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Pulse Operation of Chemical Oxygen-Iodine Laser by Pulsed Gas Discharge with the Assistance of Spark Pre-ionization

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The continuous wavelength chemical oxygen-iodine laser can be turned into pulse operation mode in order to obtain high energy and high pulse power. We propose an approach to produce iodine atoms instantaneously by pulsed gas discharge with the assistance of spark pre-ionization to achieve the pulsed goal. The influence of spark pre-ionization on discharge homogeneity is discussed. Voltage-current characteristics are shown and discussed in existence of the pre-ionization capacitor and peaking capacitor. The spark pre-ionization and peaking capacitor are very helpful in obtaining a stable and homogeneous discharge. The lasing is achieved at the total pressure of 2.2–2.9 kPa and single pulse energy is up to 180 mJ, the corresponding specific output energy is 1.0 J/L.

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Significant success has been achieved in the study of chemical oxygen-iodine lasers (COIL) in the past several decades, which operates on electronic transitions of iodine atoms at 1.315 μm. The COIL has several attractive merits for the pulse operation of COIL: First, the laser is pumped by pure chemical reaction and the chemical efficiency is very high because of its unique pumping mechanism. Second, the COIL has an excellent scalable characteristic, so it could output an extremely high average power. Third, the wavelength of this laser happens to be at the lowest optical loss region of the silica glass

These merits encouraged a number of researchers to turn the continuous-wave (CW) COIL to pulsed COIL because long-pulsed high-energy laser is very interesting in many applications such as laser-material interaction. A lot of investigations have shown that the effect of pulsed laser is better than that of continuous-wave laser in some cases (such as welding and drilling).[1] Two main approaches were used to achieve the pulse operation of CW COIL. The first is based on cavity Q switching or on modulations of the gain and losses in a cw COIL.[2–4] Its shortcoming is the low efficiency of the pulse operation, i.e. a small value of the ratio of the pulse power to the continuous-wave power at the same flow rate of chlorine gas. To obtain a high value of the ratio the active medium gain in the pulsed COIL must be as high as possible. However, the production method of atomic iodine restrains the increasing of the medium gain, so the maximum ratio achieved is about 12 up to now. The second approach is based on the instantaneous production of atomic iodine in the mixture of singlet delta oxygen by means of photolyzing iodide or dissociating iodine donor through pulsed gas discharge. The advantages of photolysis are that it is clean and photolysis does not destroy singlet delta oxygen. However, its fatal shortcoming is the low electric efficiency (ratio of laser output energy to electric energy), which makes it difficult to scale up. It is exciting that the total efficiency of pulsed gas discharge is up to 91% in Ref. [5], which is about 300 times higher than that of photolysis.

The key problem of pulsed gas discharge is how to obtain a stable homogeneous discharge in a mixture of singlet delta oxygen with iodide because most of the iodine donor and oxygen molecules are strongly electronegative gases. A pair of annular electrodes was used as cathode and anode in longitudinal electric discharge in Refs. [6,7]. Vagin and Yuryshev[8] took 120 pins as cathode and a plate as anode, carried out in a transverse electric discharge.

The key point for achieving a steady homogeneous discharge in a strongly electronegative gas is to provide original high concentration free electrons. An electron-beam or UV pre-ionization is preferable to solve the problem. Thus we achieve the pulse operation of COIL by a transverse electric discharge with the association of spark pre-ionization. A specific output energy of 1.0 J/L is obtained at the pulse duration of 20 μs, which corresponds to a concentration of atomic iodine of 0.9×10^{15} cm^{-3}. The influence of the pre-ionizer capacitor and peaking capacitor on the glow stability and homogeneity is discussed.

