第 43 卷第 11 期　　红外与激光工程　　2014 年 11 月
Vol.43 No.11　　Infrared and Laser Engineering　　Nov. 2014

Analysis on factors affecting energy stability of excimer laser for lithography

Shi Haiyan[1,2], Zhao Jiangshan[1], Song Xingliang[1,2], Sha Pengfei[1], Shan Yaoying[1], Wang Qian[1], Zhai Ye[1,2], Zhou Yi[1]

(1. Academy of Opto-Electronics, Chinese Academy of Sciences, Beijing 100094, China;
2. University of Chinese Academy of Sciences, Beijing 100049, China)

Abstract: The development of the dual-chamber amplification structure of ArF excimer laser in Cymer was reviewed. Corresponding pulse energy stability was also concluded. The effect of dual-chamber amplification mechanism on pulse energy stability was analyzed. Especially, the MOPRA structure and the MOPA structure are compared. The gas components, proportion of working gases and gas flow rate between electrodes in the discharge chamber, which have strong influence on the pulse energy stability, were also discussed. Corresponding measures were presented to improve energy stability. Finally, the energy servo system was introduced briefly.

Key words: amplification mechanism;　excimer laser;　pulse energy stability;　gas components

CLC number: TN248.2　　**Document code:** A　　**Article ID:** 1007-2276(2014)11-3540-07

光刻用准分子激光器能量稳定性影响因素分析

石海燕[1,2],赵江山[1],宋兴亮[1,2],沙鹏飞[1],单耀莹[1],王　倩[1],翟　晔[1,2],周　翊[1]

(1. 中国科学院光电研究院,北京 100094; 2. 中国科学院大学,北京 100049)

摘　要: 以 Cymer 公司为例归纳总结了 ArF 准分子激光器双腔放大结构及相应的脉冲能量稳定性的发展历程，讨论了双腔能量放大机制对脉冲能量稳定性的影响，重点分析了 MOPRA 结构较 MOPA 结构在能量稳定性方面的优缺点。着重阐述了放电腔内工作气体成分、配比、电极间流速对脉冲能量稳定性的影响以及相应的改善措施，并结合影响脉冲能量稳定性的因素简述能量控制系统在稳定脉冲能量上的应用。

关键词: 放大机制;　准分子激光器;　脉冲能量稳定性;　气体成分

收稿日期: 2014-03-11;　**修订日期:** 2014-04-15

基金项目: 国家重大科技专项(2012zx02701001-010)

作者简介: 石海燕(1987-),女,硕士生,主要从事准分子激光器及激光能量稳定性方面的研究。Email:shihaiyan@aoe.ac.cn

导师简介: 赵江山(1974-),男,研究员,博士,主要从事准分子激光器、固体激光技术、超短脉冲激光技术、相关激光器件、非线性光学技术以及相关超快现象过程和技术等方面的研究。Email:zhaojiangshan@aoe.ac.cn

0 Introduction

As the node decreasing, the lithography requirements become tighter. The exposure light source system, as core component of the lithography system, is the key for lithography technology. At present, the international main stream lithographic light source system is excimer laser system. The major manufacturers include Cymer in U.S.A and Gigaphoton in Japan, which possess over 90% of the market share in all. At home, Shanghai Institute of Optics and Fine Mechanics and Anhui Institute of Optics and Fine Mechanics[1] carried out preliminary research of excimer laser system in the early 80's.

