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稀有气体卤化物准分子激光器工作气体实时补给技术

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摘 要:为延长稀有气体卤化物准分子激光器工作气体使用寿命,在原有供气设备基础上增加了工作气体实时补给技术.该技术采用 FPGA 控制系统将逐步提高放电电压、补充卤素气体和更换部分混合气体等操作有效组合起来.随着激光脉冲能量的下降,逐步提高放电电压;当放电电压达到最大值时,开始补充卤素气体,并恢复放电电压;当补充卤素气体效果不明显时,更换部分混合工作气体.将该技术应用于医用型 ArF 准分子激光器中进行实验研究,结果表明:在没有使用工作气体实时补给技术的情况下,激光器累计工作 14.38 h 后,输出单脉冲激光能量下降了 17.2%;采用工作气体实时补给技术后,激光器输出能量下降速率明显降低,累计工作 14.38 h,其单脉冲能量下降率能控制在 3%范围内.因此,采用该技术可延长激光器工作气体的使用寿命、提高输出激光能量稳定性、减少停机次数并降低运行成本.

关键词:激光技术;自动控制技术;实时补给;卤化物准分子激光器;工作气体;能量稳定性;控制系统
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The Real-time Supply Technology of Working Gas in Rare-gas Halide Excimer Laser

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Abstract: In order to prolong the life of the working gas in rare-gas halide excimer lasers, the real-time supply technology was added. This technology used FPGA control system to combine some operations effectively, such as improving the discharge voltage gradually, adding halogen gas and replacing part of the mixed gas. With the decrease of pulse laser energy, the discharge voltage was improved gradually. When the discharge voltage reached maximizing, it was time to add halogen gas and restore the discharge voltage. When the effect adding halogen gas was not apparent, part of the mixed working gas should be replaced. The technology was applied in medical ArF excimer laser, the experimental results show that the laser output energy of the laser drops by 17.2% after working 14.38 h accumulated without the real-time supply technology of working gas. But with this technology, the laser output energy decline rate is significantly lower, and it is stabilized successfully within the range of 3% working the same hours. Therefore, using this technology can extend the life of the working gas laser, increase the laser output energy stability, reduce downtime and lower operating costs.

Key words: Laser technology; Automatic control technology; Real-time supply; Halide excimer lasers; Working gas; Energy stability; Control system
OCIS Codes: 140.2180; 170.3890; 140.3425; 150.5495

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0 Introduction

For 40 years, the excimer laser has developed rapidly, especially in the rare-gas halide excimer laser. It is used widely because of its characteristics, including the wavelength of the output laser in the ultraviolet region, narrow pulse width, large pulse energy, scaling enlarge and re-frequency operation. It is the mainly excimer laser used now[1-2]. American Coherent/Cymer[3]/Gam Laser, Canadian Lumonics, Japanese Gigraphoton and other companies specially develop and produce different types of commercial excimer laser[4]. Gigraphoton company develops a new gas management system and a high precision working gas injection and extraction module in hardware parts, which can stabilize fluorine concentration fluctuation in the range of the error less than 1 kPa and ensure the working gas life is over 1 billion pulses, and the interval time of replacing all working gas is extended from the original 3 days to 15 days[5]. Cymer company develops a gas management system Gas Lifetime extension™ (GLX™) which can ensure the working gas life is over 1 billion pulses, too[6].

Extending the life of the working gas always is a hot topic in the research of excimer laser technology. Currently, the life has become a bottleneck about how to expand the application of the excimer laser, especially the application of high re-frequency. This paper proposed the research about the real-time supply technology of working gas in 193 nm ArF excimer laser. We designed a set of real-time supply device and then gained valuable experimental data, extended the life of the working gas effectively, improved the stability of laser output energy, reduced downtime and reduced operating costs.

1 The life of the working gas in rare-gas halide excimer laser

In the process of excimer laser operation, the change of gas concentration and purity impacts the output energy stability greatly, especially halogen gas. Fig. 1 shows the relation of excemer laser halogen life "process window" and the change of its concentration[7]. The figure shows that the concentration of the halogen gas is the main cause of the influence of the life of the working gas. Thus it can be inferred that adding a small amount of halogen gas can extend the life of the working gas and increase the working gas life "process window" in the process of excimer laser operation.