The schematic of the electrical discharge is shown in Fig. 1. The electrodes, separated by 5.4 cm, are 50×110 mm aluminum bars with edges rounded with a radius of 10 mm. An aluminum pin used as a spark pre-ionizer was connected to a pre-ionization capacitor $C_{\rm pre}$ of 200–500 pF and there were 3 such pins placed

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on either side of the cathode along its longitude direction. These three pins were separated by a distance of 22 mm. A storage capacitor C_s was charged by a high voltage power supply when an air spark gap SG_1 was triggered. When another air spark gap SG_2 was triggered, the spark started to travel across the six gaps of the pre-ionizer array emitting intense UV radiation. At the same time the peaking capacitor C_p was charged until the voltage at the anode was sufficient for gas breakdown between the laser electrodes. The frequency of the pulse operation was 4 Hz.

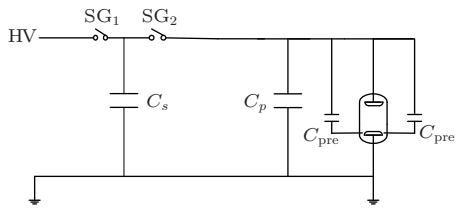

Fig. 1. Schematic of the electrical discharge circuit.

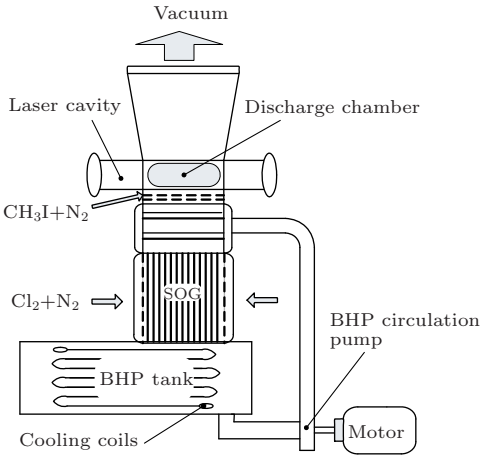

Fig. 2. Schematic of the experimental setup.

The singlet oxygen generator used was a square-pipe-array jet-type singlet oxygen generator (SPJ-SOG), which was described in Ref. [9] in detail. The schematic of experiments is shown in Fig. 2. The cross section of the reaction area was $6 \times 10\,\mathrm{cm}^2$, and the specific surface of the gas-liquid reaction was $5\,\mathrm{cm}^{-1}$. In order to enhance the chlorine utilization, the reaction zone was set to 30 cm. BHP was composed of 25 kg H_2O_2 (50 wt%) and 30 kg KOH aqueous solution (50 wt%). Nitrogen used as the primary buffer gas and was introduced together with Cl_2 into a singlet oxygen generator (SOG) from both sides. A gas distribution injector was connected to the outlet of SOG instead of the iodine nozzle used in supersonic COIL. CH_3I was delivered from a tank heated up to 50–70°C to the main gas flow through the gas injector with the aid of the secondary buffer gas. A stable resonant cavity of 60 cm was used, with a transmission of 1.4% for the plane mirror and a curvature radius of 2.5 m for the concave mirror.

The discharge current was measured with a current probe (Tektronix, TCP202) and inputed into one channel of a storage oscilloscope (Lecroy, 9310A). The discharge voltage was measured with a high voltage probe (Tektronix, P6015A) and fed into the other channel. A digital camera (Canon, G5) was used to take the images of the discharge to record the variety of the discharge status. The pulse duration of the output laser was measured by a fast response infrared detector (New Focus, 6105A) and a storage oscilloscope. The trigger signal was from the high voltage probe (Tektronix, P6015A). The laser output energy was measured with a laser power meter (Coherent A103).

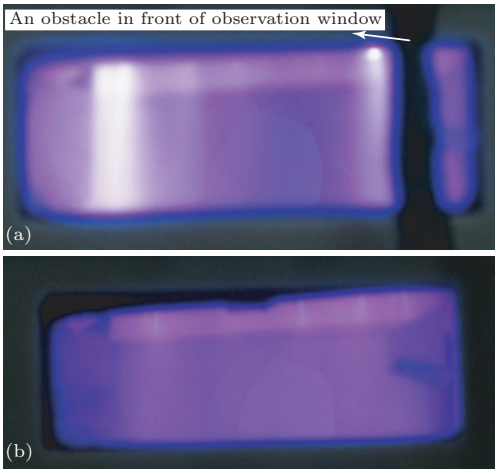

Fig. 3. Photograph in the electrode gap: (a) without C_{pre} and C_p, (b) $C_{\mathrm{pre}} = 200\,\mathrm{pF}$, $C_p = 6.6\,\mathrm{nF}$.

