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A 10-WATT CW PHOTODISSOCIATION LASER WITH IODO PERFLUORO-TERT-BUTANE

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ABSTRACT

$t-C_4F_9I$ has been successfully tested as a lasant in a solar-simulator-pumped laser system and produced a 14-W CW output. The pump-to-laser efficiency was determined to be three times that of the commonly used $n-C_3F_7I$.

A 10-WATT CW PHOTODISSOCIATION LASER WITH IODO PERFLUORO-TERT-BUTANE

Introduction

NASA has been investigating the feasibility of direct solar-pumped laser systems for power beaming in space.[1] Among the various gas, liquid and solid laser systems being proposed as candidates for solar-pumped lasers,[2-4] the iodine photodissociation gas laser has demonstrated its potential for space application.[5-8]

Of immediate attention is the determination of system requirements and the choice of lasants to improve the system efficiency. The development of an efficient iodine laser depends on the availability of a suitable iodide which has favorable laser kinetics, chemical reversibility, and solar energy utilization. Among the various alkyliodide lasants comparatively tested in a long-pulse system, perfluoro-tert-butyl iodide, $t-C_4F_9I$, was found to be the best.[9] However, the operating conditions for the laser medium in a continuously pumped and continuous-flow iodine laser differ considerably from those in the pulsed regime. [10] Therefore, this experiment reports the results of CW laser performance from $t-C_4F_9I$.

Perfluoro-n-propyl iodide, $n-C_3F_7I$ is used for comparison in this study because of its universal use in photodissociation iodine lasers.

Solar-Pumped Iodine Laser

Successful excitation of an iodine laser by a solar-simulator was first reported in 1980 [5]. The active media for such lasers are CF_3I, or C_3F_7I, and are generally described by the formula RI, where R stands for the radical CF_3, C_3F_7, C_4F_9, or C_6F_{13}. The absorption bands of these iodides are in the UV part of the solar spectrum (250-300 nm). Resulting photodissociation produces excited I^* atoms with the reaction

$$RI + h\upsilon_s \rightarrow R + I^*(5^2P_{1/2}).$$

Lasing occurs because of the atomic transitions

$$I^*(5^2P_{1/2}) \rightarrow I(5^2P_{3/2}) + h\upsilon_L,$$

where

$$\lambda_L = \frac{c}{\nu_L} = 1.315\mu m.$$

The quantum yield of the excited iodine atoms, I^*, the most important quantity in the laser kinetics, was measured to be near unity for most alkyliodides.[10] (See Table 2.)

Four other processes which occur following the photodissociation are also important and must be considered: the collisional deactivation of I*, by the parent molecule RI according to $I^* + RI \xrightarrow{(Q_1)} I + RI$; the recombination process of $R + I^* \xrightarrow{(K_1)} RI$; the dimerization $R + R \xrightarrow{(K_3)} R_2$; and formation of molecular iodine $I + I + M \rightarrow I_2 + M$ or $I^* + I + M \rightarrow I_2 + M$. These reactions are the important loss mechanisms for the iodine laser system.

t−C₄ F₉ I Laser

Perfluoro-tert-butyl iodide, $t-C_4F_9I$, is attractive for direct solar-pumped laser medium because of two important properties. First, the photodissociation absorption peak is centered at 288 nm which is red-shifted by 15 nm from the 275 nm absorption center of $n-C_3F_7I$ (see Fig. 2). This red-shift and the broader half-width (see Table 1) increase the solar spectrum utilization and result in a higher photodissociation rate. The photodissociation rate of the solar-pumped iodine laser can be calculated from[11]

$$\gamma = \frac{1}{hc} \int \sigma S_\lambda \lambda \, d\lambda$$

where h is Planck's constant; c is light velocity, σ is absorption cross-section, S_λ is solar spectral irradiance and λ is wavelength. A calculation using the data for air mass zero (AMO) solar spectral irradiance [12] provides $\gamma(n-C_3F_7I) = 0.83 \times 10^{-3}\ s^{-1}$ and $\gamma(t-C_4F_9I) = 2 \times 10^{-3}\ s^{-1}$ which is 2.4 times higher for $t-C_4F_9I$ when compared with $n-C_3F_7I$.[11] The photodissociation rate was calculated for $t-C_4F_9I$ in comparison with that for CF_3I.[11] The second advantage for this gas is the absence of extremely small contributed reactions which lead to the direct loss of radicals.[13] Particularly, recombination reaction of radicals R between each other, observed for the other iodides, are strongly inhibited for $t-C_4F_9I$.[13-15] Other kinetic rate coefficients were found to be similar to those for the $n-C_3F_7I$ molecules.[14] (See Table 2.) Therefore, the photodissociation of $t-C_4F_9I$ by solar radiation could lead to a stationary concentration of the radicals, I atoms, and I_2 molecules.

