Development of a compact and reliable repetitively pulsed Xe Cl (308 nm) excimer laser

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MS received 7 February 2011; revised 3 August 2012; accepted 11 January 2013

Abstract. Development and operation characteristics of a repetitively pulsed UV spark pre-ionized XeCl (Xenon Chloride) excimer laser is described. The laser uses discharge pumped C–C charge transfer excitation. A compact gas circulation loop was adopted to achieve high repetition rate operation. The laser generates optical pulses of energy 150 mJ at 150 Hz reliably. The electrical to optical conversion efficiency obtained is 1%. The laser pulse duration is ∼8 nS (FWHM). The single fill gas lifetime have been found to be 2×10^6 shots for 20% reduction of energy without any halogen injection. The system is compact and reliable.

Keywords. Excimer laser; xenon chloride; discharge pumped; C–C energy transfer; single fill gas life-time.

1. Introduction

With the invention of short wavelength UV lasers, a new era of lasers in industrial micro applications has started. UV lasers produce enormous advantage in micro structuring, marking and drilling applications since they can be focused to a smaller spot size. Besides, these UV lasers enable processing at higher spatial resolution than visible or IR lasers. The smallest spot size that can be produced by focused laser beam is limited by diffraction that increases with wavelength. Therefore, UV light is considered to be the best suitable source in achieving the minimum image size. The UV lasers with high quantum energy photons directly break the atomic and molecular bonds within material. The photons in this spectral range are also capable of inducing photochemical reactions. Most solid materials have high absorption in the UV. The short pulses result in reducing interaction time between laser radiation and the material being processed. The UV laser light penetrates a very small depth of the material thereby removing very thin layer of material by non-thermal (photo ablation) process. This permits excellent depth control with little or no effect on the surrounding material.

UV radiation can be produced by harmonic conversion of solid-state lasers. However, emission of all other pulsed UV lasers is based on discharge generation in gas media. Excimer lasers

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are efficient UV-coherent sources and generate a high energy-intensive beam of light through the releasing of excitation energy from excited diatomic gas (Basting & Marowsky 2004; Basting *et al* 2001; Meyer *et al* 2002). These diatomic molecules are bound in excited state only and dissociate after emission of photons. These diatomic molecules have very short lifetimes and when they dissociate, they release their excitation energy through Ultra Violet photons. These photons are easily absorbed in variety of materials like plastics, glass, ceramics, metals and biological tissues. This incident photon energy is high enough to break the chemical bonds of organic material directly without generating appreciable heat. Commonly used excimer wavelengths include Argon Fluoride −193 nm, Krypton Fluoride 248 nm, Xenon Chloride 308 nm and Xenon Fluoride 351 nm. The output wavelength depends on the active gas fill of the laser and can be changed simply by changing the gas mixture and optics. The XeCl excimer producing laser at 308 nm is particularly attractive because it allows long lifetime operation and can easily be scaled to large volumes. Self-sustained discharge pumped rare gas halide excimer lasers with ultraviolet pre-ionization are simple, most efficient and powerful source of coherent radiation in the UV region. They find numerous applications such as chemistry, spectroscopy, nonlinear optics and remote sensing. Considering the simplicity and reliability of the laser device, automatically pre-ionized discharge pumped laser of the capacitor-transfer type can be the most advantageous candidate for the practical use. Here, the pre-ionization automatically precedes the main discharge with the required delay determined by the circuit parameters and extra extensive equipment can be eliminated. Efficient operation of the discharge pumped XeCl laser with automatic pre-ionization was achieved at total gas pressure of 2–4 atmospheres. It is therefore necessary to construct the laser chamber capable of being operated at this gas pressure. In addition, uniform and sufficient pre-ionization is required to maintain stable and homogeneous discharge. In this paper, we present the development and operating characteristics of a repetitively pulsed xenon chloride laser.

Excimer lasers are used in wide range of industrial, scientific and medical applications (Kuntze *et al* 2002; Zagorulko *et al* 2004; Groothoff *et al* 2003; Hutchinson 1983). They are also used in micro machining of polymers, ceramics and semiconductors. Other applications include removing polymer films from metal substrates and marking on thermally sensitive materials (Lambda Industrial No.5 1994; Lambda Industrial No.8 1989). In optical communication, excimer is of particular importance in the production of optical fibre Bragg grating (Othonos *et al* 1999). After the effect of ablation was discovered, lasers became an imperative tool in potential material processing applications and this principle of ablation is extended even for medicinal use (Srinivasan 1986).