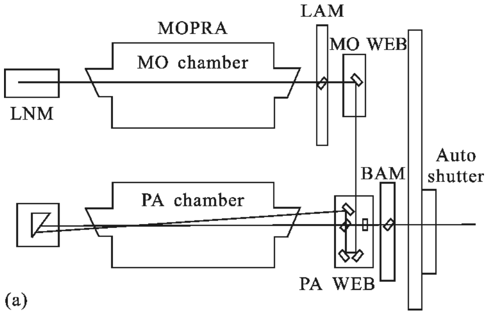
Based on the excimer laser system, industrial mass production for lithography is closely related to the improvement of the system pulse energy stability, because lithography node is directly affected by pulse energy stability. The pulse energy stability is usually defined as the degree of pulse energy deviation from pulse energy mean value in a fixed time window, expressed as σ (sigma)=**std.**/**E**, where, std. represents energy standard deviation and **E** is time average value of pulse energy in the time window. The pulse energy stability is an important indicator for application characteristics of excimer laser source, and it is vital for the development of lithography light source products. The MOPA (Master Oscillator Power Amplifier) structure was introduced into excimer laser system by Cymer in 2002 for the first time. The power amplification operates in gain saturation state, so that the pulse energy stability of excimer laser system has been effectively improved [2]. The fifth generation, the XLA300 model, was launched by Cymer in 2005. Under the discharge repetition rate 6 kHz with voltage 945 V, pulse energy stability sigma is less than 1.5% [3]. In order to meet the needs of higher stability, in 2006, Cymer introduced the ring cavity technology into the dual chamber amplifier structure-MOPRA(Master Oscillator Power Regenerative Amplifier): the XLR500i (6 kHz, 60 W@10mJ, sigma is less than 1% in operation condition of 6 kHz [4]. XLR600i, the double patterning immersion lithography light source, was launched in 2007(6kHz, 90 W@15mJ)[5]. Based on the XLR500i, the XLR600i possesses higher output power and better energy stability, realizing higher yield. In 2009, Cymer launched the world's first power adjustable XLR600ix series(60 W/90 W@6 kHz). After the system discharges 10^8 pulses, the energy stability sigma is less than 4%, which is a great improvement compared with previous XLR series [6]. Then, a new design discharge chamber is introduced with the XLR600ix series by controlling the location of electrodes automatically to compensate for electrode corrosion, which keeps the discharge gap from changing, guaranteeing stable discharge and expected pulse energy stability. Working in an accelerating manner, XLR600ix operates continually for 30 weeks with an output of 90 W, which shots about 30 billion laser pulses (simulating a year working period), obtaining pulse energy stability sigma is less than 3%[7]. In order to further expand the application of 193 nm immersion lithography at higher nodes, Cymer launched XLR600ix-HP [8] models in early 2013. For operation at 120 W nominal output power and 6 kHz repetition rate, pulse energy stability sigma is less than 4% during the stress test. This model will extend DUV lithography node to 2x nm and beyond.

The pulse energy stability stems from dynamic process of gas discharge and laser resonant energy amplification mechanism. Related factors involved in excimer laser system include the discharge chamber, stimuli circuit[9], amplification mechanism and other function modules. This article mainly analyzes the influence of dual chamber amplification mechanism and the gas components, proportion of working gases in the discharge chambers on the pulse energy stability. And corresponding measures are also presented to improve energy stability. Finally, the energy servo system is introduced briefly combined with influencing factors.

1 Dual-chamber amplification mechanism

To meet the needs for higher output power and narrower linewidth of light source, which are hardly obtained simultaneously in a single resonator, dual chamber structure MOPA is introduced to settle the contradiction between high power and narrow linewidth. The basic idea is to produce low energy seed pulse with narrow linewidth from the master oscillator, and then inject seed pulse into amplifier chamber to get amplified. As a result, high quality laser output is obtained.

At present, the structure for dual-chamber amplification mechanism mainly include: MOPA, MOPO(Gigaphoton), MOPRA(Cymer), MORRA(Lambda Physik). MOPA is short for master oscillator power amplifier, in which seed light produced by MO cavity is injected into PA cavity, and then output the laser pulse after several amplifications. MOPO structure, which stands for master oscillator power oscillator, is combined with the injection locking technique. The main difference between MOPA and MOPO is that amplifier for MOPO adopts a resonator structure, in a way of regenerative amplification. When the seed pulse reaches the amplifying chamber, the pulse oscillates in its resonator. As a result, amplification is deeper with better output beam quality, and the output laser pulse characteristics (such as repetition rate, energy) are determined by amplification resonator. Both MOPRA and MORRA are combined with the ring cavity technology to realize the amplification for the seed light. The output beam quality is modulated by amplifier. Figure 1 shows the schematic diagram of MOPRA structure and MOPA structure.