Experiment

The present experiment used the laser system of reference 6 which used the iodide, $n-C_3F_7I$, so that comparative evaluation to the $t-C_4F_9I$ could be made directly. Figure 1 shows a schematic of the experiment. A Vortek Industrial model 107 arc lamp [6] with a 0.2-m-long arc length was used as the solar-simulator. The lamp was capable of electrical input powers up to 150 kW. However, only 75 kW was used in this experiment. Considering the ~45% conversion efficiency, as claimed by Vortek Industry, a maximum of ~34 kW of visible and near-infrared radiant power could be achieved.

The arc lamp and the laser tube were optically coupled on the conjugate focal lines of a water-cooled elliptical cylindrical reflector of polished aluminum. The suprasil laser tube had a 20-mm ID and 0.45 m length. The gain medium was shadowed by the side plates of the reflector. The total pumping power used in this experiment was ~13 kW.[6] Equivalent pumping power density was 994 solar constants (1 solar constant equals 1.35 kW/m^2) on the surface of the laser tube. The pumping power density was varied by adjusting the arc current. The emission spectrum of the Vortek solar simulator was similar to the air mass zero solar spectrum and is given in reference 6.

The laser cavity consisted of a 70% output mirror and a maximum reflectivity rear mirror. The cavity length was 0.9 m, and a pyroelectric power meter was used to monitor the laser power output.

The lasant supply is shown in Figure 1. The flow of $t-C_4F_9I$ vapor was longitudinal and maintained by a pressure differential between the heated evaporator and the liquid nitrogen cooled condenser containing iodide. To obtain sufficient flow rates of $t-C_4F_9I$, the evaporator had to be heated because the vapor pressure of $t-C_4F_9I$ was only 76 Torr at room temperature which is about 5 times lower than that of $n-C_3F_7I$ (350 Torr).

The photoabsorption of $t-C_4F_9I$ was accurately measured by spectrophotometry and is compared to that of $n-C_3F_7I$ in Figure 2. Photoabsorption, vapor pressure, and heat capacity parameters for $t-C_4F_9I$ and $n-C_3F_7I$ are summarized in Table 1. Note that the high heat capacity of $t-C_4F_9I$ is advantageous for maintaining reduced lasant temperatures with high power, cw operation.

Results

CW laser operation from $t-C_4F_9I$, unlike the $n-C_3F_7I$, requires some technical efforts leading to high purity of the iodide and a large surface area of evaporator to achieve sufficient flow rate and corresponding pressure in the laser tube. $t-C_4F_9I$ is solid at room temperature and melts at 60°C. The maximum vapor pressure of $t-C_4F_9I$ obtainable with flow from a room temperature evaporator was only a few Torr and fell down to zero within a few seconds because of insufficient compensation of evaporation cooling in the reservoir. In order to increase the flow, the pressure was increased by heating the reservoir and the laser tube to 45°C. The vapor pressure of $t-C_4F_9I$ increased to 30 Torr but fell to 10 Torr and lower within one minute. Thus, the period of CW output from $t-C_4F_9I$ was limited to a few seconds in this experiment by the limitation of the amount of iodide and its evaporational cooling.

Figure 3 shows a typical oscillogram of the CW power output of $t-C_4F_9I$ (lower trace). The upper trace is the pressure of $t-C_4F_9I$ inside the laser tube during a lasing period of ~20 s. To recycle back to the initial pressure, it was necessary to shut down the flow of iodide by the controllable valve (see Figure 1) for almost 3 minutes to compensate for insufficient thermal dissipation of the evaporational cooling in the reservoir. A maximum power output of ~14 W CW was achieved for ~20 s with a flow rate and a vapor pressure of 2700 SCCM and ~19 Torr, respectively.

