Recent Progress on Copper Laser Development and Applications at IEAv*

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This paper describes the present status of copper laser development and applications at IEAv. Copper HyBrID lasers with mean power of 27 W and an efficiency of 1.3% at 17 kHz repetition rate have been developed. A prototype is being evaluated for medical applications. Microprocessing of Al, Cu, W and CVD diamond presented excellent prospects for the application of this laser in the material processing area.

Este artigo apresenta a situação atual do programa de desenvolvimento e aplicações de lasers de cobre no IEAv. Foi desenvolvido um laser de Cu-HBr (Hybrid) com 27W de potência e uma eficiência de 1,3% à taxa de repetição de 17 kHZ. Um protótipo para aplicações médicas está em fase final de testes. Testes realizados em microprocessamento de Al, Cu, W e diamante CVD mostraram excelentes perspectivas de aplicação para este laser na área de processamento de materiais.

I. Introduction

The copper laser development started at IEAv (Instituto de Estudos Avançados - Centro Técnico Aeroespacial) in 1983 with the aim of giving support to the atomic vapor laser isotope separation program. The first studied configuration was an externally heated copper salt laser, with the best results in the range of 100 mW of average power and 100 Hz of repetition rate [1]. In this laser the atomic copper vapor, necessary for laser action, is produced by heating some copper salt (CuBr usually) that has a high vapor pressure at relatively low temperature. The salt molecule is then broken into its components in the discharge, due mainly to collisions with electrons.

At the end of 1984 our attention moved towards the self heated copper vapor laser (true CVL), because of the higher output power. In these lasers the heat due to Joule effect in discharge heats solid pieces of copper placed inside the laser tube, producing the necessary atomic copper vapor. The typical operation temperature is about 1500 Celsius degrees. Several prototypes have been constructed, with some of them still in normal operation today, with the best results in the range of 40 W of average power, 0.8% efficiency, 5 kHz repetition rate and beam quality of about $M^2 \sim 100$, with plane-parallel resonators, and $M^2 \sim 6$, with unstable resonators. In 1989 we transferred CVL technology to the industry. During all this time, CVL's were applied at IEAv, almost exclusively to dye lasers pumping.

At the end of 1993 we started to work with a new technology of copper lasers, called HyBrID laser (Hydrogen Bromide In Discharge) by the group that proposed this technology [2]. This laser is actually a hybrid technology between the copper salt and the copper vapor lasers. Solid pieces of copper are placed inside the laser tube filled with a flowing mixture of neon and HBr. CuBr is produced and broken into Cu and

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Br atoms in discharge conditions. This kind of laser has many attractive characteristics when compared to the CVL: higher efficiency, higher repetition rate, lower working temperature, shorter warm-up time and intrinsically much better beam quality. The price to be paid the manipulation of HBr, a corrosive gas that demands careful handling.

The HyBrID copper laser

The HyBrID copper laser head consists on a ceramic alumina tube sleeved by a quartz tube, attached to stainless steel blocks that work as flanges, electrodes and gas in and outlet, as diagrammed in Fig. 1. The gas mixture of Ne and HBr, with typical concentrations of about 95% and 5% respectively, is introduced in the cathode side, flows through the laser tube and exits through the anode flange. The electric discharge heats the laser tube and, with the inner walls above 400°C, the HBr reacts with copper pieces, placed inside the laser tube, generating CuBr and H_2. The mentioned temperature is necessary to keep the CuBr in the vapor phase. Due to electron impact, the CuBr is broken into its atomic components and Cu atoms are excited, providing the laser pumping. Two HyBrID copper laser prototypes were constructed and are in operation nowadays in our laboratory, used in parametric studies of the laser as oscillator [3] and as amplifier [4]. Both of them have 0.7 m long and 2.5 cm diameter laser tubes.

