High-Power Diffraction-Limited Laser Systems with Variable Output Characteristics Oscillating in Visible Spectral Range on Atomic Copper Self-terminating Transitions for Advanced Material Microprocessing

I. K. Kostadinov, K. A. Temelkov, S. I. Slaveeva and G. P. Yankov

Institute of Solid State Physics, Bulgarian Academy of Sciences
72 Tzarigradsko Chaussee, 1784 Sofia, BULGARIA

temelkov@issp.bas.bg

Introduction

Though the continuous development of copper vapour lasers and their low-temperature variants (copper halide vapor and HyBrID copper lasers), which are the most powerful lasers in the visible spectral region, toward the design of compact reliable sealed-off lasers is quite successful, the competing with the solid state lasers operating in the visible spectral range via second harmonic generation is far from over. Commercial solid state lasers produced by leading laser companies usually delivers TEM_{00} Gaussian laser beam, i. e. beam propagation factor M^2 is well in the range between 1.05 and 1.3, while metal vapor lasers produce partially or near diffraction-limited laser radiation (up to 90 % of the laser output is diffraction-limited) with a record-low $M^2 = 1.3$, due to the short laser pulse and a small number of the cavity round-passes. The Master Oscillator – Power Amplifier (MO–PA) system based on the atomic Cu bromide (CuBr) vapor laser is well established as a laser source used for precise micromachining in the industry for drilling, cutting, scribing, marking, welding, etc. of various materials. Though the development and operation difficulties, the atomic Cu vapor laser has unsurpassable advantages over the Cu halide vapor lasers, namely lasing stability, higher laser pulse energy at the same average output power, two-time shorter laser pulse, the possibility to operate with small-bore laser tubes (the aperture smaller than 4 mm), etc.

Aims

To develop and investigated a new considerably improved MO–PA laser systems delivering high-power diffraction-limited laser radiation ($M^2 = 1$) at the atomic copper 510.6- and 578.2-nm lines, as follows:

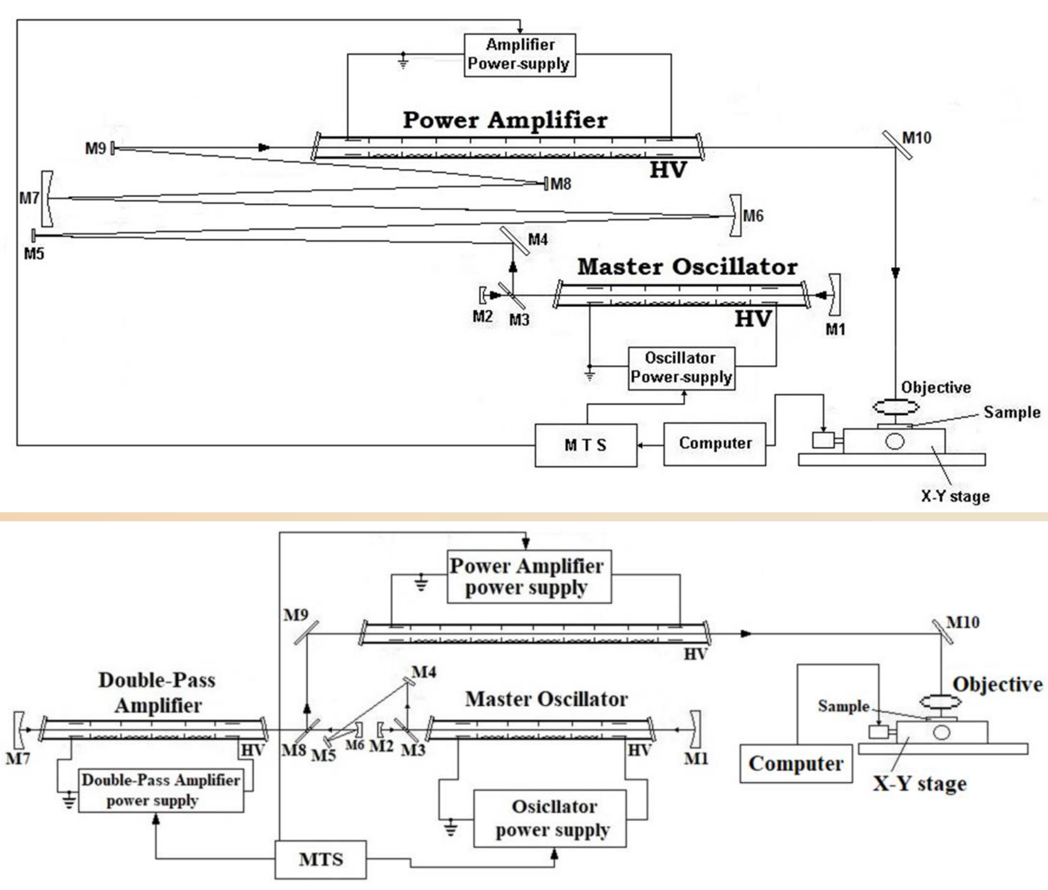
1) as a Master Oscillator (MO), to compare laser characteristics of CuBr vapor MO operating with a negative branch unstable resonator (NBUR) and small-bore Cu vapor MO oscillating with a flat-flat stable cavity and a NBUR;

