FLOWING METAL VAPOR LASERS

T.W. Karras and C.E. Anderson

General Electric Astro Space Div. King of Prussia, PA 19406, USA
Received January 25, 1993

Transverse discharge copper vapor laser experiments using a flowing metal medium, high voltages, and low inductance are summarized. Burst mode operation at 20 kHz *with specific laser output of* 50 μJ·cm^{-3} *was obtained. Measurements of spontaneous emission of* 2 μJ·cm^{-3} *indicate very high upper laser state population* ($1\cdot10^{16}$). *This is confirmed by determinations based upon independent measurements of gain* (4.5 cm^{-1}) *and computations based upon assumptions of amplified spontaneous emission. Total specific spontaneous output power of* 36 W·cm^{-3} *is indicated.*

1. BACKGROUND

Pulsed metal vapor lasers (MVL's), first described by Walter[1] and Petrash[2] and coworkers, have predominantly been pumped by fast discharges running parallel to the resonator axis. These longitudinal discharge metal vapor lasers (LDMVL's) had, at most, a slow flow of a buffer gas. Waste heat was rejected primarily by conduction. Insulation generally surrounded the discharge tube (DT) controlling its temperature, discharge circuit inductance, and specific output.

Large DT diameters and input power, needed for high output power, limited buffer gas cooling and produced an elevated gas and electron temperature (Te) near the tube axis.[3] The resulting thermal population of the lower laser state (LLS) became more severe at large DT diameter and so limited the usable tube dimensions and the total output power.

Similarly, specific output (output per unit volume of active medium) was also limited by the metal atom densities (e.g., n_{cu}) that could be used. For a given electric field strength during the pumping discharge an adequate Te could only be obtained for metal atom densities below a certain value.[4] Above that density the Te was too low to pump the upper laser state (ULS).

Such considerations were used at GE during the 1970s to develop a design for a transverse discharge flowing copper vapor laser (TDFCVL).[5] That design evolved into a device that operated at n_{cu} of $3\cdot10^{16}$ cm^{-3}, well above the ~ 10^{15} cm^{-3} reachable in LDCVL's, and produced specific output of 50 μJ·cm^{-3} that has not yet been exceeded except by individual pulses.

During the 1980s Kim and coworkers[6] produced a continuously operated, static buffer TDCVL with similar characteristics, confirming the advantages of the configuration.

In this paper we summarize the TDFCVL design using high n_{cu} and low inductance, and some of its basic output characteristics. We also, for the first time, analyze some of the output data, confirming efficient high specific excitation of the ULS.

2. FLOWING METAL VAPOR GENERATOR

The technical development that made the device possible was a generator that produced a flowing sheet of metal vapor. This was produced by electrically heating a thin strip of liquid metal confined within a hollow graphite channel with holes in one face (see Fig. 1). Surface tension forces confined the liquid metal while allowing the vapor to leave in a stream determined by the holes and the direction of the liquid surface normal.

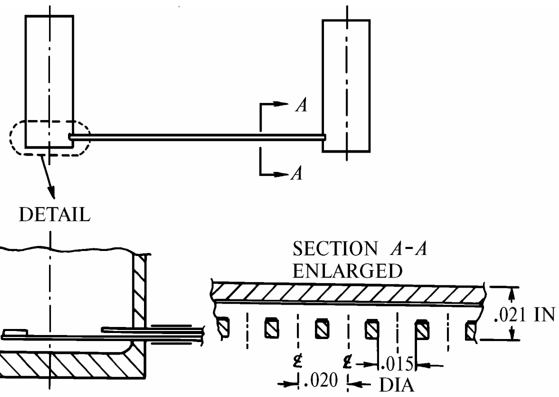

FIG. 1. Schematic of copper vapor generator.

The resistance of the liquid metal strip must be high enough to exceed the source impedance but lower than that of the confining graphite structure. The strip thickness used with high resistivity metals, such as lead, can thus be large, and so surface tension will not prevent a simple gravitational flow of liquid metal from reservoirs at each end of the strip to replenish metal lost due to vaporization through the holes.

In the case of a low resistivity metal, e.g., copper, the strip thickness had to be set at 0.127 mm, so small that surface tension forces would ordinarily have prevented filling. This was solved by coating the insides of the channel with tungsten and tantalum carbide films. The liquid copper wet these films and so was "wicked" into the channel, filling it.

This design was electrically efficient and produced a uniform sheet of pure metal vapor for many hours, limited only by the capacity of the reservoirs. Figure 2 shows the vapor density produced at a position 1 cm below the holes of a copper vapor generator (CVG). Note that the experimental points asymptotically approach the computed curve based upon complete conversion of electrical energy into vapor. At low input power, radiation and conduction losses are important but at high power levels, vaporization dominates the heat transfer.