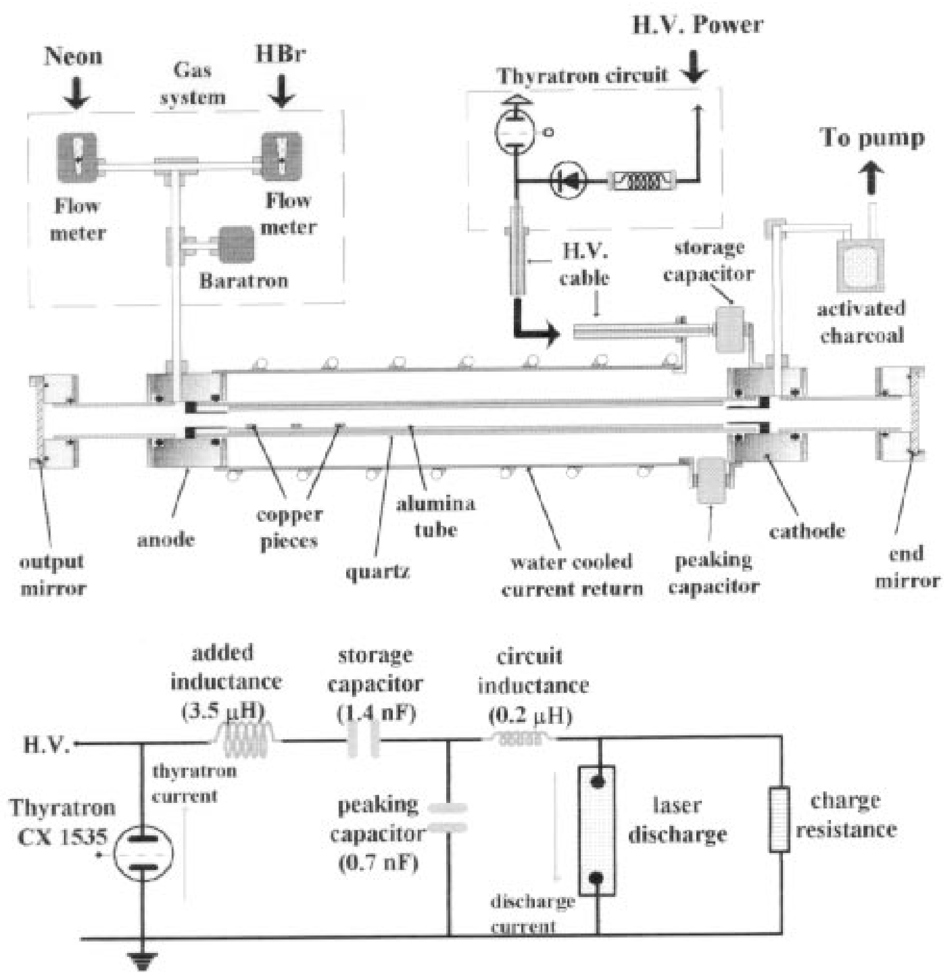

Figure 1. Diagram of the copper HyBrID laser setup.

The electric circuits are the conventionally used in CVLs, shown in Fig. 1. A high voltage power supply charges a storage capacitor through the inductance and the charge resistor. When the thyratron is triggered, the storage capacitor is grounded and it stored charge is delivered to the laser tube. These circuits allowed testing the laser operation with pulse repetition rates up to 20 kHz.

The study of the laser performance as function of different parameters allowed the optimization of these prototypes. The Ne:HBr proportion that resulted in maximun output power was 95:5 and the optimum pressure was between 20 and 25 mbar. Fig. 2 shows the laser output power and conversion efficiency against electric input power, with the gas proportion and pressure as above. The maximum output power obtained with these prototypes was 27 W, which is twice the power density that is possible to obtain with a simular conventional Copper Vapor Laser. The maximum conversion efficiency, around 1.3%, is also higher than in the case of Copper Vapor Lasers (about 1.0%).

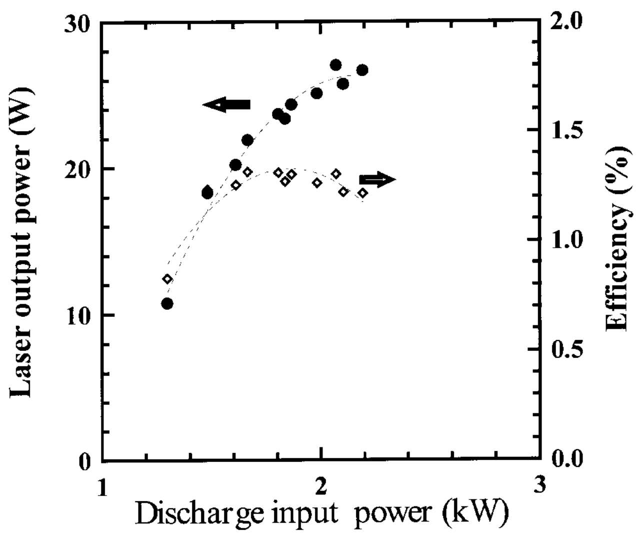

Figure 2. Dependence of laser output power and efficiency with discharge input power.

