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TITLE OPTICALLY PUMPED ULTRAVIOLET AND INFRARED LASERS DRIVEN
BY EXPLODING-METAL FILMS AND WIRES

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Optically pumped ultraviolet and infrared lasers driven
by exploding metal films and wires

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Abstract

The 342-nm molecular iodine and 1315-nm atomic iodine lasers have been optically pumped by intense light from exploding-metal-film and exploding-wire discharges. Brightness temperatures for the exploding-film discharges were ~25,000 K and for the wire discharges were ~30,000 K.

For the I_2 laser the 3.5-cm-diameter by 40-cm-long pumped volume lies adjacent to the wire or film of the same length. Pressures of 1-6 torr I_2 and 1-3 atm SF_6 , CF_4 , or Ar were used in the stainless-steel cell. Using 20- μF capacitance charged to 40 kV, a 0.25-mm tungsten wire, 3-torr I_2 , and a 2-atm SF_6 , an energy of 2 J was obtained from the laser in a pulse of 8- μs duration. The specific output energy was 7 J/l. Substitution of a cylindrical Al film for the wire, under otherwise similar conditions, led to a X10 output energy reduction. With an active volume and wire of 70-cm length greater output energies and efficiencies were obtained with similar input energy. An output pulse of 12 J and 12- μs duration was measured for a specific output energy of 18 J/l.

A laser energy of 110 J in a 20- μs -long pulse has been measured from atomic iodine using a wire discharge along the axis of a larger cell. The active volume available was 20 cm in diameter and 80 cm in length. Input energy was 32 kJ. In similar measurements using a cylindrical Al film for discharge initiation, the measured output energy was 40 J.

Introduction

Optically pumped lasers can be pumped by a variety of high-intensity light sources, both coherent and noncoherent. Among the latter type, xenon flashlamps have been the popular choice for more than two decades. Their widespread use results from their long lifetime, reliability, familiarity to researchers and designers, and good match of their spectral output with visible or near-ultraviolet pump bands of most laser media. Brightness temperatures of these sources are usually 6-12 kK and efficiencies for converting electrical energy to broadband radiant energy can be as high as 0.5.

Recently, other noncoherent sources have been introduced as laser pumps. Exploding-wire discharges have been used extensively by Soviet researchers for pumping the photolytic atomic-iodine laser, and others to a lesser extent, over the past decade. Surface discharges have received modest attention as pump sources. Belonging also in this category is a related source, the ablating-wall flashlamp. In the Soviet Union plasmadynamic discharges (plasma focus) and magnetoplasma compressors have been introduced as laser optical pump sources. The ordinary z-pinch discharge has also been used to pump atomic-iodine lasers.

The introduction of new laser media and changing requirements for older laser media have precipitated development of, or adaptation of, these more exotic light sources for this task. Most of these sources have the capability of producing much greater light intensities, especially in the ultraviolet, than xenon flashlamps. This follows from many of these sources having blackbody temperatures in the 30 kK range, compared with the 10 kK typical value of xenon flashlamps. Lasers requiring excitation in the vacuum ultraviolet (vuv) are especially benefitted by these higher brightness temperatures, since the peak emission for a 30 kK blackbody occurs near 100 nm. Many of these advanced sources do not require envelopes, a situation allowing vuv radiation to be deposited efficiently in the laser medium.

In addition to brightness and spectral content, another useful feature of several of the above sources is the available time scale. Shorter pulse lengths, and therefore much greater peak optical powers, can be generated using most of these sources compared with xenon flashlamps.

In our laboratory we are exploring several of these pump sources: exploding-wire discharges, exploding-film discharges, surface discharges, and ablating-wall flashlamps.

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Some of this work has been described in a separate paper at this conference.¹ Here, gas-phase lasers pumped with exploding-wire and film-discharges will be discussed.