To compare the CW output of $t-C_4F_9I$ to that of $n-C_3F_7I$ another set of experiments was performed for both iodides under the same operational conditions of flow rate, flow velocity, and pressure. The results of the tests for the two iodides pumped by different simulator arc currents are shown in Figure 4. The flow rate and the vapor pressure of $n-C_3F_7I$ were constant at 900 SCCM and 6 Torr, respectively, throughout the tests, but those of $t-C_4F_9I$ unavoidably decreased from 1200 to 700 SCCM and from 9 to 5 Torr, respectively. The measurements were made from low to high arc currents. In spite of the reduced flow rate of the $t-C_4F_9I$, more than a three-fold increase in the power output was measured.

CW Laser from the Mixture of $t-C_4F_9I$ and $n-C_6F_{13}I$

To maintain the flow and pressure of $t-C_4F_9I$ throughout the lasing period we attempted to mix it with $n-C_6F_{13}I$ which is liquid at room temperature and has much lower vapor pressure than $t-C_4F_9I$ (see Table 1). We dissolved equal amounts of $t-C_4F_9I$ in $n-C_6F_{13}I$ until it reached saturation. The idea was to speed the heat conduction by stirring the liquid mixture.

The absorption band of the mixture of equal amounts of each iodide was measured by the OMA spectral analyzer (see Table 1). The mixture had a 285 nm absorption peak and 85 Torr vapor pressure at room temperature. This mixture was used for the CW laser. The conditions of the experiment were kept the same as for the pure $t-C_4F_9I$. A typical oscillogram of CW output from the mixture of $t-C_4F_9I + n-C_6F_{13}I$ (1:1) is shown in Figure 5 (lower trace). The upper trace is the pressure of the mixture inside the laser tube during the lasing period of 4.6 minutes. Evidently, the lasing period for the mixture increased considerably in comparison to that for pure $t-C_4F_9I$. A maximum power output of 11.5 W was achieved with a pressure of 25 Torr and a flow rate of ~4300 SCCM. The results of these tests indicate some usefulness of the mixing of $t-C_4F_9I$ in $n-C_6F_{13}I$ to maintain the flow rate and the pressure during the longer lasing time period but the mixture is less efficient than pure $t-C_4F_9I$.

It is important to note that the power output of this mixture after treatment with $Na_2S_2O_5 + Ag$, which acts as an I_2 absorbing agent, decreased by half from the power output of the first run. The treatment period was about one week. The power output of the third run of the mixture which was chemically treated for a longer period of about one month still decreased. The measurement of the absorption band of the used mixture demonstrated an absorption peak of 275 nm indicating the presence of iodides other than $t-C_4F_9I$ in the medium.

Conclusion

The iodide $t-C_4F_9I$ was successfully tested in a solar-simulator-pumped CW laser. Its efficiency (pump-to-laser) was measured to be three times that of the commonly used iodide $n-C_3F_7I$. $t-C_4F_9I$ also demonstrated a higher chemical reversibility than that of $n-C_3F_7I$. However, some technical efforts are required for obtaining and maintaining high flow rates and pressures throughout the CW laser operation.

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Appendix A: Human Resources

Graduate students continue to be trained in this area of research at the University. To date, five students have completed theses and four students are enrolled. Eight of the nine MS students are American citizens and seven of the nine are considered members of an underrepresented minority in physics. Table A1 lists students and thesis titles.

GRADUATE STUDENT TRAINEES

STUDENT	THESIS TITLE	DATE
Gill Lee (NASA-GRTP)	A Parametric Study of the Threshold Pump Power of a Direct Solar Simulator Pumped C_3F_7I Laser	'84
Kenneth Preston	A Study of Selected Dyes for Enhancement of Lasing Using the Converter Technique	'86
Julie Williams	Solar Simulator Pumped Waveguide Amplifier for Dye Laser	'87
Won Yi	UV Dye Lasers Pumped by Hypocycloidal Pinch Plasmas	'87
Todd Pilot	Solar Simulator Waveguide Dye Amplifier Under a Long Excitation Pulse	'88
Lamarr Brown	Nd:YAG and Nd:Cr:GSGG as Candidates for Solar Simulator Pumped Solid State Laser	'89
Vincent Jones	Comparison of t-C_4F_9I and C_3F_7I for Direct Solar Pumping	*
Abdulaziz Gambo	???	*
Clarence Wells (US Military)	???	*

Note: 8 of the 9 MS students are American citizens.
7 of the 9 MS students are considered under-represented minorities in physics.