A series of simulation experiments were carried out to investigate the influence of the peaking capacitor and pre-ionization capacitor on discharge homogeneity and voltage-current characteristics. In the series of simulation experiments the gas mixture from the singlet oxygen generator was replaced by oxygen and nitrogen, and nitrogen was used as buffer gas, CH_3I was used as the iodide donor. The images along the electrode longitude of the discharges were taken to record the discharge status. The typical comparison images of the influence of C_{pre} and C_p on discharge homogeneity are shown in Fig. 3. It shows that discharge homogeneity was extremely enhanced with the aid of spark pre-ionization. The relative position of the pre-ionizer pin to the ground electrode is very important to obtain discharge homogeneity. In our experiments these pre-ionizer pins were fixed near the ground electrode and below its surface, i.e. farther away from the anode, otherwise discharge would occur between these pins with the anode. The gap of 6 mm is optimum to our experiments. The capacitance of C_{pre} and C_p was also the key point in achieving discharge homogeneity. C_{pre} from 200 to 500 pF and C_p from 3.3 to 10 nF were investigated to seek the most appropriation under our

experiment condition. Finally $C_{\rm pre}$ and C_p were fixed at 200 pF and 8.9 nF, respectively. In the above serial experiments the voltage of the storage capacitor C_s was equal to 14–18 kV and the capacitance of C_s is 11.2 nF. The total pressure of the mixture gas was about 2.2–2.9 kPa, the mix ratio of the three gases was similar to the actual laser operation.

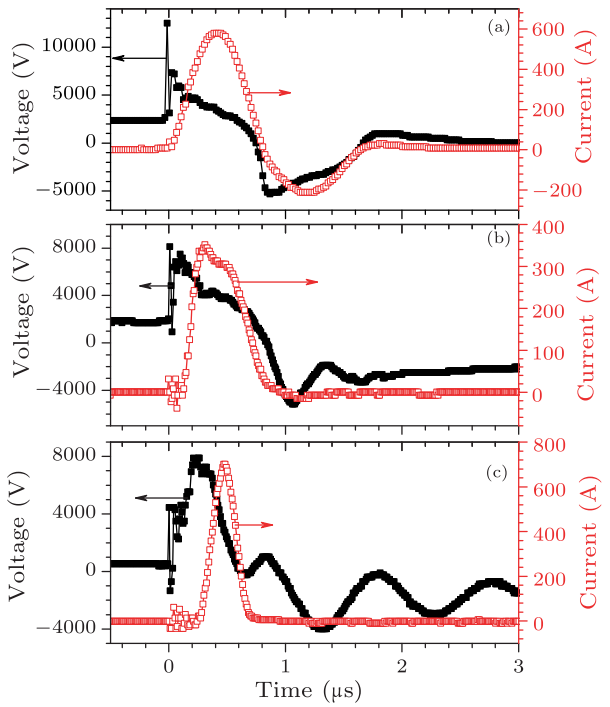

Fig. 4. Typical voltage and current woveforms across discharge gap, $V = 14$ kV, $P = 2.5$ kPa: (a) without $C_{\rm pre}$ and C_p, (b) without C_p and $C_{\rm pre} = 200$ pF, (c) $C_p = 6.6$ nF and $C_{\rm pre} = 200$ pF.