2. Construction

The cross sectional view of the laser system and the photograph of the developed system are shown in figures 1 and 2, respectively. The system mainly consists of laser housing, laser head, excitation circuit, gas circulation and gas cooling system. The details of each of the subsystem are as given below.

The excimer laser requires low inductivity laser head, the gas tightness and the cleanliness under highly reactive nature of the gases used in excimer lasers. A chamber capable of withstanding 4 atmospheric pressures has been designed and built out of an aluminum alloy that has low percentage of silicon. The laser head consists of two nickel electrodes and a UV preionizer. One of these electrodes is a profiled ground electrode and the other is a semi-cylindrical high voltage electrode with inbuilt pre-ionizer. These electrodes are made of nickel having an

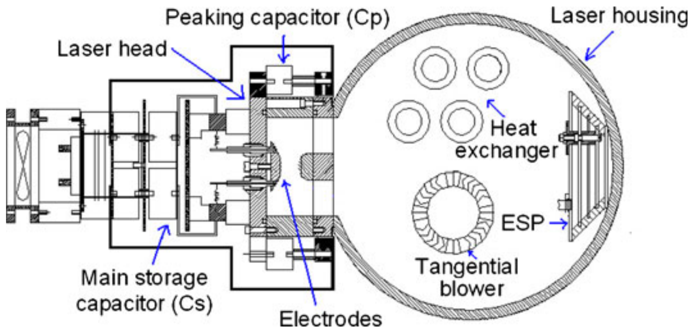

Figure 1. Cross sectional view of the system.

effective length of 50 cms. The gap between the electrodes is 2.3 cm. One of the electrodes is located along a central position in the cavity and is grounded to the housing structure. Here, the discharge gas is pre-ionized by sparks generated between pins and HV electrode. Two arrays of tungsten pin gaps are placed along the length of the HV electrode. In order to provide ballasting to the pins individually, each pin is connected through a small inductor to a common lead hooked up to the storage capacitor. There are 49 such pins and a gap of 2 mm for pre-ionizer is kept between tip of the pin and high voltage electrode. This arrangement is mounted on PVDF housing which provides HV isolation. Furthermore, PVDF is UV non-degradable and suitable for halogen gas environment.

For high repetition rate laser operation, the gas is circulated in the active region using a tangential blower. The gas circulatory system mainly consists of a tangential blower and a set of heat exchangers. The laser gas flows transversely in the discharge zone and sweeps out the discharge volume between two pulses. This gas then passes through a set of water-cooled aluminum finned tube heat exchangers. The blower is magnetically coupled to the driver motor. The magnetic coupling permits the blower to be driven with an external motor with out using mechanical seals, which have chances of leakage. The velocity of gas flow in the discharge region was measured with a flow meter in neon gas. It was found to be 6 meters/second. This resulted in a clearance ratio of 4 for 150 Hz operation of the laser. In high repetition excimer lasers, solid metal dust is a major problem as far as the laser optics is considered. Due to sputtering of pins and electrodes,

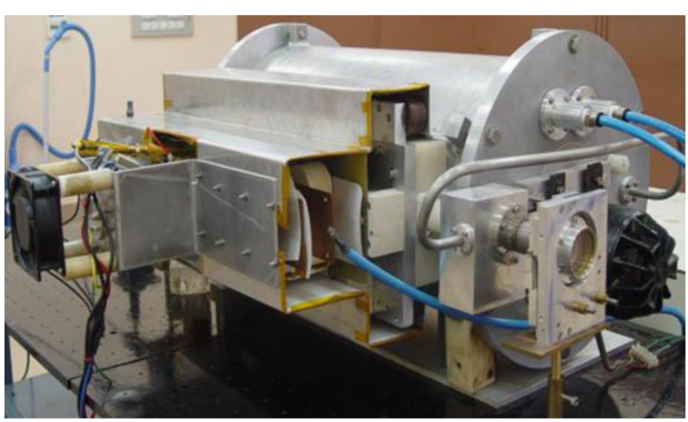

Figure 2. Photograph of the laser system developed.