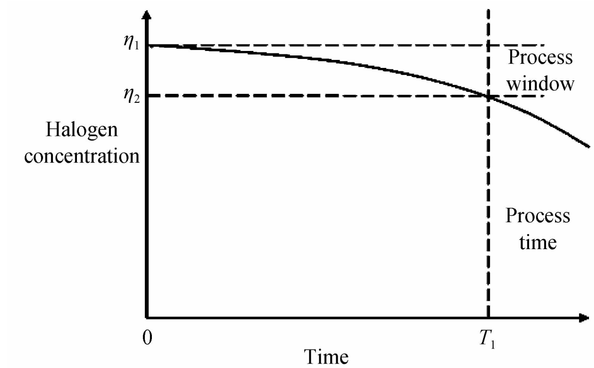

Fig. 1 The relation chart of the life "process window" of excimer laser halogen gas and its concentration

The life of the excimer laser working gas is short and its main expression is that the output energy declines gradually with the increase of the number of pulses and the time. The main reason is that ionized halogen ions are more active and easily react with other materials to reduce the concentration. Some of the reaction product may result in laser quenching matter. Early ArF and XeCl excimer lasers mainly use aluminum alloy and polyvinyl fluoride material[8]. It is the main reason to lower the output energy of the laser that the reactions between halogen ions and carbon containing material or some metal elements in the working gas produce laser quenching matter, and lead to the decrease of the working gas concentration and purity. In order to generate lower laser quenching material, people use high purity aluminum oxide ceramic material with excellent fluorine resistance and good mechanical properties as the cavity structure, use the nickel or nickel material as the main discharge and preionization electrodes. It reduces the generation of laser quenching matter to extend. But we can not completely block the halogen gas consumption and the generation of other impurities[9]. Therefore, it is necessary to use the real-time supply technology of working gas to make up for the halogen gas consumption and the decrease of working gas purity.

2 The working principle of the experimental device and the control system

2.1 The working principle of the experimental device

We used the medical ArF excimer laser to do the research about the real-time supply technology of working gas. The working gas of the ArF excimer laser includes F_2, Ar and Ne/He. The laser output is a super ultraviolet light[10]. The cutting precision of the laser can reach micron level, the scope of damage is only nanometre level and there is no heat effect and damage to adjacent tissues. It is wildly used in medical field, such as corneal surgery, vascular plastic and neurosurgery. Fig. 2 shows the schematic diagram of the real-time supply device structure in the medical ArF excimer laser (the solid modules are new real-time working gas supply devices and control system). The laser output energy feedback signal is the judgment to control the real-time supply device of working gas through the control system in the process of excimer laser operation. The working process is as follows, with the decrease of pulse laser energy, the discharge voltage increases gradually, when the discharge voltage reaches maximizing, began to add halogen gas and restore the discharge voltage, when the effect of energy stability is not apparent by adding halogen gas, replace part of the mixed working gas.