Table 1. Characteristic Parameters of Iodides.

Iodide	Absorption Peak, λ[nm]	Δλ[nm]	Absorption Cross Section, $\sigma_{max}[10^{-19} cm^2]$	Room Temperature Vapor Pressure [torr]	C_V [J/MoleºK]	C_P [J/moleºK]
t-C_4F_9I	288	50	4.8 ± 0.05	76	181	189
n-C_3F_7I	273	42	6.6 ± 0.1	350	146	154
n-$C_6F_{13}I$	272	42	6.0 ± 0.5	~16		
t-C_4F_9I + n-$C_6F_{13}I$	285	- -	---	85		

Table 2. Kinetic Parameters for Iodides.

Parameter	t-C_4F_9I	n-C_3F_7I
Quantum Yield	0.88	0.98
K_2, cm^3/s	6.0×10^{-12}	8.0×10^{-12}
K_3, cm^3/s	≈ 0	2.0×10^{-12}
Q_1, cm^3/s	2.9×10^{-16}	3.0×10^{-17}

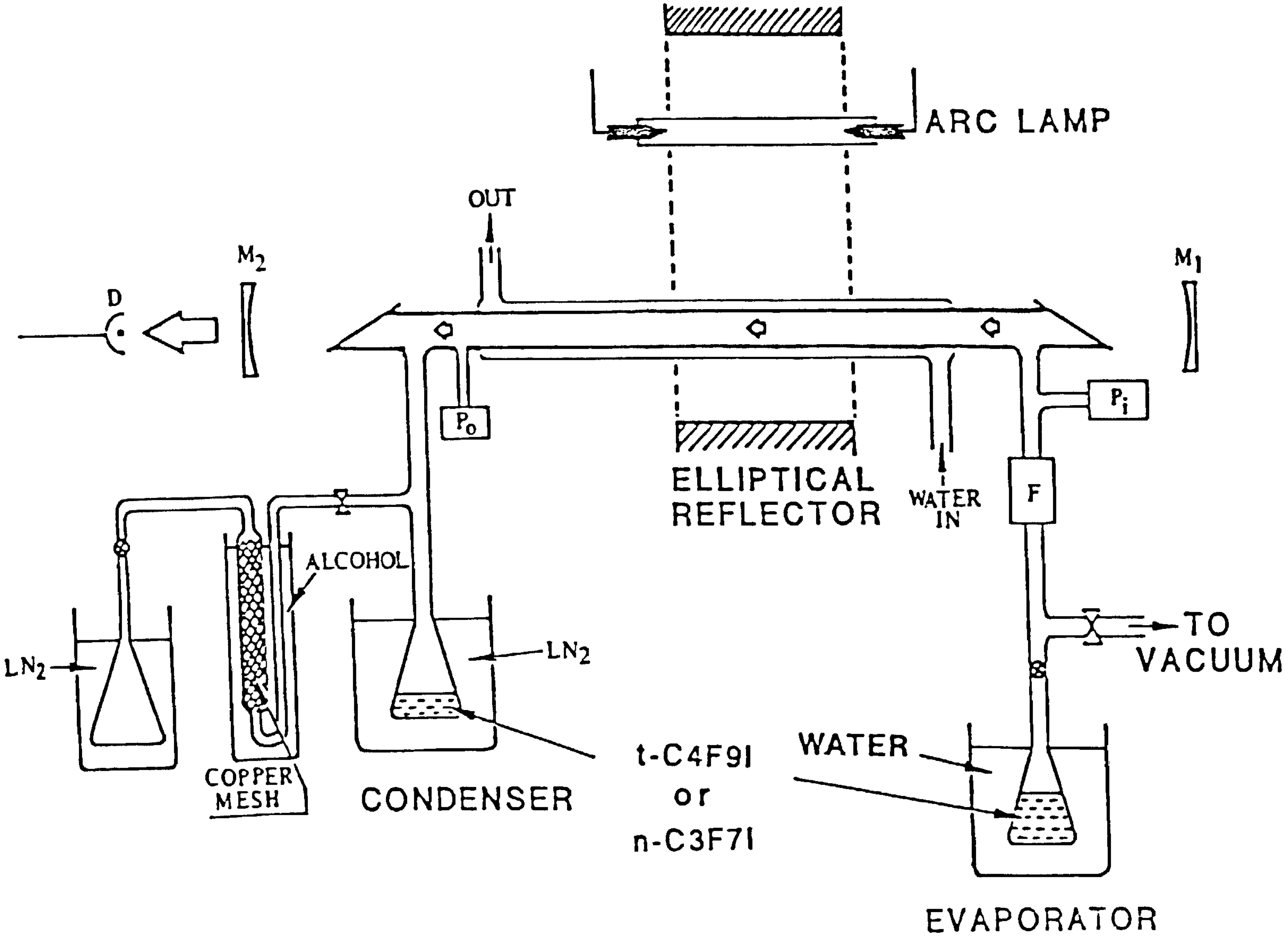

Figure 1. CW solar-simulator-pumped laser experiment.