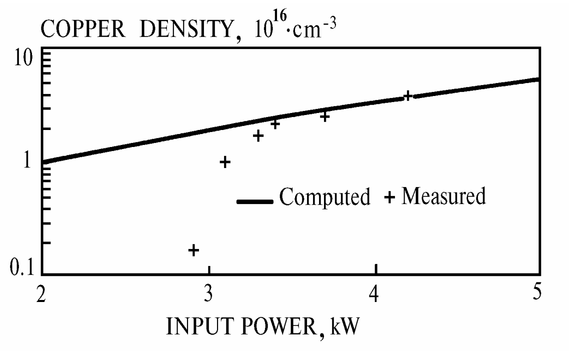

FIG. 2. Density produced by copper vapor generator.

Generators of high vapor pressure metals were built which produced metal atom flow rates over 100 mg/cm^2·sec and densities up to 10^{16} cm^{-3} with input power of only a few hundred watts. However, CVG's required several kW to produce even $3\cdot10^{16}$ cm^{-3}. Consequently, copper vapor generators are only suitable for experiments, as we shall describe below, or for very high average power systems.

The highest average laser power can only be maintained if the buffer gas and copper vapor flow velocity are sufficient to carry away the waste heat. A sonic velocity for a neon buffer, 435 m/sec, is practicable. For copper vapor density of 10^{15} to 10^{18} cm^{-3} this corresponds to copper flow rate of 0.04 to 40 mg/sec·cm^2. The particular CVG used in the laser experiments to be discussed achieved temperatures of only 2100 K and so produced CVG flow rates below 1 mg/cm^2. In a static neon buffer the copper vapor flow velocity was measured, by an absorption technique, to be only 100 cm/sec, producing the densities shown in Fig 2.

This generator was not suitable for steady high average power operation but could be used to explore the characteristics of moderate TDFCVL operation in a burst mode.

3. TRANSVERSE DISCHARGE FLOWING COPPER VAPOR LASER

The flowing CVG just described allowed the use of a water cooled housing and small discharge circuit dimensions, leading to low inductance, high voltage, and transverse discharges for laser pumping. All the principal parameters we understand today as being necessary for operation with high copper densities were provided. Table I summarizes the nominal design parameters.

Low inductance high rate switching was accomplished with small quenching spark gaps designed for burst mode operation at up to 30 kV at 100 kHz Ref.7. The switch, a strontium titanate capacitor, and a current monitor were contained in a coaxial housing that fed a parallel plate transmission line and the laser discharge gap. Voltage, laser energy, buffer gas pressure, CVG characteristics, etc. were monitored with 500 MHz instrumentation. Radiation could be measured from both ends of the laser optical axis and from one side normal to the optical axis.

TABLE I. Laser design parameters.

Parameter	Value
Capacitor Voltage	2 to 20 kV
Discharge Capacitance	0.5 to 100 nF
Electrode Separation	2 cm
Excitation Volume	~ 2·1·(2 to 10) cm
Discharge Circuit Inductance	50 to 100 nH
Current Density	100 to 500 A/cm^2
Matched Circuit Impedance	~ 3 Ω
Repetition Rate	5–70 kHz
Copper Vapor Flow Rate	~ 0.1 to 0.3 mg/cm^2·sec
Copper Vapor Flow Velocity	~ 100 cm/sec
Copper Vapor Density	0.5 to $3\cdot10^{16}$ cm^{-3}
Neon Buffer Pressure	30 to 100 Torr

4. LASER CHARACTERISTICS

Several of the observed TDFCVL output characteristics were quite different from what one would expect from most other LDCVL and TDCVL work.

Laser specific output of as high as 100 μJ·cm^{-3} in single pulses and 50 μJ·cm^{-3} in bursts with rates up to 20 kHz was obtained. For fixed discharge and CVG conditions and varying only repetition rate, the specific output was found to remain constant at up to some maximum rate. At repetition rates above this value the specific output would "roll–over" and gradually fall. The repetition rate for this roll–over increased as the specific loading (discharge capacitor energy per unit volume of active medium) increased, as shown in Fig. 3.

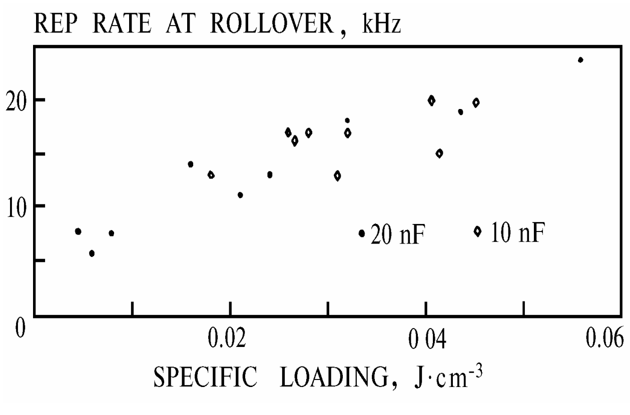

FIG. 3. Maximum rep rate without loss in pulse energy.