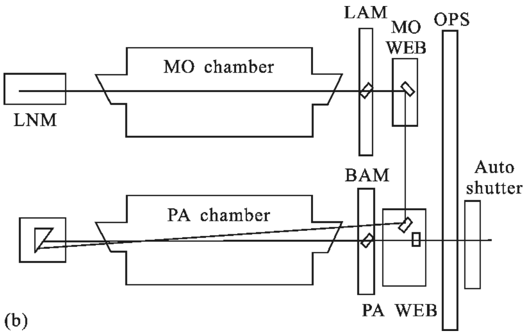


Fig.1 Schematic diagram of MOPRA and MOPA architectures (Cymer)

The MOPA structure is introduced as lithography light source into the XLA100 model (2002) by Cymer. Higher operation efficiency and better output are obtained compared with previous single chamber structure. To keep high output efficiency, discharge synchronization between MO and PA is required to be precise. Discharge in PA chamber starts while the seed reaches amplifier. However, laser pulse transmits just a few times in the PA chamber. Short duration staying in amplifying chamber demands more precise synchronization control. So the output is susceptible to MO and PA synchronization jitter effect and the output laser energy stability is difficult to improve[10]. However, for the MOPRA structure, the seed is injected into the amplifier chamber and reciprocates. So duration of stay is much longer than it in MOPA structure. As a result, the ring cavity is less sensitive to synchronization variations. At the same time, when the output energy requirement is certain, the multiple pulse passes ensure that MOPRA structure needs smaller input energy compared with MOPA structure. Therefore, in MOPRA, energy density is lower in LNM (Line Narrowing Module) module, and the lifetime of optical elements is prolonged. LNM stability tends to be maintained for a longer time.

On the other hand, take XLR500i for example. As shown in Fig.2[4], the output energy in MOPA structure is susceptible to energy fluctuations of the seed pulse. But the MOPRA works in deeper state of saturation than MOPA mechanism, which dampens the input pulse instabilities from the MO chamber. Therefore, the instabilities caused by discharge and input energy from MO chamber are diminished. The pulse-to-pulse energy stability is increased by 1.5X than the traditional dual-chamber[4]. In addition, for MOPRA structure, the output beam characteristics are modulated by the ring resonator structure of amplifier, which is different from the travelling wave amplifier. Therefore, the beam quality can be effectively improved under reasonable designed parameters of the ring resonator structure. For example, spatial modulation module can be introduced in the ring optical path. As a result, controllability of the laser output can be improved. However, MOPRA structure is more complex than MOPA structure, so more factors should be taken into consideration in design, such as power amplifier chamber structure and mode matching problems between oscillator and amplifier chamber and so on. Only if the structural design is reasonable, the advantages of MOPRA structure could be exploited.

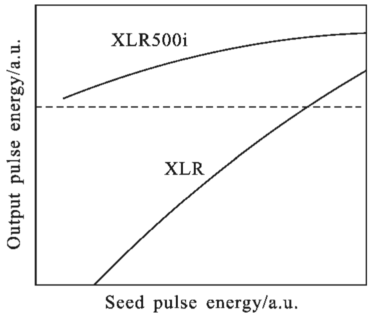


Fig.2 Saturation curves for system output as a function of seed power (injected power MO)[4]

2 Gases in discharge chamber

Gases in discharge chamber work as gain media of excimer laser, its characteristics affect output beam quality directly. Gas components, working gas components, gas flow rate between electrodes and along electrode surface are discussed to find the influence of gases in discharge chamber on pulse energy stability.

2.1 Working gas components

Components relation of gas mixture in laser chamber has a lot to do with production efficiency of excimer, which directly affects pulse energy stability in turn. Koji Kakizaki et al[11]. verify that pulse energy stability in ArF excimer is affected by the content of F_2 and Ar directly. And under the condition of 3 a.t.m., 6 kHz repetition rate, pulse energy stability is the best for a sigma value of 3.5% ,with the content of F_2 being 0.07%, Ar being 3%. This is because halide is easy to absorb electrons when its content is excessive in discharge chamber, which leads to the decrease of the electron concentration among the main discharge electrodes and is not conducive to stable glow discharge. But when the halide content is too low, it cannot provide enough gain particle to form excimer[12]. In the practical design of the ratio of working gas in excimer laser, as the discharge chamber, gas pressure and discharge conditions are different, the specific laser needs experimental verification to obtain the optimum gas ratio, which meets the demand of energy and pulse energy stability. In addition, optimum gas ratio will be slightly different under different operation repetition rate[13].

2.2 Gas components

In order to promote ionization process and keep optical modules from contamination, certain auxiliary gas is injected into discharge chamber. When excimer laser starts to work, gas components in the discharge chamber change gradually, resulting in impurity generation, which would cause energy instability.

