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RECENT ADVANCES IN ULTRAVIOLET LASER TECHNOLOGY

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ABSTRACT

The science and technology of violet and ultraviolet lasers has matured rapidly in the last five years. High average power lasers have been demonstrated and several commercial product lines are now available. Single pulse devices have successfully demonstrated large output energies in well controlled beams. In this presentation we will review some of the current laser development programs in progress at Los Alamos. We will describe research in both discharge pumped lasers and E-beam pumped lasers and we will review methods of wavelength conversion in these devices. Finally we will discuss the current understanding of laser induced damage to optical components in the uv.

I. INTRODUCTION

The successful development of reliable UV lasers based on electrical pumping of rare gas halogen mixtures has lead to an increasing array of commercial and research applications that has served to further speed the development of these devices. Commercial applications which range from semiconductor processing to arterial reconstruction have driven the development of more efficient, more reliable, more versatile and eventually less costly laser devices. Research applications in atomic physics and plasma physics have led to interests in aperture scaling and short pulse operation of excimer lasers. At Los Alamos development programs address high power discharge lasers, high energy E-beam lasers and efficient methods of achieving tunability of the laser output.

II. DISCHARGE LASERS

Population inversion in an excimer discharge laser is achieved by separately initiating and maintaining a Townsend avalanche in a high pressure gas mixture. Because of the electro-negativity of the gases used, recombination of the initial preionization occurs very quickly and the entire discharge can collapse into a destructive arc if no precautions are taken. Advances in high speed pulse power and novel redesigns of the discharge electrode structures have been used to produce stabilized discharges at pulse repetition rates approaching 1000 Hz.

A series of laser systems have been designed and built to explore the laser science and technology required to generate high average power from XeCl lasers. These devices have specifically addressed the areas of magnetic pulse compression, prepulsing techniques, x-ray preionization, advanced thyratrons, gas cleanup techniques, inert construction materials and optically uniform gas flow. Prototype devices have achieved powers approaching 1KW at repetition rates of 1 KHz. Optical quality of the discharge medium is well controlled with RMS wavefront errors of less than 0.07 waves at 308 nm. These initial prototype devices have led to the development of advanced designs where compactness and reliability have been emphasized. Figure 1 shows a view of such a system currently under development. Design goals of this system are 250 W of average power operating at 308 nm.

The above devices typically operate with conventional pulse durations in the 20 - 50 ns range. A second type of discharge device has been developed that extends the output pulse duration into the 200 ns range while achieving a compaction of the physical design. In these devices the

usual solid cathode of the discharge volume is replaced by an inductively stabilized electrode. The electrode is composed of a segmented array of conductors each of which is connected to the main ground return by a separate inductor. If the discharge starts to become unstable, the current rises through one portion of the electrode, and the induced voltage drop in the ballasting inductor reduces the current thereby stabilizing the discharge. These devices have proven to be very robust in their operation. Because of the inherent stability against arc formation these lasers can operate at longer pulse durations and at reduced flow requirements in high pulse repetition rate applications. Figure 2 shows a cross sectional view of an inductively stabilized XeCl laser, referred to as the STABLEX design. Prototype devices have produced 165 mJ/pulse and 1000 Hz operation in separate devices. The long pulse output of these devices makes the use of modelocking a practical means of producing subnanosecond pulses of 308 nm radiation. Actively modelocked cavities have produced pulses in the 300 - 500 ps range that approach the transient limit of 160 ps. Tests are currently in progress to demonstrate 200 W of average power from an extended cavity version of the STABLEX design and to extend the modelocking studies by the use of passive modulators to the sub-100 ps regime.