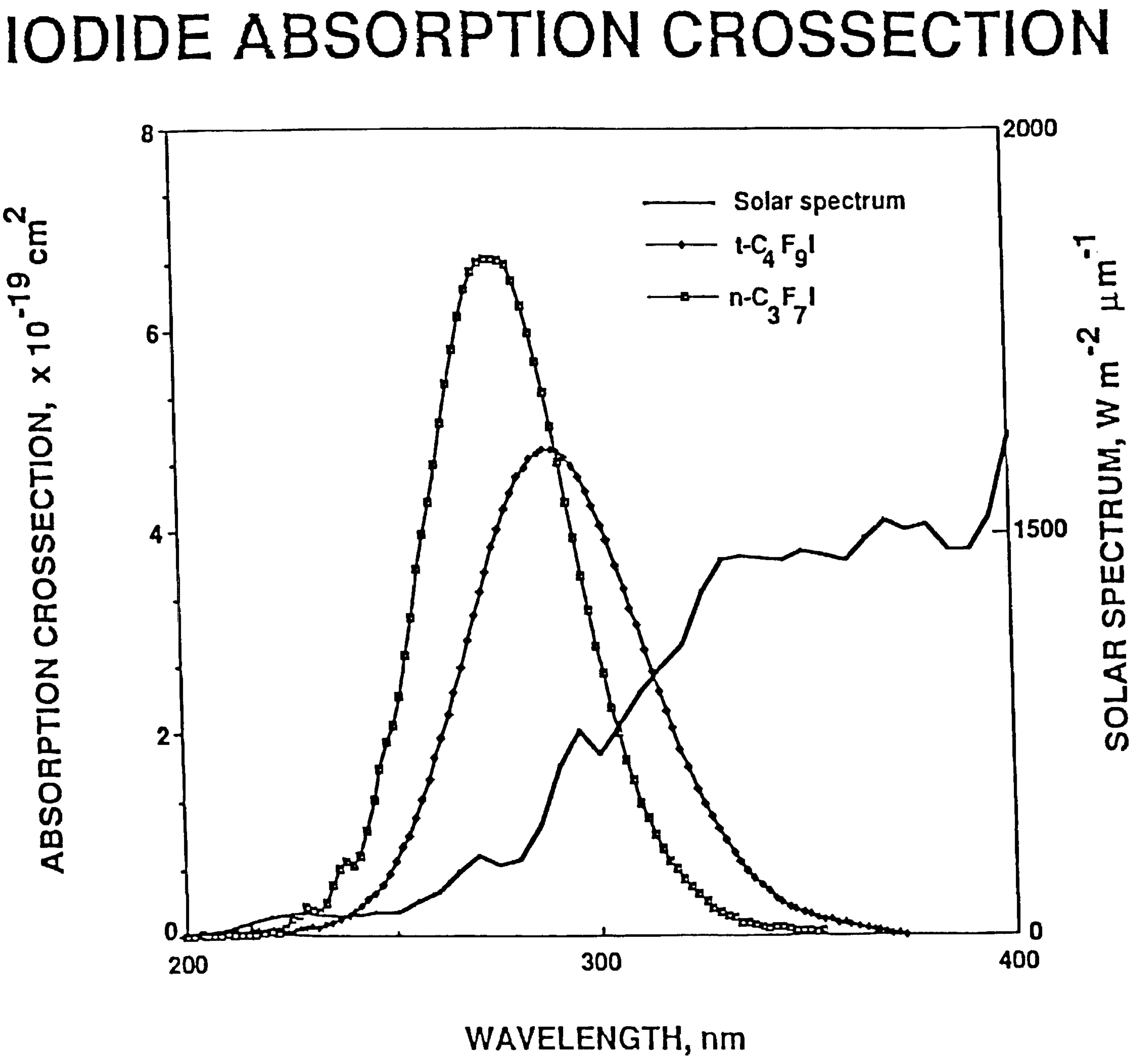

Figure 2. Absorption cross-section of iodides.