2) 2) to compare two CuBr vapor laser tubes with a significantly enhanced active volume as a Power Amplifier (PA), in order to increase considerably the output parameters;

3) 3) to realize various designs of the MO–PA laser systems, namely single- and double-pass PAs (PA and DPA), matching telescopes (MTs) with different magnifications *M*;

4) 4) laser radiation is applied in precise micron-sized material processing of silicon (Si) using achromatic short-focus focusing lenses.

Experimental setup



(a)

Fig. 1. Schematic diagram of studied MO–PA (a) and MO–DPA–PA (b) laser systems.

(b)

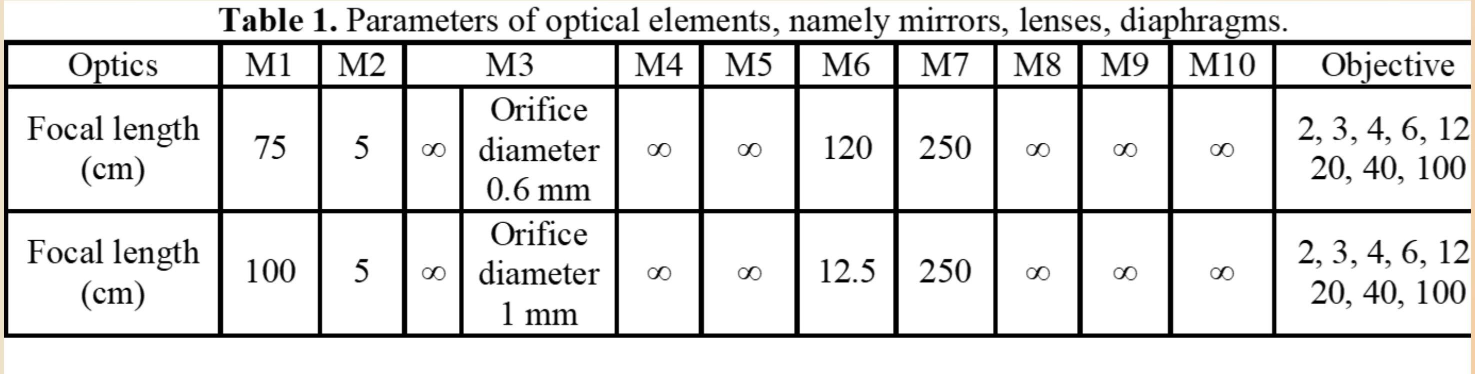


Table 1. Parameters of optical elements, namely mirrors, lenses, diaphragms.

Optics	M1	M2	M3		M4	M5	M6	M7	M8	M9	M10	Objective
Focal length (cm)	75	5	∞	Orifice diameter 0.6 mm	∞	∞	120	250	∞	∞	∞	2, 3, 4, 6, 12 20, 40, 100
Focal length (cm)	100	5	∞	Orifice diameter 1 mm	∞	∞	12.5	250	∞	∞	∞	2, 3, 4, 6, 12 20, 40, 100