We speculate that, since maximum repetition rate is usually limited by LLS population, increased specific loading must in some way lead to deactivation of those states. Increased specific loading and field strength could correlate with increased electron density (n_e) and increased deactivation by electron collisions of the second kind during the interpulse period.

Operation at copper densities above 10^{16} cm^{-3}, generally not possible with even moderate bore LDCVL (see paragraph below for high current density exception), was obtained through the use of high voltage transverse discharges. As shown in Fig. 4, lasing was not reliably obtained in copper vapor densities of $3\cdot10^{16}$ cm^{-3} until the discharge capacitor voltage exceeded 7 kV. Voltage increase to 19 kV raised the specific output so that values of 50 μJ·cm^{-3} were reached.

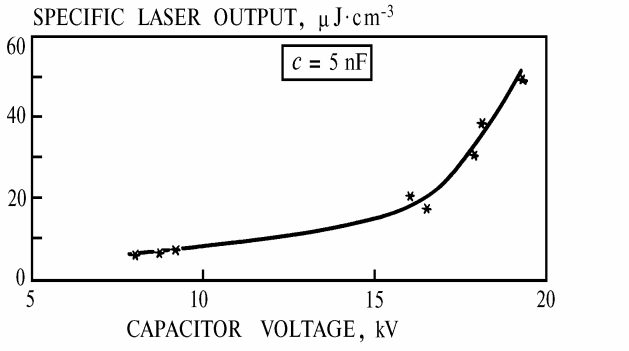

FIG. 4. Specific output rises with capacitor voltage.

This behavior is consistent with computations based on the work of Lewis[4] that indicates that E/N values of several hundred townsends (10^{-17} V·cm^2) are needed in the media shown in Table I to produce sufficient Te for lasing. An alternate approach for lasing at high n_{cu} is to use short longitudinal discharges and high current densities in small–bore tubes. Comparable n_{cu} ($3\cdot10^{16}$ cm^{-3}) has yielded a specific output of 39 μJ·cm^{-3} in this way.[8]

The laser power efficiency obtained in both high specific output lasers was below 0.1 %, well below ~ 1 % commonly obtained in other CVL's. However, in both cases there was indication that there was significant loss due to amplified spontaneous emission (ASE). The power radiated out of the LDCVL tube was independent of the presence of mirrors,[8] presumably because of the very high gain of the device. Consequently there should be radiation modes carrying ASE power into the walls, depleting the upper ULS without adding to the laser output.

Measurements on the TDFCVL device were more complete, allowing semiquantitative tests of this hypothesis. Spontaneous emission (SE) observations were made in the side light as well as out the two ends, and the small signal gain was determined. Furthermore, the gain medium was made nearly cubic in dimension to simplify analysis.

The SE was filtered at 510.5 nm and the measurements without mirrors were assumed typical for all angles because of similarity in measured values in the three positions and the symmetry of the active medium. No significant difference was found in the side light with and without mirrors.

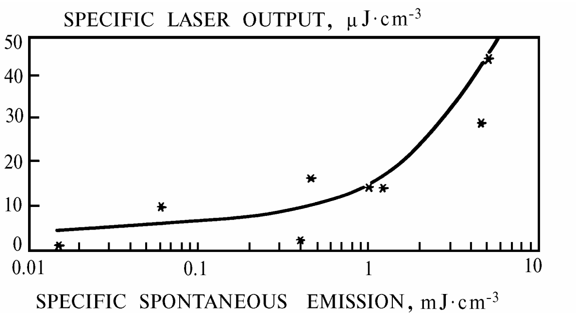

FIG. 5. High specific spontaneous output strongly correlates with high specific laser output.

From this the total energy radiated into 4π sr, without mirrors, was found to be as high as 2–5 mJ·cm^{-3} of active volume. This corresponded to operating conditions that produced specific laser output of 50 μJ·cm^{-3} and small signal gain of almost 5 cm^{-1}. Strong correlation of high specific SE output operating conditions with those producing high specific laser output can be seen in Fig. 5.

Measurements of the duration of the SE for the high gain conditions were of the order of 10 nsec. Similar ULS lifetime shortening has been observed for the SE from high gain longitudinal discharge lasers.[9] This shortening from the single atom lifetime is most easily explained by ASE depletion of the ULS or some cooperative emission process. Similarly, ASE is a plausible loss channel to explain the low laser efficiency. These hypotheses and the very high level of ULS excitation need confirmation.

