tube lengths

electrons temperature for forming of desirable population inversion. The amplifier output power is increased linearly by increasing of the tube length, due to increasing of gain medium volume, which is obvious. One of the shortest tubes, 28 cm, is employed as an oscillator and the other tubes are employed, individually as an amplifier in the CBL MOPA system. Helium is utilized as the buffer gas. Maximum output powers are obtained from the amplifier at optimum conditions, i.e., 11 torr of buffer gas pressure, 20 kHz of frequency, and its optimum electrical input power.

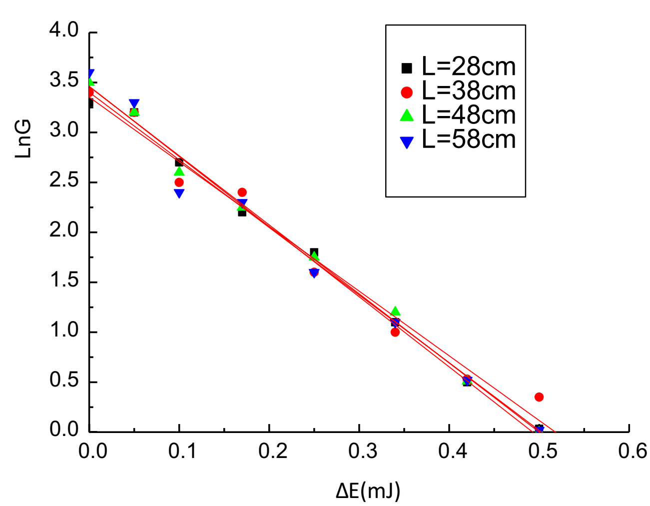
Since the Doppler broadening is sufficiently greater than the pressure broadening linewidth for a typical CBL as the CVL one, the amplifying medium is assumed to be an inhomogeneous broadened gain medium. Here, g_0 (cm^{-1}) and E_S (μJ/cm^2) can be calculated with a least-square fitting of the experimental data into the Hargrove equation given by [12, 16, 17]

$$\mathrm{Ln}G = g_0 l - \left(\Delta E / A E_S\right), \quad (1)$$

where $G = E_{out}/E_{in}$ is the energy gain, $\Delta E = E_{out} - E_{in}$ is the energy difference, and A, l, $E_{out,}$ and E_{in} are the probe beam area, the length of the amplifying medium, and output and input optical energies to the amplifier, respectively. The amplifying parameters can be determined by the graphical representation of ln$G$, on the ordinate, versus the difference output and input energies of amplifier, ΔE, on the abscissa. The experimental results for different lengths of amplifier tubes are shown in Fig. 3.

From Fig. 3, the amplifying parameters can be determined. By Eq. 1, the values of g_0 are determined between the interval of 0.069 and 0.073 cm^{-1}, and the values of E_s are determined between 45 and 48 μJ/cm^2. These results indicate that the amplifying parameters nearly kept constant at different lengths of the tubes and a little difference between them

Fig. 3 Variation of the energy gain (LnG) versus energy difference (ΔE)



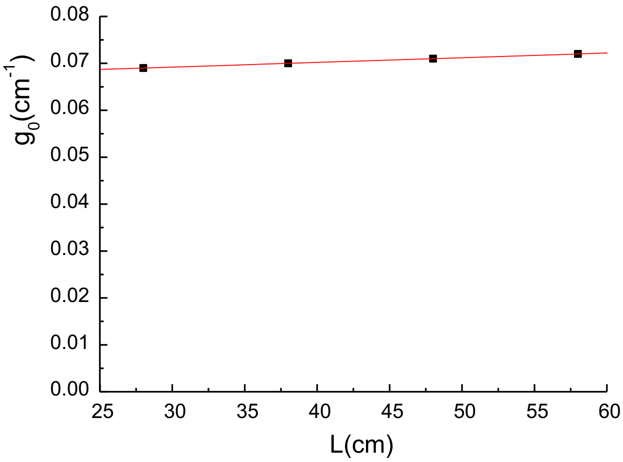


Fig. 4 Variation of the small-signal gain versus tube length

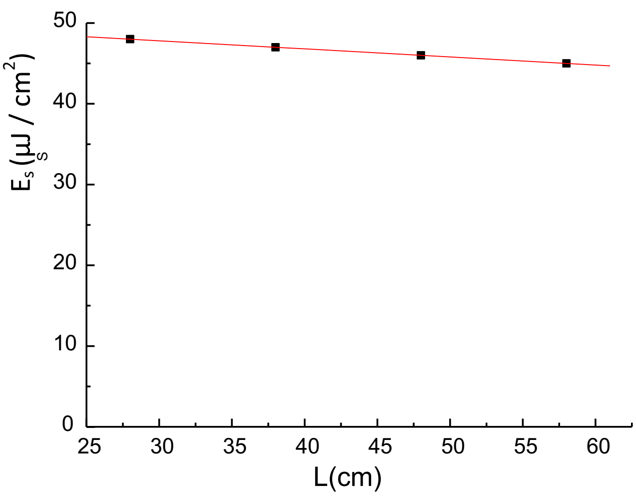


Fig. 5 Variation of the saturation intensity versus tube length

can be related to the experimental errors. The tube length independency of g_0 and E_s is shown in Figs. 4 and 5, respectively, at the corresponding optimum electrical input power. As we can see, the variations of both amplifying parameters versus tube length are negligible.