2.2.1 Auxiliary gas

Take ArF excimer laser as an example, in which helium or neon is usually injected as buffer gas into the discharge chamber in certain proportion, due to higher electric potential for atoms at metastable state, collision process with helium or neon would promote the ionization of argon atoms (Penning effect). Moreover, injection of buffer gas increases the total gas pressure, which helps to reduce evaporation of cathode material. However, compared with helium, neon behaves better in photon extract efficiency and faster gain rise time, as well as lower absorption coefficient[12], which promises neon a better performance.

On the other hand, because it is easier for xenon to start photo ionization, xenon is usually injected as auxiliary gas into discharge chamber, to achieve higher initial electron density during preionization process[14], which results in an improvement in glow discharge performance. Wakabayashi demonstrated the optimal xenon injection about 10 ppm for ArF excimer laser gas mixture by experiment[15]. However, excessive xenon would absorb laser radiation and deteriorate the output beam quality[16]. In addition, Optical components are purged by dry pure nitrogen frequently to keep themselves from surface contamination, and an optical path in nitrogen would not suffer from atmosphere absorption loss, which may cause energy instability.

2.2.2 Impurities in discharge chamber

The impurity products produced by discharge cause gas life decreasing, optics and cavity contaminated, and even the absorption of laser radiation, which affect the output beam quality. The gaseous impurities in the cavity may result from the interaction between the halogen gas and the electrode and the laser cavity materials, and chemical reaction among gas mixture under high pressure discharge, or being directly diffused from the materials. Or the filled gas itself is impure. Take ArF excimer laser for example, HF and O_2 are generated by the reaction of F_2 and H_2O in the cavity. When the content of HF, as the main pollutants in the laser cavity, becomes over 10 ppm (1 ppm=10^{-6}), laser energy drop 10%; "spiking" is clearly shown when the concentration of O_2 is above 10 ppm [17]. If the working gas is circulated through liquid N_2, gas lifetime will be greatly improved [18]. Therefore, to prolong the gas lifetime, it's better to choose the metal ceramic cavity, the fluoride resistant electrode materials, and to reduce usage of materials containing carbon in the cavity. And the discharge chamber should be passivated fully with halogen gas before normal operation. On the other hand, the gas purification device can purify the filled gas and remove impurities produced during discharge process. For example, in Cymer's excimer laser of ELS-6000 series, impurities are blown into the MFT (metal fluoride trap) through the air circulation fan, and clean working gas is regained[19].

2.3 Gas flow rate

Often, the gas flow rate between discharge electrodes and along electrode surface is required to guarantee that the current discharge products do not affect next discharge pulse, which means clearing current discharge products before next discharge. Sufficiently high gas flow rate is a prerequisite to obtaining stable glow discharge. Therefore, clear ratio between electrodes[20] is defined as follows:

$$CR=\frac{\text{minium time between are-free pulses}}{\text{time for gas to transverse gap}}=\frac{1/f_m}{w/v}=\frac{v}{f_m v}$$

where, **w** is discharge width; **v** is gas flow rate between electrodes; f_m is maximum repetition rate.

From the formula above, it needs higher gas flow rate or narrower discharge width, to maintain normal glow discharge, which guarantees energy stabilization for output laser pulses in turn. Therefore, excimer laser operation at high repetition rate usually requires high speed and uniform gas circulation system.

In addition to three factors above, halogen gas in discharge chamber degrades with discharge pulse counts increasing, which leads to lower concentration, also contributes to energy loss. Considering factors affecting gas lifetime in discharge chamber, a gas control system can be designed to prolong gas lifetime by means of combining the hardware and software platform. Cymer has developed gas management system GLX and iGLX, prolonging gas lifetime to 10^9 and 4×10^9 pulses[21-22] from 10^8, respectively.

3 Energy servo system

Energy servo system for excimer laser stabilize the output laser energy by adjusting discharge voltage and adding new halogen gas periodically[23]. Besides, pulse energy is related with repetitive rate and the discharge time delay between dual chambers[2], which makes it feasible to stabilize the output energy by adjusting repetition rate and optimizing discharge time delay. Theoretically, the servo system should work out the logical factor weight for energy stabilization, according to actual work mode, discharge characteristics and controlling demands, which forms an effective control strategy by combining refills, adjusting the discharge voltage and the repetition rate as well as the time delay to feedback energy change and make it more stable. Figure 3[24] shows the process of energy stabilization by means of refilling halogen with voltage adjustment at intervals of partial gas replacement. Obviously, the energy servo system gives good results for stabilizing energy.