Another remarkable advantage for the HyBrID laser is the radial gain profile. The Copper Vapor Laser has a characteristic gain concentration close to the laser tube walls, as seen in Fig. 3, while HyBrID lasers have a bell shaped gain distribution, which is greatly favorable for good beam quality generation. In fact, comparing the measured M^2 for both kinds of lasers, operating with plane-parallel resonator, resulted in nearly 100 for a conventional Copper Vapor Laser and about 32 for the HyBrID one.

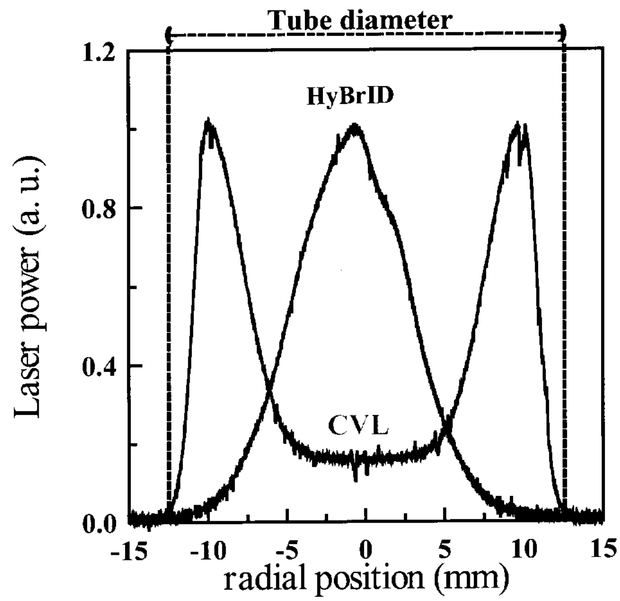

Figure 3. Emission profile of CVL and HyBrID lasers. The straight lines indicate a tube walls.

In Table 1 some experimental results with HyBrID lasers are compared with the best results obtained with conventional CVL's, also built at IEAv, in order to stress the advantages of the HyBrID laser over conventional CVLs.

Amplification studies have been accomplished using one of the HyBrID prototype as oscillator and the other as amplifier. The experimental results are shown in Figs. 4 and 5. We measured saturation fluences of 51.3 e 40.7 $\mu J/cm^2$ for the green (510,6 nm) and yellow (578,2 nm) transitions respectively and a small signal gain of about 0.18 cm^{-1} for both lines. It was also observed that it is possible to extract about 30% more power using these copper HyBrID lasers as amplifier than as oscillator. In the same condition in which the laser produced 19 W of output power as oscillator it was possible to extract 25.5 W operating it as amplifier. However, it is still necessary to study the influence of amplification on the laser beam quality to evaluate the advantage of amplifiers over powerful oscillators.

Characteristics	Cu10	Cu40	Cu-HBr
Average Power (W)	11	38	27
Opt. pulse repetition rate (kHz)	9	6	18
Pulse repetition rate range (kHz)	6-12	5-10	12-22
Green/Yellow ratio (typical)	1.5:1	1.5:1	1.3:1
Pulse energy (mJ)	1.6	6.5	1.5
Pulse width (ns)	40	50	30
Peak power (kW)	30	160	50
Beam diameter (mm)	18	42	15
Full angle divergence (mrad)			
standard cavity	8	8	6
unstable resonator	0.5	1.0	0.4
(average power)	(6 W)	(25 W)	(20 W)
Runtime on one metal load (hours)	200	300	50
Efficiency(%)	0.7	0.95	1.3
Gas consumption (liter-atm/hr)	1	1	1
Warm-up time (min)	90	130	10