The results of our experiments demonstrated that, by increasing of tube length, g_0 and E_s are approximately constant.

It should be noted that during our experiments, the tube wall temperature (here 510 °C) is kept constant, and then, the stimulated emission cross section, σ_{st}, is approximately remain constant. Therefore, the small-signal gain, $g_0 = \sigma_{st}\Delta N$, may be only dependent on population inversion, ΔN. By increasing of the laser tube length, the electrical input power for discharging is increased, so. However, at each optimum electrical input power due to the related tube length, the temperature of electrons to produce of maximum ΔN is nearly constant for different lengths of tubes; therefore, ΔN is nearly remain constant, and then, g_0 is independent on tube length, as shown in Fig. 4. The experimental result is in agreement with the definition of g_0, i.e., the gain per length unit. On the other hand, because the collisions rate remains constant at fixed temperature, the upper level lifetime, τ_2, is nearly kept constant for different lengths of tubes; therefore, the saturation intensity, $E_s = h\nu/\sigma_{st}\tau_2$, is kept constant and independent on the tube length, as shown in Fig. 5. Finally, the output power, P_{out}, is increased linearly by increasing of tube length, due to more copper atoms to involve in laser processing, which is in agreement with relation of $P_{out} \sim g_0 E_s A l$, and the laser output power is dependent on medium volume, Al, and then tube length, l, as shown in Fig. 2b.

It is necessary to mentioned that the average small-signal gains of tubes have been measured in this work. It is essential to study the gain characteristics of the active medium in particular; the radial gain distribution which depended on bore, not length of laser tube. The gain profile in large and medium bores of CBLs tubes, through one pass gain [18], and double pass gain [6] methods have been investigated. The axial dip of the intensity in the tubes of large and medium bores can be due to the different efficiencies of excitation of the resonant and metastable levels because of increasing electron concentration during the pumping pulses, or due to the different velocities of volumetrically and near-wall mechanisms of plasma relaxation. The overheating at the axis, the radial inhomogeneity of electric field, and skin effect can also contribute to the radial inhomogeneity [6]. However, it seems that the above-mentioned mechanisms have less effect on gain profile in small-bore tubes. Therefore, we expected that the gain profile of our small-bore tubes can be flatter and close to the Gaussian's shape.

In our previous works, a semi-experimental method was used for measuring the plasma temperature and obtaining the temperature profile of CVL and CBL [19–21]. The temperature of the center region is higher than that of the tube wall. At temperature above that of the optimum value (here 510 °C) in the center region, σ_{st} increases through increasing of Doppler width proportional to $T^{1/2}$, and the Doppler broadened line shape, so, but ΔN decreased mainly due to inelastic collisions. In this case, ΔN has a dominant effect relative to σ_{st}. The result indicates that g_0 and the gain will decrease [21]. At optimum temperature, g_0 and the gain have highest value, which this occurs between axial and wall region. At temperature lower than that of optimum value, the gains are dropped, especially, near the tube wall. Therefore, the radial gain distribution has a similar behavior to radial temperature profile. Moreover, the radial gain distributions are the same for identical bore and different lengths of tubes.

It seems that the gain profile in small-bore tubes can be flatter and close to the Gaussian's shape.

4 Conclusion

The small-signal gain and saturation intensity of a couple of copper bromide laser in an oscillator–amplifier configuration, with different tube lengths of amplifier, are obtained. The values of small-signal gain are determined interval of 0.069 and 0.073 cm^{-1}, and the values of saturation intensity are determined interval of 45 and 48 $\mu J/cm^2$. It is shown experimentally that the amplifying parameters of a CuBr laser are independent on the laser tube lengths, which are in agreement with their theory relations. The laser output power is increased linearly from 5.8 to 11.7 W by increasing of tube length from 28 up to 58 cm. The result indicates that the laser output power is dependent on tube length. On the other hand, it is predicted that the laser output power will be decreased at higher tube lengths, due to beam absorption by tube wall. In accordance with theoretical relations, the amplifying parameters are only dependent on microscopic parameters such as stimulated emission cross section, population inversion and upper level lifetime, and independent on geometry of laser tube such as tube length, as a macroscopic parameter.

The radial gain distribution has a similar behavior to that of the temperature profile, and the profiles are the same for tubes with identical bores and different lengths. It seems that the gain profile in small-bore tubes can be flatter and close to the Gaussian's shape.

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