Experimental results

First method for M^2 experimental determination

$$M^2 = \frac{\theta}{\theta_{00}} = \frac{\pi}{4\lambda f} Dd$$

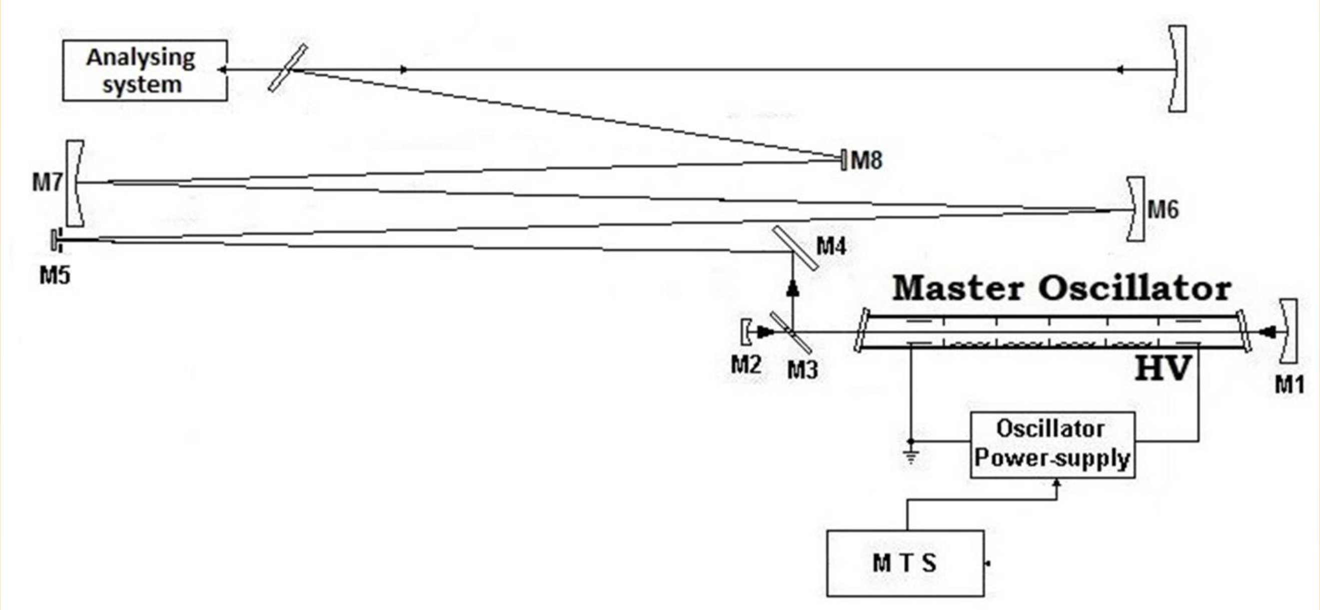


Fig. 2. Experimental setup for M^2 determination.

Table 2. Laser beam divergence for 510.6-nm wavelength: D – laser beam diameter; d^{exp} – laser spot diameter measured in focal plane of concave mirror with focal distance of 2.5 m; θ^{exp} – experimentally determined laser beam divergence using the expression $\theta^{exp} = d^{exp} / f$; θ_{00} – laser beam divergence calculated for TEM$_{00}$ Gaussian beam with diameter D; $M^2 = \theta^{exp}/\theta_{00}$.

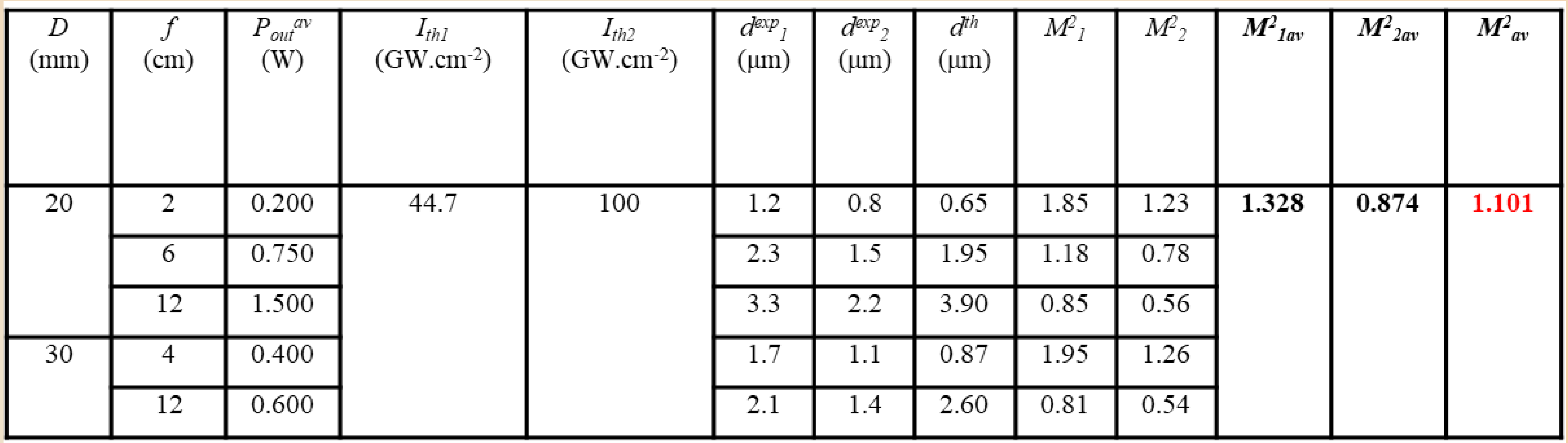
D (mm)	d^{exp} (μm)	θ^{exp} (μrad)	θ_{00} (μrad)	M^2
5	330 ± 20	132 ± 8	130.0	**1.02**
10	165 ± 10	66 ± 4	65.0	**1.02**
15	110 ± 10	44 ± 4	43.3	**1.02**
20	82 ± 5	33 ± 2	32.5	**1.02**
25	67 ± 5	27 ± 2	26.0	**1.04**