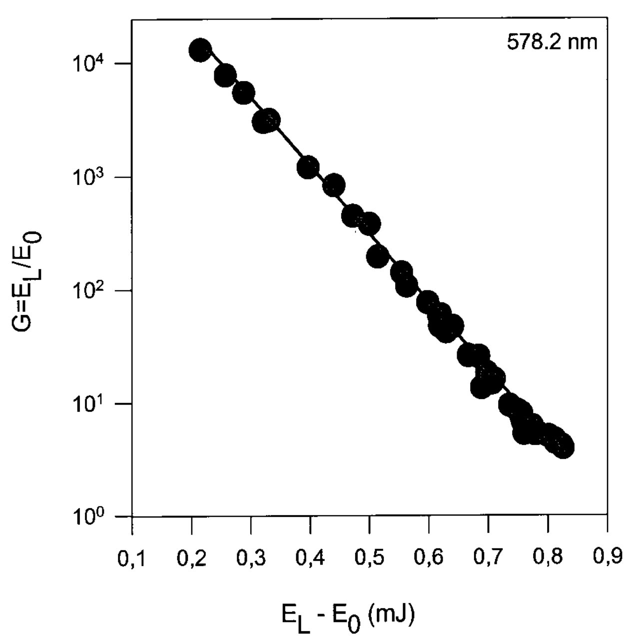

Figure 4. Amplification measurements for the 578.2 nm transition.

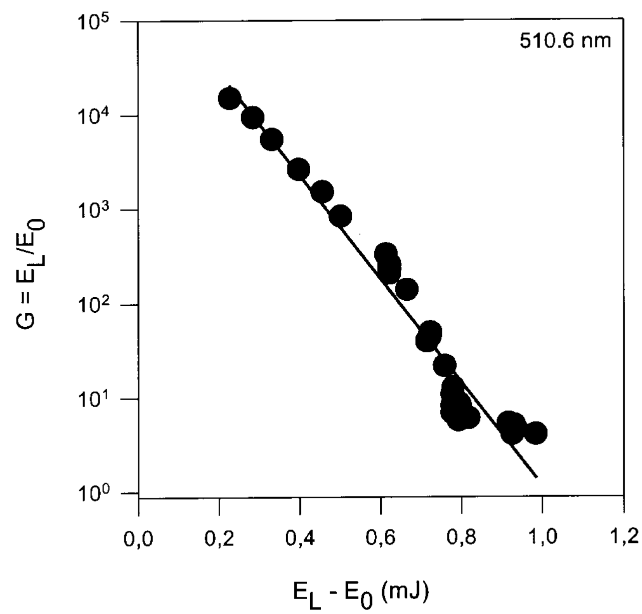

Figure 5. Amplification measurements for the 510.6 nm transition.

HyBrID copper laser applications at IEAv

The copper laser development at IEAv aimed, until recently, almost exclusively to give support to the laser isotope separation project. The objective of the HyBrID copper laser development was initially to increase the optical power in this project facilities. In 1994, applications of the copper laser other than laser isotope separation activities to be emphasized at IEAv.

We started by building a prototype for medical applications, funded by the PADCT program [5]. This device consists on a laser with laser head, circuits, gas and vacuum equipment, all assembled in the same cabinet. The laser beam is separated in wavelength and coupled to a large bore fiber-optic beam-delivery ended by a light-pen [6].

More recently, we started to study the application of the copper HyBrID laser in material processing. The great interest in Copper Vapor Lasers for material processing is due to their specific properties, not found in lasers commonly used at present (Nd and CO_2 lasers, for instance). Copper Lasers emit 20-50 ns pulses of light at 510 nm and 578 nm that are well absorbed in practically all materials. In the case of HyBrID lasers, the beam quality can be improved up to 2-3 times the diffraction limit. The short laser pulsewidth allows small thermal diffusion lengths. The laser pulse energy is lower than other lasers but the high repetition rate allows reasonable processing speeds. At last, the high average power of this visible laser can be delivered easily using optical fibers [6].