III. ELECTRON-BEAM PUMPED LASERS

In addition to the small aperture, high average power devices described above, work is in progress to explore aperture scaling of large excimer lasers that are pumped by direct electron beam excitation. The Aurora laser is a large aperture long pulse KrF laser specifically designed for the inertial confinement fusion program that will be optically multiplexed to produce a single pulse 5 to 10 ns in duration for target irradiation experiments. The Aurora amplifier features a pumped volume of 2 m^3 with an output aperture of 10^4 cm^2 . Electrical power is provided by four pulse-charged water lines that drive opposed electron guns to achieve a uniform gain distribution in the lasing media. Figure 3 shows a view of the Large Aperture Module of the Aurora laser system. Two of the water storage lines are shown in the foreground attached to the electron gun and laser pumping chamber. The 10.8 m long water lines each store 150 KJ of energy and deliver approximately 31% of this energy to the laser gas at a cathode voltage of 675 KV. The carbon felt electron gun produces 25 A/cm^2 into a $100\text{cm} \times 200\text{cm}$ emitting area at an impedance of 2.7 ohm. Preliminary testing of the device in an unstable resonator configuration has been completed and output energies in excess of 10 KJ have been obtained in pulse durations of 500 ns at an electrical pumping rate of 133 KW/cm^3 to the laser gas.

IV. WAVELENGTH CONVERSION

Although efficient excimer lasers have been developed to cover the wavelength range from 190 nm (ArF) to 350 nm (XeF) some applications require wavelength tunability throughout this range. The use of organic dyes pumped by excimer lasers have provided complete tunability while the use of stimulated raman scattering has provided efficient stepwise tunability in the near ultraviolet.

* Laser-pumped dye lasers

The commercial availability of reliable, high average power excimer lasers has led to the development of high repetition rate dye lasers operating in the ultraviolet. In order to achieve large pulse energies at high PRFs, master oscillator/power amplifier configurations have been used. Master oscillators have been designed and tested that produce 375 mW of power in a 3X diffraction limited beam operating at 250 Hz. Power amplifiers have been designed for pumping volumes of $3.5 \times 3.5 \times 70 \text{ mm}^3$ and intrinsic conversion efficiencies in the range of 18% to 22% have been measured for a variety of dyes. For saturated MOPA amplifier chains, system efficiencies in the range of 14% have been achieved for specific operating ranges. Figure 4 shows the saturation characteristics of a such a power amplifier operating in the near uv.

* Raman conversion

Although the dye lasers possess inherent tunability they suffer from being complex devices with limited efficiency. An alternate method of obtaining UV radiation is through the use of stimulated Raman scattering. This technique provides only stepwise tunability but has the potential advantage of increased conversion efficiency. Experiments with single focus Raman generators have demonstrated intrinsic photon conversion efficiencies of 85% in single shifts in methane (CH_4) driven with XeF discharge lasers. Figure 5 shows the measured photon conversion efficiency as a function of input pump energy. First Stokes generation (open circles) reaches 85% before the first indication of second Stokes generation (closed circles) is experimentally observed. These high efficiencies are due in part to the increased suppression of second stokes generation that have been observed for the large f/No. geometries used in these experiments that tend to suppress the four wave mixing contribution to the second Stokes onset.

V. LASER INDUCED DAMAGE

The ability of optical components to survive and maintain their performance in the presence of high radiation fields is of important fundamental and practical concern to the designers and builders of laser devices. The current programs at Los Alamos are directed toward quantifying and understanding the damage processes that occur for the ultraviolet wavelength range. Of particular concern is the variation of damage thresholds with wavelength and optical pulse duration. Figure 5 shows a compilation of experimental results for several different materials for three different laser wavelengths, 248nm, 308nm and 351nm. Laser pulse duration was approximately 15 ns for all these tests and the damage threshold is defined as the fluence producing a zero probability of damage independent of laser spot size. For the data shown the damage threshold appears to scale at least as $(\text{wavelength})^2$ over the wavelength range investigated with an upper limit of $(\text{wavelength})^4$. The specific trends are also seen to be material dependent, e.g. the two different polishing techniques on Suprasil.