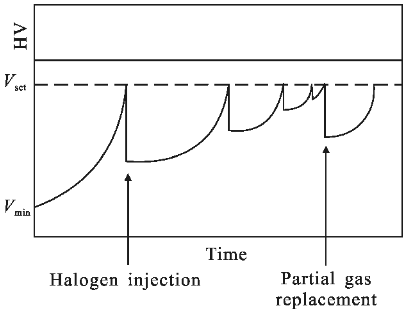


Fig.3 Schematic of pulse energy stabilization and gas lifetime extension[23]

4 Conclusion

Lithography nodes decrease tracing Moore's law trajectory, which leads to tighter linewidth, energy and stability requirements for the excimer laser light source system. The dose stability is impacted significantly by the pulse-to-pulse energy stability, which is affected by the amplification mechanism, the components,proportion of working gases, gas circulation system and work temperature and so on.

The pulse energy and energy stability of the dual-chamber structure combined with the ring cavity technology, compared to traditional dual-chamber, are continually improved. But the mode matching problems and discharge synchronization issues still need to be further optimized. Based on injection locking techniques, the amplifier of MOPO structure employs the resonator structure, which is the biggest difference from the MOPA structure. This ensures good beam quality and achieves higher magnification at the same time. And the amplifier determines repetition rate and energy of the output beam. Both MOPRA and MORRA are combined with the ring cavity technology to realize the amplification of seed light. The seed pulse with narrow linewidth and small energy is injected into the amplifier and reciprocates. Multiple passes ensure longer duration of stay in the amplifier. Therefore, the ring cavity is less sensitive to synchronization variations. Meanwhile, the MOPRA works in a deeper state of saturation than MOPA mechanism, which dampens the input pulse instabilities from the MO chamber. So the pulse-to-pulse energy stability is greatly improved.

Dual-chamber amplifier structure with energy feedback system could stabilize output energy by adding new halogen gas, regulating voltage and delay time. In addition, the stability of the system could also be improved by adding moderate amount of Xe and other auxiliary gases in high purity working gas. On the other hand, the pulse-to-pulse energy stability could be deteriorated by factors such as working pressure decreasing, working gas components changes and optical elements contamination, caused by gas impurity, electrode sputtering under high temperature, outgas from cavity components, working gas attachment, absorption and permeability and other causes. Therefore, to prolong gas lifetime and improve pulse-to-pulse energy stability, it is feasible to choose metal ceramic cavity, fluoride resistant electrode materials, and to reduce usage of materials containing carbon in the cavity. And the discharge chamber should be repassivated fully with halogen when air contamination occurs. At the same time, in order to keep the output energy stable for a long time, the gas management system is introduced to extend the gas lifetime.

Usually, as the pulse energy density of excimer laser for lithography is high (about 100 mJ/cm^2), color centers and dense problem of the optical elements are also important factors that limit pulse energy stability of excimer laser to be improved. Thus, the lifetime of the optical elements can be prolonged by extending the pulse width, optimizing the coating design of the substrate, improving technological level and keeping optical elements dry and clean and so on. In a word, to improve the pulse energy stability is a system project that many factors need to be considered. A more stable output would be realized by optimizing the structure design, light utilization mechanism and control strategy continually.

References:

[1] Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Science. Excimer Laser [EB/OL].(2011-03-23) [2014-03-11]. http://www.aiofm.cas.cn/kycg/xycp/jgzxcp/201103/t20110323_71637.html(in Chinese)

[2] Fleurov V B, Colon Ⅲ D J, O'Keeffe P, et al. Dual-chamber ultra line-narrowed excimer light source for 193nm lithography[C]//SPIE, 2003, 5040: 1694-1703.

[3] Gillespie Walter D, Toshihiko Ishihara, Partlo William N, et al. 6 kHz MOPA light source for 193nm immersion lithography[C]//SPIE, 2005, 5754: 1293-1303.

[4] Brown D J W, O'Keeffe P, Fleurov V B, et al. XLR500i: Recirculating ring ArF light source for immersion lithography [C]//SPIE, 2007, 6520: 652020.