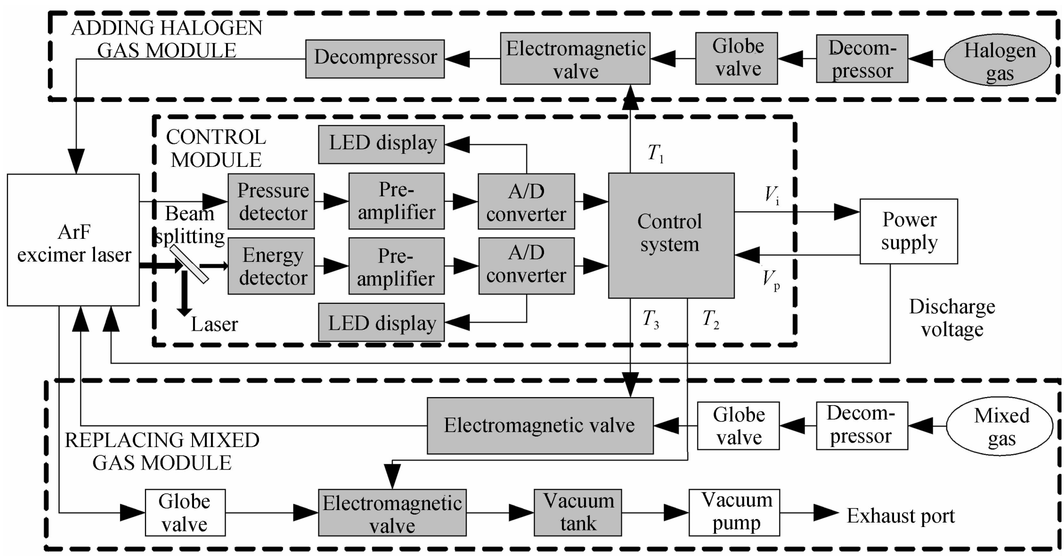

Fig. 2 The real-time supply device structure of working gas in ArF excimer laser

This device consists of control module, adding halogen gas module and replacing mixed gas module. The control module is made up of the laser output energy detector, the pressure detector, the pre-amplifier, the A/D (analog-to-digital) converter, the Light Emitting Diode (LED) display and the control system. It is used for the signal sampling of the laser output energy and the gas chamber pressure, signal amplification, analog-to-digital conversion, numerical processing, numerical display and function control. The adding halogen gas module is made up of the halogen gas cylinder, the electromagnetic valve, the decompressor, the globe valve and so on. It is used for the supply of halogen gas. The replacing mixed gas module is made up of the mixed gas cylinder, the vacuum tank, the vacuum pump, the electromagnetic valve and so on. It is used for the replacement of part of the mixed working gas or all working gas.

2.2 The control system

The control system is the main part of the real-time supply device of working gas. It is based on Field Programmable Gata Array (FPGA), which makes the laser output energy as the judgment signal and combines improving the discharge voltage, adding halogen gas, replacing part of the mixed working gas and other operations effectively by a certain control method. Its design scheme is mainly divided into the following steps.

2.2.1 *Laser energy acquisition and data processing*

When the laser emits light, the beam splitter disengages 10% laser output energy to the photoelectric detector for real-time monitoring and it converts the laser output energy into electric signal. The signal is transferred to the control system after the amplification by the pre-amplifier circuit and analog-to-digital conversion circuit[11]. After the control system receives the first group of 100 pulse laser output energy signals, it calculates the average and assigns it to P_0. Then after it continues to receive the next group of 100 pulse laser output energy signals, it calculates the average and assigns it to P_1 gradually. The control system continuously compares P_0 with P_1 to calculate the energy drop rate η, and the calculation equation of the η is $(P_0 - P_1)/P_0$. In the aspects of data processing and data security, the method based on FPGA has a certain advantage.

2.2.2 *Improving the discharge voltage step by step*

Fig. 3 shows the work diagram of improving discharge voltage step by step. With the increase of the number of laser pulses and time, laser output energy is declining. When the laser energy drop rate η is greater than 3% for three times continuously ($\eta > 3\% \& T > 2$), the control system sends a request to the power supply system to improve the discharge voltage $\Delta V (V_i = 01)$. If $\eta < 3\%$, the running state of the laser remains unchanged and the control system continues to calculate and judge the laser output energy drop rate η. Until the discharge voltage beyond the normal scope of work, the control system begins to enter the adding halogen gas stage.

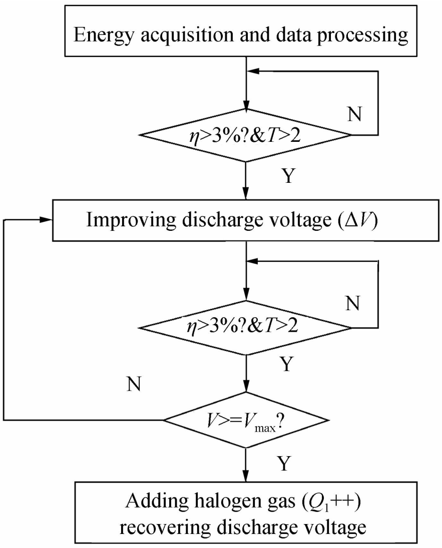

Fig. 3　The work flow diagram of improving discharge voltage step by step

2.2.3　*Adding halogen gas*

Fig. 4 shows the work flow diagram of adding halogen gas. When the discharge voltage can not continue to improve and η is greater than 3% for three times continuously, the control system requests adding halogen gas module to add a small amount of halogen gas and the power supply system to restore the discharge voltage to the initial value ($V_i=10$) at the same time. If η is also greater than 3% for three times continuously, it continues to add a small amount of halogen gas and the maximum number of adding gas Q_1 is m (m is taken by the empirical value).