Atomic-iodine laser

Experiments on the atomic-iodine laser have been conducted using both exploding-metal-wire and exploding-metal-film discharges. The cell was constructed of aluminum and had a 20-cm bore. The axial discharge occurred between two strut-type electrodes of brass material, one located at each end of the cell. A simplified schematic drawing of the cell is shown in Fig. 1. A section of Kynar insulating material electrically isolates one end of the cell from the other. This arrangement can be seen in the photograph of Fig. 2. The wire was typically 4-mil tungsten. The metal film was $\sim 1\text{-}\mu\text{m}$ -thick Al vacuum-deposited onto an acrylic tube of 1.27-cm diameter. Each end of the tube was firmly attached to an electrode. The length of the discharge could be varied but for laser experiments reported here was 75 cm.

Figure 1. Schematic drawing of 20-cm bore, 110-cm length laser cell.

The total cell length was 110 cm. The ends of the cell were sealed with 25-cm-diameter laser mirrors, which were aligned accurately by compressing the sealing o-rings. Both mirrors were polished to better than one-quarter visible wavelength flatness. The pyrex rear mirror was coated for a reflectivity greater than 0.99 and the BK-7 output coupler was coated for a reflectivity of 0.3, both for wavelengths near $1.3\text{ }\mu\text{m}$. For preliminary measurements, 5-cm-diameter sampling mirrors were used as shown in Fig. 2. The axis of this resonator lay 3.7 cm from the wire.

The capacitor bank consisted of four 10- μf , 60-kV capacitors. A Physics International Model T-508 spark gap switched the power to the load via eight coaxial cables. Connections for several of these cables to the cell can be seen in Fig. 2. The capacitor header plate design allowed any number of capacitors up through four to be used. The charging voltage range was 25-55 kV. Inductance of the complete discharge circuit was approximately 1.9 μH regardless of the number of capacitors connected. Measured peak currents were about 200 kA at 40- μf , 45-kV charge.

The discharge occurs in a narrow, expanding channel in the laser mix, since the exploding conductor is embedded in that gas without a partition. As such, the properties of the gas mixture affect the discharge and the transmission of the pump light to each part of the laser medium, as well as the usual laser kinetics. In laser experiments SF_6 or CO_2 was used as the buffer gas at pressures between 0.5 and 3 atm. The high-voltage holdoff capability of SF_6 represents the practical reason for using this gas. However, at conditions of less high-voltage stress CO_2 , CF_4 , or Ar could be used. While lasing was obtained from atomic iodine using any one of the other three gases, use of Cl_4 appeared to prevent lasing.

Figure 2. Photograph of the atomic iodine and molecular iodine laser cell, shown here with 5-cm diameter sampling optics on end plates.

The maximum laser energy measured from this apparatus was 110 J. The laser pulse length was ~ 20 μ s full length. The diameter of the burn patterns, which was quite symmetric azimuthally, was 9-11 cm. One of these is shown in Fig. 3. The temperature of the wire discharge at the 520-nm wavelength was $T = 28$ kK. For this experiment, the 40- μ F bank was charged to 40 kV, for a stored energy of 32 kJ. The first half-cycle of current oscillation was 25 μ s in duration. The tungsten wire was 75 cm in length. The gas fill was 40 Torr CF_4 and 310 Torr CO_2 .

The energy budget for the laser can be approximated by noting that if the discharge radiates as a blackbody source at $T = 28$ kK (at peak), it has a peak optical radiated intensity of 3.5 $MW\text{-cm}^{-2}$. Since the discharge channel has a radius of 1 cm at peak emission, the peak optical radiated power is 1.7 GW. For an average power of 1 GW over 20 μ s, the total radiated energy is 20 kJ. At this temperature, 5% of the optical power lies in a 50-nm-wide band centered at $\lambda = 270$ nm, giving an available pump energy of 1 kJ. Taking into account degeneracies and the quantum efficiency for producing I^* , the laser energy stored is 20% of the absorbed pump energy, or 200 J. For the gain length used here a large fraction of this energy is extractable, so the attainable laser energy should be near 200 J. It appears that improvements on the 110 J measured energy could be made. Note that this analysis shows that 62% of the stored bank energy appears as optical radiation from the exploding-wire discharge.