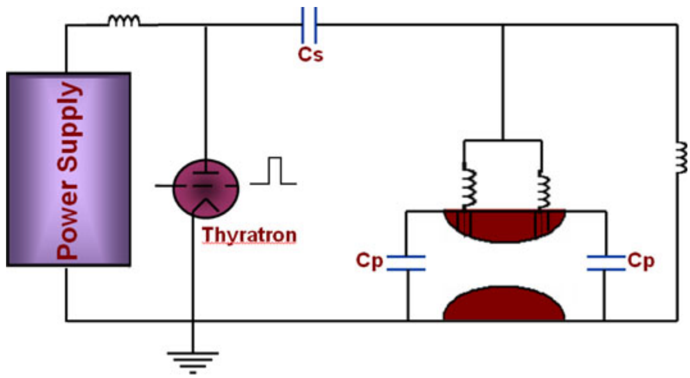

Figure 3. Schematic of excitation circuit.

the sputtered material reacts with halogen gas and forms metal dust. This metal dust deposits on the windows necessitating the cleaning of windows frequently. To remove this metal dust from active region, a 2-stage parallel plate type electrostatic dust remover has been developed. In the first stage, metal dust gets ionized and in second stage, it precipitates. All the internal parts of the sub systems have been meticulously cleaned and assembled in a clean room. The system has been made leak tight better than 10^{-5} mbar–liter/sec. The optical cavity is formed by a flat total reflecting mirror and a plane quartz window separated by 120 cm.

3. Excitation circuit

The schematic of charge-transfer excitation circuit used for this laser is depicted in figure 3. The excitation circuit primarily consists of a high voltage power supply, a thyratron (CX 3608)

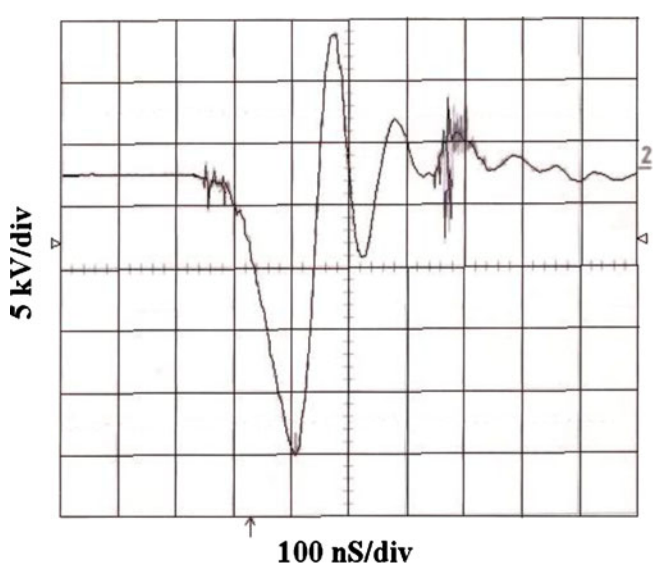

Figure 4. Discharge voltage pulse.

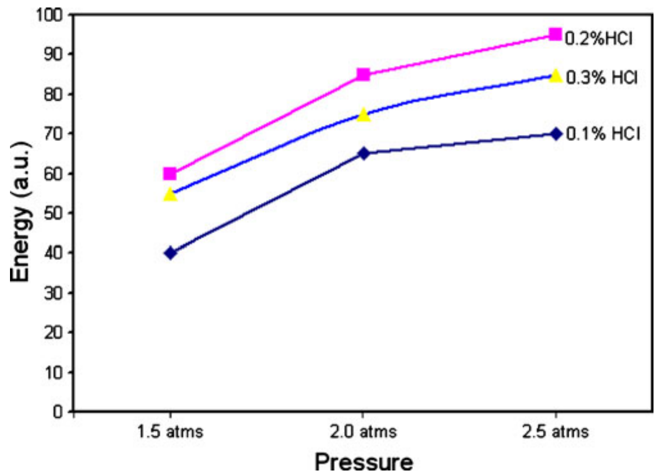

Figure 5. Laser energy as a function of total gas pressure for different HCl concentrations.