The short pulsewidth of the Cu-HyBrID laser is very important to define a small Heat Affected Zone (HAZ). The HAZ depends on the thermal diffusion length L_D defined by [7]:

$$L_D = (DT_p)^{1/2}$$

where T_p is the laser pulse width and D is the thermal diffusivity constant. For aluminum, for example, we obtain $L_D = 1.5\ \mu$m. So, the kerf width or the hole diameter can be controlled within this dimension, or in other words, the dimensions of the drilled hole fit very well the intensity distribution of the laser beam.

A second factor affecting the size of the HAZ is the energy of the laser pulse. In our case, it is very small: between 0.2 and 0.6 mJ. A rough approximation of the laser fluence necessary to heat the surface material up to the vaporization temperature is obtained by considering the energy absorbed by the material at a volume defined by 0.5 $L_D.A$, where A is the area of the laser beam at the material surface. In this case, the minimum laser fluence F_M to achieve the boiling temperature T_B at the surface is described by:

$$F_M = E_P/A = 0.5\ L_D \rho C_P (T_B - T_0)/(1 - R)$$

where E_P is the laser pulse energy, R is the reflectivity of the material for the laser wavelength, ρ is the density of the solid, C_P is the specific heat, and T_0 is the temperature before the incidence of the laser pulse. In fact, this only describes the minimum energy to increase the surface temperature up to the boiling point. For a laser fluence F_L higher than this minimum, the boiling temperature can be sustained beyond the surface to a depth d, that can be estimated by [7]:

$$d = (1 - R)F_L / \{\rho[C_P(T_B - T_0) + H_L]\}$$

where H_L is the latent heat of vaporization.

Table 2 shows the minimum laser fluence necessary to vaporize several metals, and the depth of the removed material per laser pulse, for a typical laser energy utilized in this work (0.4 mJ per pulse in a laser focused at a 100 μm diameter spot, leading to 15 J/ cm^2). We take into account the mean reflectivity of each material for 510 nm and 578 nm laser wavelengths.

Material	Reflectivity (%)	Minimum Laser Fluence (J/cm^2)	Depth / pulse (μm)
Aluminum	92	5.0	0.3
Copper	70	1.8	0.1
Tungsten	46	1.1	0.06

Table 2: Minimum laser fluence necessary to heat the sample surface to the boiling temperature and depth of removed material per laser pulse, considering 0.4 mJ pulse energy, for the three materials.

Although the quantity of removed material per pulse is small, the high repetition rate of HyBrID lasers allows material processing at high speeds. In addition, by using small laser pulse energies, we can control the cut depth very precisely, with negligible HAZ.

Some preliminary experiments were performed with very encouraging results [8,9]. This laser showed excellent prospects for micro-processing of good heat conductors and refractory materials, as, for instance, copper, aluminum, tungsten and CVD diamond. Cut widths of about 60 μm were obtained in aluminum and copper. We drilled holes with 50 μm diameter in CVD diamond and 20 μm in tungsten, with controllable depth. Fig. 6 shows a side view of a cut in a 0.2 mm thick aluminum foil. The edge is clear and sharp and there is no evident thermal distortion. Fig. 7 shows a 0.15 mm thick tungsten foil drilled by using a HyBrID laser. The hole diameter ($\sim$ 5 μm) is smaller than the laser spot on the foil surface ($\sim$ 100 μm) and can be controlled by controlling the number of laser shots.

Figure 6. Cut of aluminum foil 0.2 mm thick.

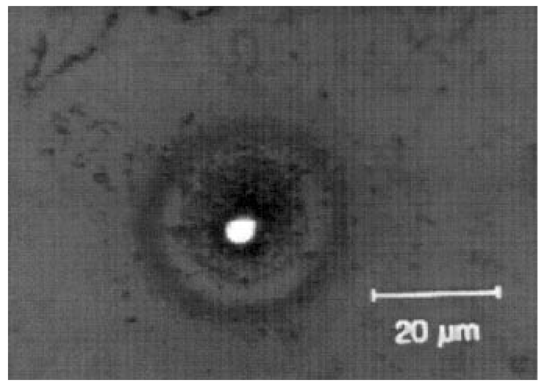

Figure 7. Microscope view of a hole drilled with Cu-HyBrID laser in a 0.15 mm thick tungsten foil.

A new prototype, designed to produce about 60 W of output power, is expected to start working in the middle of 1998 in order to give continuity to the material processing experiments.

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