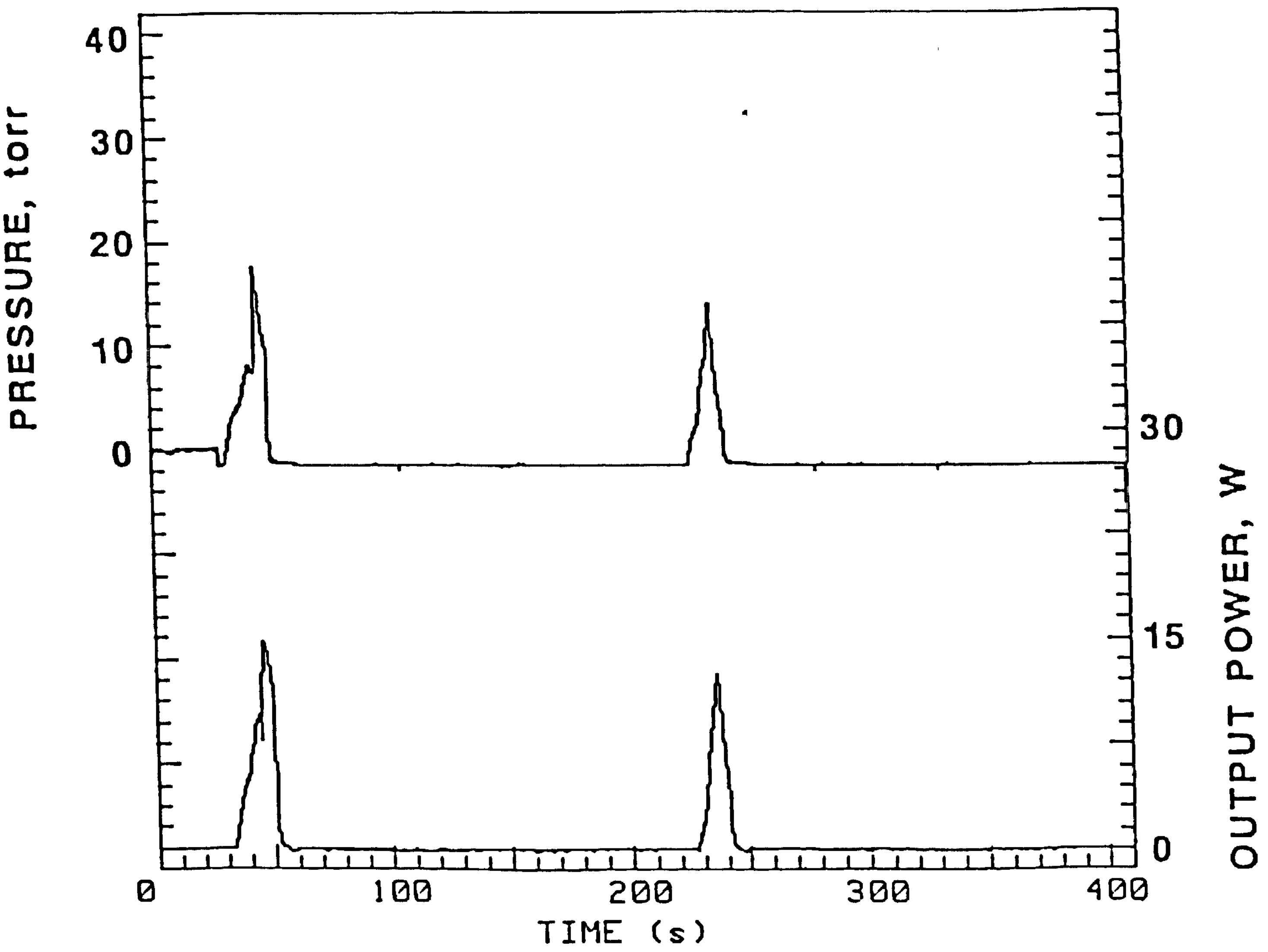

Figure 3. Oscillogram of CW output from t-C_4F_9I (lower trace) and its