as a controllable high voltage switch, main energy storage capacitors and peaking capacitors. Due to short wave lengths, the pumping energy density in an excimer laser has to be very high and due to very short pumping time, the power density is remarkably high. Hence, one of the important requirements of Excimer laser development is fast excitation circuit for driving power into the discharge. The best design to fulfill these requirements is the C–C charge transfer circuit. Considering the simplicity and reliability of the laser device, automatic pre-ionized discharge pumped excitation has been chosen (Hiramastsu & Goto 1986; Miyazaki *et al* 1986). This is most advantageous for practical purposes as it can be incorporated easily in the laser head and the pre-ionization automatically precedes the main discharge with a time delay determined by

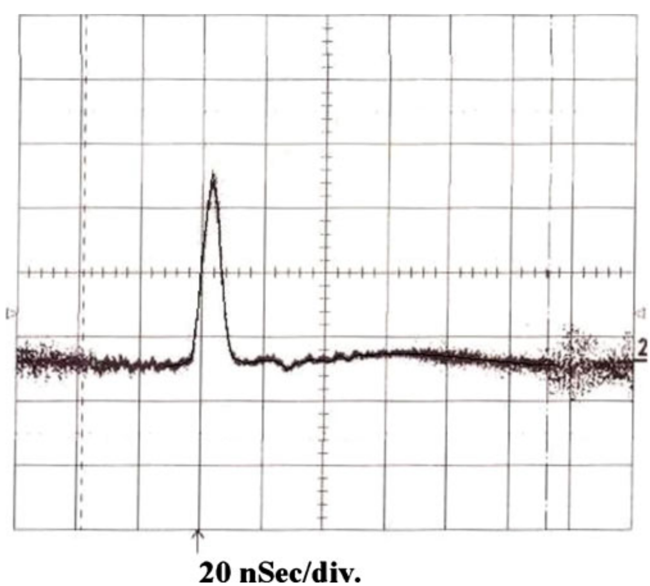

Figure 6. Laser pulse.

the circuit parameters (Sato *et al* 2002; Tatsumi *et al* 1997). A single switch is sufficient for pre-ionizer as well as main discharge and no external delay generating circuits are required. All the electrical components of the discharge circuit except the electrodes and pre-ionizer pins are placed outside the discharge chamber. This reduces problems of contamination due to corrosive gases besides minimizing halogen gas consumption.

4. Laser performance and results

Initial experiments were carried out with primary storage capacitor Cs = 51.3 nF and peaking capacitor Cp = 16.1 nF (Benerji *et al* 2009). The storage capacitor is in the form of an array of 19 doorknob ceramic capacitors of 2.7 nF each whereas the peaking capacitor consists of 23 doorknob capacitors (each 0.7 nF). Cs is charged to 24.5 kV using home built HV resonant charging power supply. Triggering the thyratron transfers the charge from C_S to C_P until discharge breakdown occurs. For effective pumping of the laser gas, a very fast high current discharge is required. This is achieved by placing peaking capacitors very close to the electrodes and due care has been taken in the design of the discharge loop to keep as close as possible. This arrangement resulted in producing high voltage pulses with a rise time of 100 nS across the laser head. The discharge voltage pulse is shown in figure 4.

We studied the dependence of laser energy on different concentrations of the HCl of the laser gas mixture at different gas pressures. Results of the energy dependence on three different concentrations of HCl at various pressures are shown in figure 5. It was found that the optimum concentration of HCl is 0.2% in the gas mixture over range of 1.5 to 2.5 total gas pressures. The maximum operating pressure was limited due to safety considerations of the laser head. The gas mixture has been optimized with respect to laser output energy. The optimum gas mixture was found to be 5 mbar-HCl, 80 mbar-xenon and rest is neon at total operating pressure of 2500 mbar. The percentages of concentration of constituents of the gas mixture are 0.2%, 3.2% and 96.6% HCl, Xe and Ne, respectively. The laser could produce optical pulses of energy 85 mJ at 150 Hz reliably. The pulse shape of the laser is shown in figure 6. The laser pulse duration is ∼8 nS (FWHM). The single fill gas lifetime has been found to be 2×10^6 shots for 20% reduction of energy without any halogen injection. Further experiments were carried out with above-mentioned mixture at 2500 mbar operating pressure.