Similar experiments were performed using exploding metal-film discharges as the pump source. These discharges offer the advantages of lower inductances and larger surface areas in comparison with wire discharges. Under conditions similar to the wire experiments above (except that the film was 87 cm in length), a discharge temperature of 20 kK at $\lambda = 520$ nm and a laser energy of 40 J were measured. An approximation of energy flow predicts values about half of those for the wire discharge. The considerably lower temperature of the film discharge is compensated for to within a factor of two by its larger area during the pump cycle. A burn pattern from this laser is shown in Fig. 3.

Figure 3. Beam impressions from atomic-iodine laser. Cross cut in print paper allowed fraction of beam to be sampled by laser calorimeter. Upper: Pattern of 90-1 wire-initiated laser pulse. Lower: 40-3 film-initiated pulse.

These atomic-iodine laser experiments were prematurely terminated by production of corrosive and possibly toxic chemical products of the discharge through the laser mix. Use of either SF_6 or CO_2 buffer gas led to oily and deliquescent deposits on the cell walls after exploding the metal conductor. We believe HF was also produced because the

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dielectric coatings on the large mirrors rapidly deteriorated. Apparently, aluminum played a role in this chemistry in that the problem was eliminated by nickel-plating of the aluminum cell.

Molecular-iodine laser

The molecular iodine laser was successfully operated using two separate cells, a smaller stainless-steel cell and the cell previously described (after nickel-plating). Experiments using the smaller cell will be described first. The apparatus is shown schematically in Fig. 4. The cell was constructed of 15-cm-diameter stainless-steel tubing and end plates. The insulator for the high-voltage electrode was constructed of Kel-F material. The brass electrodes were configured to allow the tungsten wire to lie along the edge of the 3.5-cm-diameter active volume, which was defined by the clear aperture of the extension tubes on which the internal laser mirrors were mounted. Heat tapes wrapped around the cell maintained all surfaces at temperatures of 65-75°C to support the necessary iodine vapor pressure of a few Torr.

Figure 4. Diagram of the smaller I_2 laser cell.

Most experiments were conducted using tungsten wire of 0.25-mm-diameter and 40-cm length. Peak brightness temperature of the discharge at 40 kV on 20 μ F was 27($\pm$ 2)kK in the ultraviolet and visible spectral regions. (Results of extensive experiments on the uv-visible radiating properties of exploding metal films and wires are presented elsewhere.¹) The laser was operated with several Torr I_2 vapor mixed with a buffer gas at 1-2 atm. Buffer gases examined were SF_6 , CF_4 , and Ar. The optimum buffer gas pressure was approximately 2 atm, with CF_4 and SF_6 performing somewhat better than Ar. (A few hundred Torr SF_6 was mixed with Ar to suppress extraneous discharges inside the cell.) Using 2 atm SF_6 as the buffer gas, the dependence of the laser output energy on I_2 pressure was examined, and an optimum pressure near 3 Torr was found. The I_2 pressure was measured with an optical absorption probe. Transmission of the 442-nm HeCd laser probe beam through I_2 vapor was found to have an absorption coefficient of $1.8(\pm 0.1) \times 10^{-19}$ cm². This wavelength lies in the continuum of the I_2 (B-X) band and therefore its absorption is unaffected by collisional broadening.

A typical laser output pulse at optimum conditions is shown in Fig. 5 along with the current trace. The pump light pulse, not shown, had a duration approximately equal to that of the first current half-cycle. The laser energy corresponding to this laser pulse was 2.0 J. This energy was a combination of that emitted from both ends of the cavity. Both internal mirrors were plano, one having a transmittance at 342 nm of 4.5% and the other 1.5%. The beam pattern, recorded on Dylux paper, uniformly filled the 3.5-cm-diameter laser aperture. Since optical pumping was azimuthally symmetric about the wire discharge, we may conservatively extrapolate to an 8-J total output energy from this laser. This value corresponds to a specific output energy of 7 J/g and an electrical efficiency of 5×10^{-4} .