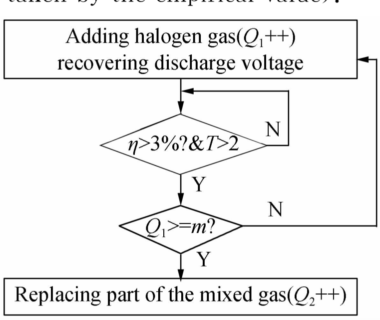

Fig. 4　The work flow diagram of adding halogen gas

2.2.4　*Replacing part of the mixed gas*

Fig. 5 shows the work flow diagram of replacing part of the mixed gas. When the effect of adding halogen gas is not obvious (i. e. the Q_1 is greater than or equal to m), the control system requests replacing mixed gas module to replace part of the mixed gas for excimer laser. The excimer laser continues to run. When η is greater than 3% for three times continuously again, it continues to replace part of the mixed gas and the maximum number of replacing gas Q_2 is n (n is taken by the empirical value).

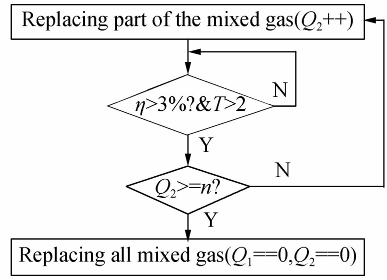

Fig. 5　The work flow diagram of replacing part of mixed gas

3　Experimental study

3.1　Experiment introducing

3.1.1　*Data acquisition and data processing*

The energy output of the ArF laser is monitored by high ultraviolet sensitive laser photoelectric detector[12-13] (the laser should have a attenuation processing before reaching the detection surface[14]). The pulse energy signal through amplification and analog-to-digital conversion is assigned to the array $I[7:0]$ and then plus to the array $S[15:0]$. When the cumulative number reaches 100 energy pulses, it is time to calculate the average of pulse energy $A[7:0]$ and display on the LED display board. When the control system checks $A[7:0]$ out that the data updates, it will calculate the energy drop rate η and account the times T of $\eta>3\%$. Finally, it controls the gas supply solenoid switch by judging T. It is particularly pointed out that the control system does not account and manage the laser pulse energy collected by photoelectricity detector while supplying the halogen gas and replacing part of the mixed working gas. The laser chamber pressure is monitored by pressure sensor, the number is also transmitted to the control system and assigned to the array $P[7:0]$ to judge the amount of working gas to replace.

3.1.2　*Working gas supply device*

The gas supply device includes adding halogen gas module and replacing mixed gas module, which structure shows in Fig. 2. Adding halogen gas module is made up by small high purity fluorine gas cylinders, decompressor, 24V Direct Current (DC) electromagnetic valve and globe valve. Adding a little of fluorine gas to laser in real-time is to make up for the consumption of elemental fluorine in the processing of laser operation. The time to open electromagnetic valve is determined by the pressure of decompressor, the cross-sectional area of gas pipeline and the flow velocity of fluorine gas and so on[15], we use empirical value 1.8～2.1s in the experimental process. Replacing mixed gas module only needs two 24V DC electromagnetic valves and a vacuum tank on the base of original mixed gas supply device and then can achieve the replacement of part of the mixed gas. When a command is received to replace part of the mixed gas, it opens the electromagnetic valve on the exhaust pipe and part of the working gas in the laser chamber goes into the vacuum tank, the working gas will be take away by the vacuum pump. When the laser chamber pressure drops to the original 9/10, the electromagnetic valve is closed. Then, the electromagnetic valve on the gas supply pipe opens to inject some fresh mixed gas. When the laser chamber pressure returns to the initial value, it is time to close this electromagnetic valve and stop the replacement of mixed gas.