The voltage and current waveforms across the discharge gap are shown in Fig. 4. In contrast to the case without $C_{\rm pre}$ (Fig. 4(a)), the breakdown voltage with the assistance of spark pre-ionization (Fig. 4(b)) is lower due to intense seed electrons yielded by spark pre-ionization. In addition, a slight current took place before the main gap was ignited. It is also obvious that there was a time delay of 110 ns between the spark and the main gap discharge. In the case of the existence of C_p and $C_{\rm pre}$ the voltage-current characteristics were changed, as shown in Fig. 4(c). The time delay was about 250 ns, which was longer than that in the presence of only $C_{\rm pre}$. Pre-ionization pins produced a more intense pre-ionization current, which narrowed the main discharge current and enhanced its Amplitude. C_p, $C_{\rm pre}$ and the main discharge gap were charged by the storage capacitor C_s when SG_1 was triggered. First the spark gap was ignited and generated the intense pre-ionization electrons. Then the main gap was ignited and the peaking capacitor was discharged through the main gap. The peaking capacitor acted by slowing down the growth of the main gap voltage, but sharpened the rise in current once the discharge breakdown occurred.

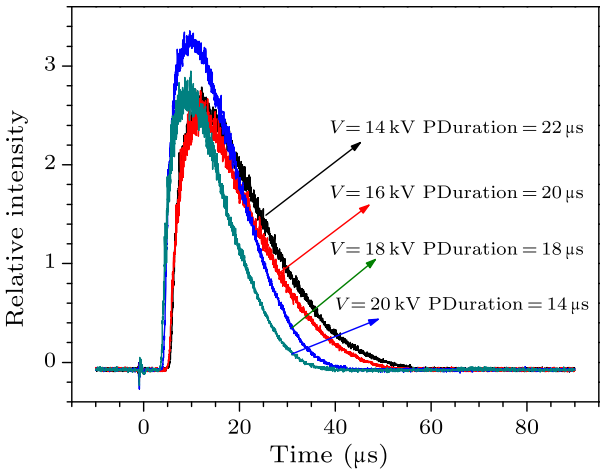

Fig. 5. Influence of the voltage of storage capacitor on pulse waveform.

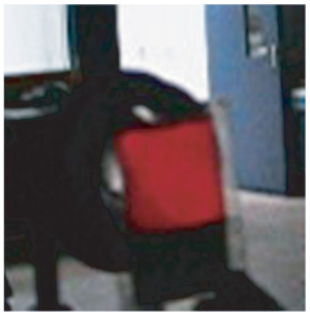

Fig. 6. Output laser spot.

The preliminary experiments of laser output were carried out after the homogeneous discharge was obtained. We studied the influence of the deposited energy on the output laser characteristics. The results of the typical experiments are shown in Fig. 5. The time delay between the discharge voltage and lasing pulses increases from 3 to 6 μs. Along with this, the pulse duration narrowed with the increasing deposited energy. According to the analysis in Ref. [10], the pulse duration of laser is determined by

$$\tau = \frac{1}{k_f \times [\mathrm{I}]},$$

where k_f is the forward rate of energy transfer of singlet delta oxygen with atomic iodine, [I] is the concentration of the ground state iodine. The concentration of iodine atoms generated by pulsed discharge was estimated to be about $0.6–0.9 \times 10^{15}$ cm^{-3}. The single pulse energy up to 180 mJ was achieved in the case of the chlorine flow rate of 32 mmol/s and the total pressure of 2.9 kPa in the optical resonator. The specific energy output of 1.0 J/L was obtained. We believe that some specific characteristics will be better because some experimental conditions such as different output coupling and various chlorine flow rates have

not been carried out. The near-field beam spot was recorded by an infrared sensor card, as shown in Fig. 6. One can see that the spot is very uniform, which illuminated the discharge homogeneity.

The investigation of a pulsed COIL initiated by a transverse electric discharge with the assistance of spark pre-ionization has been carried out. Spark pre-ionization extremely improves the discharge homogeneity and stability. The peaking capacitor sharpens the rise in current once the discharge breakdown occurs. The breakdown voltage is lower due to the intense seed electrons produced by spark pre-ionization. On the basis of the investigation of discharge homogeneity, the lasing is obtained in the case of the pre-ionization capacitor of 200 pF each pin and the peaking capacitor of 6.6 nF. The single pulse energy up to 180 mJ and the specific output energy of 1.0 J/L are obtained.

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