pressure (upper trace).

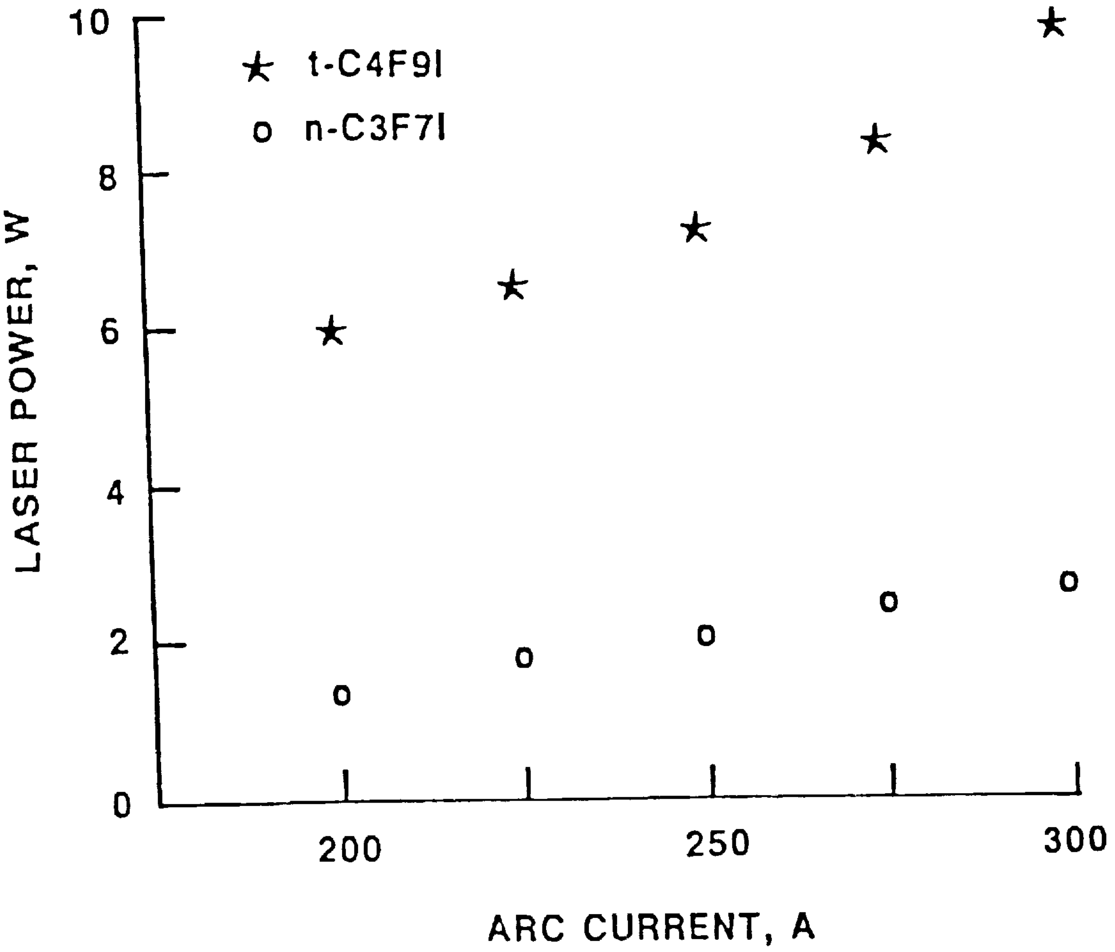

Figure 4. CW power output vs. the arc current.