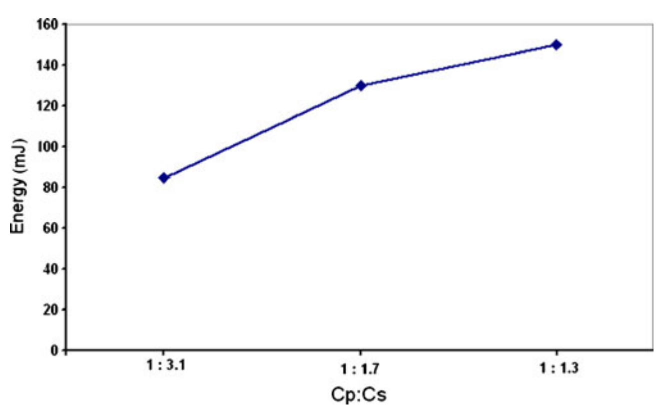

Figure 7. Laser energy as a function of different ratios of Cp: Cs.

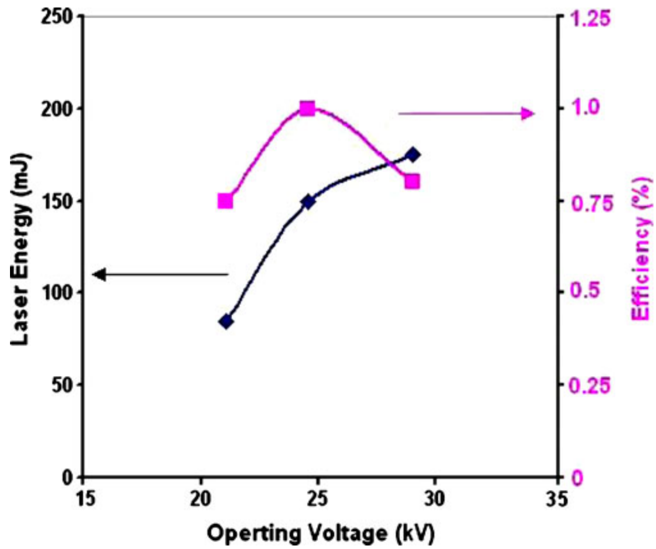

Figure 8. Output energy and efficiency of the laser for different charging voltages of main storage capacitor.

With a view to improving energy transfer, experiments were carried out by changing the Cp value. Here, when Cp was increased to 30 nF keeping the Cs and charging voltage same. The laser could produce 130 mJ pulses. The conversion efficiency obtained is 0.8%. On further increasing the value of Cp to 40 nF, the laser could produce 150 mJ pulses for same Cs and charging voltage. The figure 7 shows the relation between output energy and Cp: Cs. It resulted that at small ratio of Cp: Cs maximum energy was obtained. This is due to better energy transfer efficiency from Cs to Cp at small ratio of Cp:Cs. This corresponds to electrical to optical efficiency of 1%. Further, optimization of the Cp value could not be carried out due to space constraints for the accommodation of peaking capacitors very close to laser head.

The laser energy and efficiency at different operating voltages are given in figure 8. The laser energy increases with voltage where as efficiency decreases at higher voltages in the studied range of these parameters. Further, when the charging voltage was increased to 29 kV, the laser could produce energy of 175 mJ. The corresponding efficiency is 0.8%. On further increasing charging voltage the output energy not only decreased, but also leading to major energy fluctuations. This is due to inefficient energy transfer and gas clearance at higher input energy densities.

5. Conclusion

In conclusion, the development of a compact and reliable repetitively pulsed UV spark preionized XeCl and operating characteristics of the laser are reported. The system uses discharge pumped C–C charge transfer excitation. The laser generates optical pulses of energy 150 mJ at 150 Hz reliably. The electrical to optical conversion efficiency obtained is 1%. The operating characteristics of the laser have been presented. The laser pulse duration is ~8 nS (FWHM). The single fill gas lifetime has been found to be 2×10^6 shots for 20% reduction of energy without any halogen injection.

Acknowledgements

Authors are thankful to Shri K H Modi, Shri O Dogre and Laser workshop team of Raja Ramanna Centre for Advanced Technology, Indore (RRCAT) for their technical support during the development of the system.

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