5. ANALYSIS AND DISCUSSION

Table II tabulates the small signal gain and the SE radiated per pulse into 1 cm^2 at a distance of 1 m from the active medium for three TDFCVL conditions for which complete measurements are available. The third column shows the ASE energy per pulse radiated into 1 cm^2 at a distance of 1 m that should be expected if the SE from one end of the active medium is amplified by that gain during the observed emission time. Saturation effects will modify this estimate, however, agreement with the measurements of the first column clearly supports the hypothesis that ASE is responsible for the time scale and magnitude of the measured fast spontaneous emission.

TABLE II. Comparison of measured spontaneous emission with ASE computed from measured gain.

Measured spontaneous emission·10^8 J/cm^2	Measured ss gain, cm^{-1}	ASE computed from ss gain×10^8 J/cm^2
0.37	1.57	0.3
1.70	3.30	1.6
8.50	4.50	10.6

Integration of the radiated energy over 4π leads to the conclusion that the ULS must be heavily excited. Peak specific SE output of 5 mJ·cm^{-3} corresponds to excitation of $2.1\cdot10^{16}$ atoms·cm^{-3} to the ULS, 70 % of the available atoms at a density of $3\cdot10^{16}$ cm^{-3}. Even more commonly observed values of 2 mJ·cm^{-3} correspond to 30 % copper excitation and a discharge energy efficiency of 30 %, comparable to that originally projected by Walter.[1]

Despite the fact that two independent determinations, gain and direct radiation measurements, have produced similar estimates of the ULS excitation density, the extremely high values found led us to explore analytic confirmation.

If the total excitation into the ULS is assumed to be due to direct electron collisions, the ULS excitation density, n_x, can be expressed by

$$n_x = t\cdot S\cdot n_{cu}\cdot n_e ,$$

where t is the excitation time and S is the excitation rate. For high n_{cu} ($3\cdot10^{16}$ cm^{-3}), high gain operating conditions with high specific SE output, the time was measured to be about 10 nsec. Since E/N was 500 Td (mean voltage of 3 kV/cm during the discharge, a buffer density of

$6 \cdot 10^{17}$ cm^{-3} and n_{cu} of $3 \cdot 10^{16}$ cm^{-3}, then $E/N \sim 0.5 \cdot 10^{14}$ V·cm^2) one can compute from Lewis[4] a Te of roughly 8 eV and an ULS excitation rate, S of $1.5 \cdot 10^{-7}$ cm^3/sec. The n_e can be estimated from a mean current density of 300 A/cm^2 and drift velocity of $\sim 1 \cdot 10^7$ cm/sec to be about $\sim 2 \cdot 10^{14}$ cm^{-3}. This leads to an expected ULS excitation density of about $1 \cdot 10^{16}$ cm^{-3}, very close to that inferred from the above measurements.

These high ASE losses can be recovered if a high intensity master oscillator is used to pump the active medium as it is excited by the discharge. A 110 kW/cm^2 oscillator can stimulate the ULS atoms to emit at a sufficient rate so as to suppress the gain below 1 cm^{-1}.

6. CONCLUSION

High voltage, low inductance transverse discharges can excite greater than 30 % of a high density copper vapor flow to the ULS with subsequent radiation by ASE. Over 36 W·cm^{-3} of emission at 510.5 nm (2 mJ·cm^{-3} at 18 kHz) can be inferred from independent measurements and calculations. A technique for generating the flowing copper medium necessary to sustain such an operation was described and a MOPA approach for extracting the emission into a coherent beam has been suggested.

ACKNOWLEDGMENTS

The authors would like to thank B.G. Bricks and R.S. Anderson who conducted much of the work reported in Refs. 5.

REFERENCES

1. W.T. Walter, M. Piltch, N. Solimene, and G. Gould, IEEE J. Quant. Elect. QE–2, 474 (1966).
2. A.A. Isaev, M.A. Kazaryan, and G.G. Petrash, JETP Lett. **16**, 27 (1972).
3. M.J. Kushner and B.E. Warner, J. Appl. Phys. **54**, 2970 (1983).
4. R.R. Lewis, Optic. and Quant. Electron. **23**, 5493 (1991). Also see Oxford University Phd dissertation (1985).
5. B.G. Bricks, T.W. Karras, R.S. Anderson, and C.E. Anderson, Bull Amer. Phys. Soc. **22**, 190 (1977). Also IEEE J. Quant. Elect. QE–11, 57 (1975).
6. J.J. Kim and Nackchin Sung, IEEE J. Quant. Electron. **26**, 818 (1990) and J.J. Kim, K. Im, and N. Sung, SPIE **737**, 31 (1987).
7. W.E. Austin, Laser Focus, No. 6, 79 (1975).
8. R.S. Anderson, L. Springer, B.G. Bricks, and T.W. Karras, IEEE J. Quant. Elect. QE–11, 173 (1975).
9. T.W. Karras, Proceedings from the Conference on Lasers, 80, STS Press, 1981.