Experimental results

Second method for M^2 experimental determination

$$I_{th}=\frac{4P_{out}^{\;p}}{\pi.d^2}=\frac{4E}{\pi.d^2\tau_p}=\frac{4P_{out}^{\;av}}{\pi.d^2\,prf.\tau_p}\Rightarrow d=\sqrt{\frac{4P_{out}^{\;av}}{\pi.prf.\tau_p.I_{th}}}$$

Table 3. Laser spot diameter determined through volumetric optical breakdown for 510.6-nm wavelength: f – focal distance; $P_{out}av$ – threshold average output power; I_{th1} and I_{th2} – threshold laser intensity taken from the references; d_{exp1} and d_{exp2} – laser spot diameter experimentally determined using Ith_1 and Ith_2, respectively; $d_{th} = f.\theta_{00}$; prf – 20 kHz, τ_p = 20 ns.



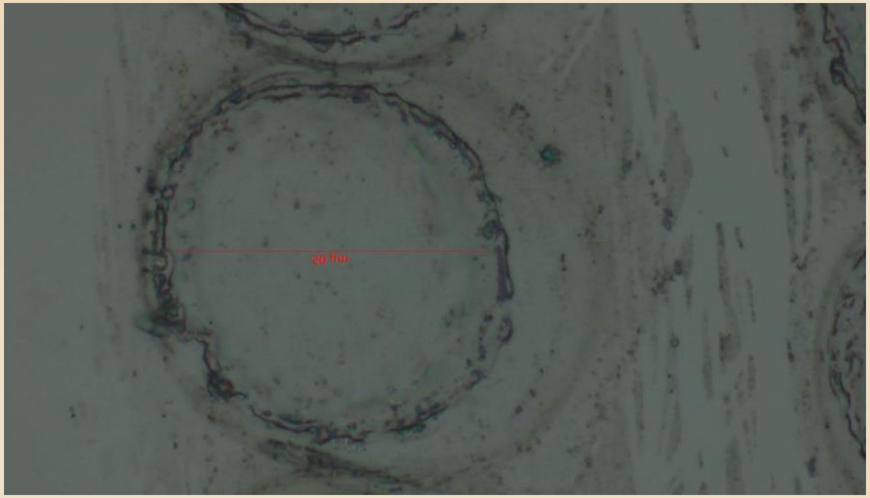
D (mm)	f (cm)	P_{out}^{av} (W)	I_{th1} (GW.cm^{-2})	I_{th2} (GW.cm^{-2})	d^{exp}_1 (μm)	d^{exp}_2 (μm)	d^{th} (μm)	M^2_1	M^2_2	M^2_{1av}	M^2_{2av}	M^2_{av}
20	2	0.200	44.7	100	1.2	0.8	0.65	1.85	1.23	**1.328**	**0.874**	**1.101**
	6	0.750			2.3	1.5	1.95	1.18	0.78			
	12	1.500			3.3	2.2	3.90	0.85	0.56			
30	4	0.400			1.7	1.1	0.87	1.95	1.26			
	12	0.600			2.1	1.4	2.60	0.81	0.54			

Experimental results

Precise microprocessing of Si samples at various focusing distances and average output powers

(a)

(b)



(c)

Fig. 3. Microcraters and microchannels drilled or cut at 2- (a) and (b) and 100-cm focusing distances (c) with 10- (left image) and 100-mW (right image) average laser power in Si samples.

Conclusions

The highest beam quality achieved so far with laser systems oscillating on the metal self-terminating transitions is confirmed by precise measurement of the threshold average output power for volumetric optical breakdown at different focusing distances *f* and a known breakdown threshold I_{th}. Laser radiation with both record-high average output power of 50 W and beam quality is obtained. Precised micromachining of Si samples with crater diameter or trench width of 1.5 µm is accomplished applying achromatic 2-cm focusing lens.

Acknowledgements

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