As described earlier, metal film was substituted for the wire. In separate experiments,¹ exploding cylindrical-metal-film discharges have been shown to have brightness temperatures under these conditions of 23($\pm$ 2)kK. The laser output was ~0.2 J when the exploding-film discharge was used.

The near-optimum resonator transmittance of 6% indicates that a greater net gain would probably increase laser efficiency. The cell length was therefore increased to accommodate a wire length of 70 cm. The laser was operated under conditions similar to the earlier version, except that 40 μ F of capacitance charged to 30 kV was used. Higher output energy, and longer pulse lengths resulted. Maximum measured laser output energy was 12 J.

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Figure 5. Laser current and signals. The laser pulse is the upper trace and the current waveform, at ~ 100 kA/div, is the lower trace. The time scale is 5 μ s/div.

which extrapolates geometrically to 48 J from the full 7-cm-diameter aperture surrounding the wire. The electrical efficiency for the laser under these conditions was 2.7×10^{-3} and the specific output energy was 18 J/l. Greater efficiencies can be expected with a larger output coupling, but these measurements have yet to be completed.

In more recent work the larger cell described earlier has been used for extracting higher-energy 342 nm pulses from the I_2 laser. Plano mirrors coated for 342 nm were used. A large oven, made from nichrome wire secured inside plywood walls, was used to maintain the entire cell and attached plumbing at a temperature of ~ 70 C. In Fig. 2 the base of the oven can be seen, but the top, which has the heating wire, has been removed for firing the laser. Also in this photo can be seen one of the thermocouple gauges, the gas-fill line, the I_2 reservoir, and the variable-reluctance pressure gauge.

The 75-cm long tungsten wire was exploded with 47 kV on the 40-pF bank. For the first series of experiments sampling mirrors were used. This resonator sampled a portion of the pumped volume and used much cheaper optics. Using 3 Torr I_2 and 2 atm SiF_4 , an optimum output coupling of 0.50 was found, which produced a 2-J output from the 3.8-cm diameter clear aperture.

For extraction from the entire volume, 25-cm-diameter plano mirrors coated for 342 nm were used. The pyrex substrate was coated for max-R, and the quartz substrate for a reflectivity of 0.70 (unfortunately not the optimum reflectivity). At the previously stated conditions, a maximum laser energy of 20 J was measured. This corresponds to a specific output energy of 1 J/l. The beam spatial profile, recorded on Dylux uv-sensitive paper, covered the entire 20-cm aperture. The discharge temperature, measured at $\lambda = 280$ nm, was 28 kK. The much lower specific output energy of this laser compared with the smaller one is partially explained by the higher volume-averaged pump intensity in the latter.

The energy budget for this uv laser is similar to that for the atomic-iodine laser pumped with a wire. Because of the shorter pump wavelength ($\lambda = 192$ nm) a greater fraction, 7%, of the blackbody emission lies in the pumpband, despite its lesser spectral width of 25 nm. Hence, there are 1.4 kJ of pump radiation absorbed. The fact that only a very small fraction of this is extracted leads to the possibility of serious kinetic difficulties in this system. Some of these problems are probably caused by the vacuum-uv radiation that can interact with the medium, depleting the ground state and forming unusable, and perhaps, absorbing transient species.

Zuev et al.² have recently reported interesting results on the I_2 laser.

Summary and conclusions

Infrared and ultraviolet lasers have been optically pumped by exploding-metal-wire and exploding-metal-film discharges. Using the wire discharge we have obtained 110 J at $\lambda = 1.3$ μ m and 20 J at 0.34 μ m. Using metal-film discharges, 40 J has been measured at 1.3 μ m and 0.2 J at 0.34 μ m. This is the first reported use of exploding films or foils used to pump any laser.

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The low efficiency for pump utilization suggests a serious kinetics problem in the I_2 laser. Nevertheless, the 20-J output represents the largest energy obtained from an optically pumped uv or visible gas laser. Experiments with a smaller system showed that higher efficiencies and greater specific output energies could be obtained under different conditions.

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