3.1.3 *Working gas supplies in real time*

The initial value of the laser working gas pressure is set about 0.3MPa. The F_2 constitute 0.2～0.3% of total number of molecules. The operating frequency is 1～100 Hz (adjustable). The threshold value of energy drop rate η is set to 3% in the control program. When η is greater than 3% for three times continuously, the control system sends a signal Vi to the power supply system to improve the discharge voltage (this work is completed by modifying the power control commands). When the discharge voltage can not be increased continually and η is greater than 3% for three consecutive times again, control system sends control commands T_1 and V_i. The electromagnetic valve is opened to add a small amount of F_2 and restore the initial discharge voltage. When the effect of halogen gas supply is not obvious, the control system will send control commands T_2 and T_3 by turn to the electromagnetic valve in the replacing part of mixed gas device to replace part of mixed gas.

In the process of experiment, the gradually increased discharge voltage ΔV is determined to be 0.25kV. Each supplement of halogen gas volume is about 0.02L and each replacement of part of the mixed gas volume is about 35L in atmospheric pressure. It is attention that the halogen gas should not be added too much, if not, the surplus F_2 will bring quenching effect to the excited ArF * molecule, and will reduce the energy of laser output. In the entire process of ArF excimer laser experimental operation, the discharge voltage is gradually improved 4 times, the halogen gas is added 10 times and part of the mixed gas is replaced 4 times.

3.2 Experimental data analysising

Fig. 6 shows the stability comparison chart of the laser output energy under circumstances of with or without working gas supply (sample a pulse laser output energy per 100s and correct individual abnormal data).

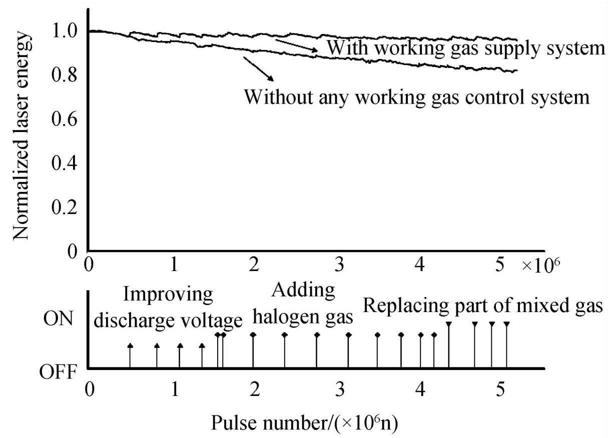

Fig. 6 The stability comparison chart of the laser output energy

As can be seen from the experimental results: 1) Without working gas supply technology, the laser output energy declines by 17.2% after the excimer laser working 14.38 h accumulated (about 5.18×10^6 pulses). 2) With working gas supply technology, the rate of decline of the laser output energy significantly lowers. After the excimer laser works 14.38 h accumulated, the rate of decline of the laser output energy is controlled within 3% effectively. 3) Compared with the operations of adding halogen gas and replacing part of the mixed gas, the laser output energy restores faster obviously after improving the discharge voltage. 4) In the entire process of the laser operation, the laser output energy recovers because of improving the discharge voltage, adding halogen gas and replacing part of the mixed gas. However, the maximum after recovery is a downward trend each time and all stages of the rate of decline of the energy after recovery is a upward trend. The operating frequency of improving the discharge voltage, adding halogen gas and replacing part of the mixed gas gradually increases at the same time.

4 Conclusion

Experimental results show that the real-time supply technology has a very significant effect on the long-time and stable operation of the ArF excimer laser. It extends the life of the working gas, improves the stability of laser output energy, reduces downtime, reduces the medical risks and operating costs. In addition, this technology also has a strong versatility and can be directly used for all rare-gas halide excimer laser systems.

The next main work is to optimize the control procedures of the real-time supply technology of working gas in excimer laser in order to improve control accuracy and achieve long-time and stable laser output of the rare-gas halide excimer laser.

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