A second area of interest is the scaling of optical damage with pulse duration. At present no complete, self-consistent data is available that covers the entire range of interest. However by comparing the existing data we can obtain an indication of the trends to be expected. In figure 7 we have plotted data from three different experiments as noted, where the absolute damage thresholds have been normalized at the pulse duration boundaries for each experiment. The data of Newnam and Gill and Rainer were taken with tripled Nd:YAG at 353nm, whereas the rest of the data was obtained with a discharge XeF laser (Foltyn) and a frequency doubled dye laser (Foltyn and Marrs) at 351 nm. For short duration pulses below 1 ns we see that damage is no longer dependent on the fluence of the laser radiation but rather becomes linearly dependent on the laser intensity reminiscent of an electron avalanche initiation process. At the longer pulse durations, up to 450 ns, the scaling of the damage threshold becomes a very weak function of the pulse duration, scaling as $(t_p)^{0.2}$. This is much slower than the $(t_p)^{0.5}$ expected for a completely thermal process and at present is not understood.

VI. CONCLUSIONS

The science and technology of ultraviolet lasers using electrical pumping of excimer gases has developed rapidly in recent years. The results achieved to date have been quite impressive for the short time involved. Average powers in excess of 1 KW have been demonstrated and commercial devices exist with output powers approaching 300 watts. Single pulse

energies in excess of 10 KJ have been demonstrated in laboratory devices and efforts are in progress to scale these single pulse energies into the 100 kJ range.

Future developments in laser devices will emphasize aperture scaling of discharge and e-beam pumped devices, approaches to cw operation, improved efficiency and lifetime and the development of very high brightness laser sources.

Methods of wavelength conversion will continue to be refined in the ultraviolet. Improved uv dyes, with enhanced lifetime and efficiency will be developed, increased emphasis will be placed on the development of efficient and scalable Raman converters, and the potential of optically pumped X-ray lasers will be explored.

FIGURE CAPTIONS

- Fig.1 High average power prototype XeCl laser. Optical axis, gas flow and discharge current are mutually orthogonal. Discharge length is 60 cm.
- Fig.2 High average power Stablax laser. Laser consists of four separate discharges, each $1 \times 1 \times 40 \text{ cm}^3$, controlled by a thyatron switch. System includes axial fan and heat exchanger. Scale is noted in figure.
- Fig.3 View of the Large Aperture Module of the Aurora laser fusion facility. Water lines are 91 cm in diameter and the laser volume (located between the Helmholtz coils) is $100 \times 100 \times 200 \text{ cm}^3$.
- Fig.4 Amplifier saturation curve for XeCl laser pumped dye laser amplifier using solution of TBS in cyclohexane. For this double sided pumped amplifier, 50mJ/pulse was extracted for a pump energy of 200mJ/side in a 22ns pulse.
- Fig.5 Measured Raman conversion efficiency for first Stokes (open circles) and second Stokes (closed circles) for 110 atm cell of CH_4 pumped by a 20 ns pulse of 351nm radiation from a XeF laser. Threshold for second Stokes is nearly x6 that for the first Stokes emission.
- Fig.6 Wavelength scaling of laser induced damage for several uv materials and coating combinations for KrF, XeCl and XeF lasers. Solid curves are contours for $(\text{wavelength})^2$ scaling of the damage threshold. Data taken with approximately 15 ns pulses.
- Fig.7 Normalized pulse duration scaling of damage threshold. Open triangles are data from B.E.Newnam and D.H.Gill, "Ultraviolet damage resistance of laser coatings", NBS Special Publication 541, p.190, 1978. Closed squares are taken from Foltyn and Marrs(unpublished). Closed circles are from F.Rainer, C.L.Vercimak, D.Milam, C.K.Carniglia, T.Tuttle Hart, "Measurements of the dependence of damage thresholds on laser wavelength, pulse duration and film thickness", presented at the 15th Annual Symposium on Optical Materials for High Power Lasers, Boulder, Co, Nov. 14-16, 1983, in press.

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OSCILLATOR/PREAMP DELIVERS REQUIRED SATURATION FLUENCE

HIGH EFFICIENCY RAMAN CONVERSION OF AN XeF LASER IN CH₄

DAMAGE OF EXCIMER LASER COMPONENTS - WAVELENGTH SCALING

LONG-RANGE PULSELENGTH SCALING FOR REFLECTORS AT 350 nm