[5] Vladimir Fleurov, Slava Rokitski, Robert Bergstedt, et al. XLR 600i: Recirculating ring ArF light source for double patterning immersion lithography[C]//SPIE, 2008, 6924: 69241R.

[6] Slava Rokitski, Vladimir Fleurov, Robert Bergstedt, et al. Enabling high volume manufacturing of double Patterning immersion lithography with the XLR600ix ArF light source [C]//SPIE, 2009, 7274: 72743O.

[7] Rostislav Rokitski, Toshi Ishihara, Rajeskar Rao, et al. High reliability ArF light source for double patterning immersion lithography[C]//SPIE, 2010, 7640: 76401Q.

[8] Rokitski R, Rafac R, Melchior J, et al. High power 120W ArF immersion XLR laser system for high dose applications [C]//SPIE, 2013, 8683: 86831H1-7.

[9] Li Tan, Chen Changle. Design and optimization of the XeCl excimer laser's stimuli circuit [J]. Infrared and Laser Engineering, 2005, 34(5): 617-621. (in Chinese)

[10] You Libing,Zhou Yi,Liang Xu, et al. Recent development of ArF excimer laser technology for lithography [J]. Chinese Journal of Quantum Electronics, 2010, 27 (5): 522-527. (in Chinese)

[11] Koji Kakizaki, Takashi Matsunaga, Yoichi Sasaki, et al. Ultra-high-repetition-rate ArF excimer laser with long pulse duration for 193-nm lithography[C]//SPIE, 2001, 4346: 1210-1218.

[12] Deng Guoqing, Liu Yong, He Longhai, et al. Optimization of gas performance of the compact excimer laser [J]. Laser Technology, 2010, 34(4): 529-531. (in Chinese)

[13] Koji Kakizaki, Yoichi Sasaki, Toyoharu Inoue. High-repetition-rate (6 kHz) and long-pulse-duration (50 ns) ArF excimer laser for sub-65nm lithography [J]. Review of Science Instruments, 2006, 77(3): 035109.

[14] Taylor R S. Preionization and discharge stability study of long optical pulse Duration UV-preionized XeCl lasers [J]. Appl Phys, 1986, B41(1): 1-24.

[15] Wakabayashi O, Enami T, Ohta T, et al. Billion-level durable ArF excimer laser with highly stable energy [C]// Microlithography' 99, International Society for Optics and Photonics, 1999: 1058-1068.

[16] Kataoka N, Itagaki M, Uchino K, et al. Performance improvement of a discharge-pumped ArF excimer laser by xenon gas addition[J]. Japanese Journal of Applied Physics, 1999, 38(12R): 6735.

[17] Sumitani A, Andou S, Watanabe T, et al. Output stabilization technology with chemical impurity control on ArF excimer laser [C]// Microlithography 2000, International Society for Optics and Photonics, 2000: 1424-1434.

[18] Gower M C, Kearsley A, Webb C. Gas composition and lifetime studies of discharge excited rare-gas halide lasers[J]. IEEE Journal of Quantum Electronics, 1980, 16(2): 231-235.

[19] Song Jian, Zhu Peng, Zhang Wenya, et al. The principle and application of Cymer excimer laser[J]. EPE, 2008, 162: 60-62. (in Chinese)

[20] Dzakowic G, Wutzke S A. High-pulse-rate glow-discharge stabilization by gas flow [J]. Appl Phys, 1973, 44 (11): 5061-5063.

[21] Kevin O'Brien, Dunstan Wayne J, Riggs Daniel J, et al. Performance demonstration of significant availability improvement in lithography light sources using GLX control system[C]//SPIE, 2008, 6924: 69242Q.

[22] O'Brien K, Riggs D J, Thornes J, et al. Field performance availability improvements in lithography light sources using the iGLX Gas Management System [C]//SPIE, 2012: 83261O-83261O-9.

[23] Ogura S, Kawakubo Y, Sasaki K, et al. Output power stabilization of a XeCl excimer laser by HCl gas injection[C] //SPIE, 1991, 1412: 123-128.

[24] Yu Yinshan, You Libing, Liang Xu, et al. Progress of excimer lasers technology [J]. Chinese Journal of Lasers, 2010, 37(9): 2253-2270.