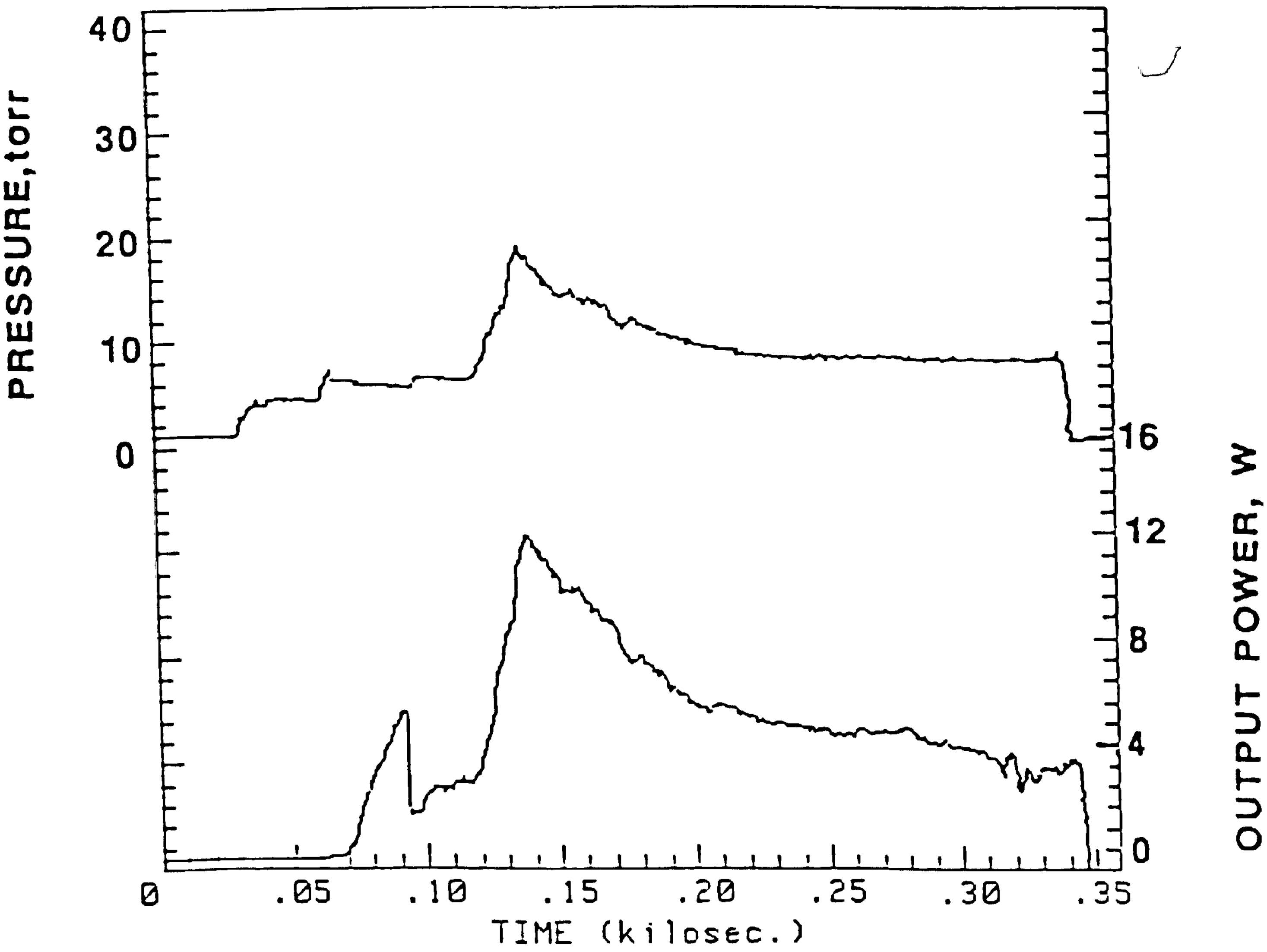

Figure 5. Oscillogram of CW output from a mixture of t-C_4F_9I and n-$C_6F_{13}I$.