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基于XeF(C-A)放大器的混合(固态/气态)超高功率飞秒激光系统

LOSEV V,ALEKSEEV S,IVANOV N, KOVALCHUK B, MIKHEEV L[2], MESYATS G[2],
PANCHENKO Yu,PUCHIKIN A,RATAKHIN N,YASTREMSKY A
(1. Institute of High Current Electronics of Siberian Branch of Russian Academy of Sciences, ave, Akademichesky 2/3, Tomsk 634055, Russia;
2. Lebedev Physical Institute of Russian Academy of Sciences, Leninsky Prospekt, 53, 119991 Russia)

摘要:提出了基于前端发生器和终端放大器,使用光泵浦XeF(C-A)激活介质的太瓦级混合激光器(THL-100)系统。前端发生器由长532 nm的连续激光泵浦的钛宝石飞秒脉冲振荡器,脉冲展宽机构,532 nm的脉冲激光泵浦的再生多通道放大器,衍射光栅压缩器和二次谐波发生器(KDP)组成。其光束输出参数为:脉冲持续时间50 fs,二次谐波(475 nm)辐射能量5 mJ。前端发生器以10 Hz的单脉冲模式工作。XeF(C-A)放大器由双高压脉冲发生器(线性变压器),爆炸式阴极发射真空二极管,电子束注入系统,充满Xe的气室转换器和激光单元组成。高压发生器包括12个变压器,每个变压器有8个电容(40 nF)和火花隙,电容可以充电至100 kV。真空二极管中的电子束参数为:总电流300 kA,峰值电压550 kV,脉冲持续时间约150 ns。穿透金属箔片到达Xe转换器的6个100 cm×12 cm电子束的总能量为6~7 kJ。激光系统通过泵浦能量的级联处理导致Xe_2^*的快速形成,并在(172±5) nm连续辐射。真空紫外辐射通过CaF_2窗口辐射到含有XeF_2蒸汽和氮气缓冲气体的激光单元中,使XeF_2光解,形成XeF^*准分子。由真空紫外辐射泵浦的放大器激活介质长110 cm,直径为24 cm。文中通过数值模拟给出了输出参数和第一实验结果,根据XeF(C-A)放大器参数模型和增益测量结果,得到的输出能量高达2~3 J,这意味着50 fs脉冲的峰值功率高达40~60 TW。

关 键 词:混合激光器;XeF(C-A)放大器;飞秒脉冲宽度;电子束;紫外转换器
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Development of hybrid (solid/gas state) ultra-high power femtosecond laser system on the basis of XeF(C-A) amplifier

LOSEV V,ALEKSEEV S,IVANOV N, KOVALCHUK B, MIKHEEV L[2], MESYATS G[2],
PANCHENKO Yu,PUCHIKIN A,RATAKHIN N,YASTREMSKY A

(1. *Institute of High Current Electronics of Siberian Branch of Russian Academy of Sciences, ave, Akademichesky* 2/3, *Tomsk* 634055, *Russia*;
2. *Lebedev Physical Institute of Russian Academy of Sciences*, *Leninsky Prospekt*, 53, 119991 *Russia*)

Abstract: A terawatt hybrid laser (THL-100) system on the basis of a starting complex and a final

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amplifier with gaseous optically driven active media on XeF(C-A) molecules is presented. The starting complex manufactured consists of a Ti: sapphire master oscillator pumped by femtosecond pulses from a continuous laser pumped by (Verdy-8) at a wavelength of 532 nm, a femtosecond pulse stretcher, regenerative and multipass amplifiers pumped by a pulsed laser at a wavelength of 532 nm, a diffraction grating compressor and a second harmonic generator (KDP). The complex has the following output parameters of the laser beam: pulse duration is 50 fs, the energy of radiation at the second harmonic (475 nm) is 5 mJ. The complex can operate in a single pulse mode and a frequency of 10 Hz. The XeF(C-A) amplifier consists of a two high-voltage pulsed generator (linear transformer), a vacuum diode with six cold explosive-emission cathodes, a electron beam injection system, a Xe filled gas chamber-converter and a laser cell. The high-voltage generator consists of 12 transformer stages, and each of them involves eight capacitors (one is $C=40$ nF) and spark gaps. The capacitors can be charged up to voltage of 100 kV. E-beam in vacuum diode has the parameters in total current of 300 kA, peak voltage of 550 kV, pulse duration of e-beam power about 150 ns (FWHM). The total energies of the six 100 cm ×12 cm e-beams which pass through the foil into the Xe converter are 6—7 kJ in the 150—160 ns pulse (FWHM). Pump energy cascade processes lead rapidly to the formation of Xe_2^* , which radiates a fraction of the deposited energy in the continuum at (172 ± 5) nm. This VUV radiation is transmitted through CaF_2 windows into the laser cell containing the mixture of XeF_2 vapour and N_2 buffer gas. VUV radiation makes photolysis of XeF_2 molecules form XeF^* excimer molecules. The active medium of the amplifier pumped by VUV radiation has 24 cm aperture and 110 cm length. The results of numerical modeling of the output parameters and first experimental results are presented in this paper. According to the modeling of the XeF(C-A) amplifier parameters and the first measurement of gain, it is shown that the maxmum output energy is 2—3 J, which means that the peak power has been up to 40—60 TW in a 50 fs pulse. Furthermore, It is very important that this laser system can provide a high temporal contrast up to 10^9-10^{10}.

Key words: hybrid laser system; XeF(C-A) amplifier; femtosecond pulse duration; electron beam; VUV converter

1　Introduction

Research and development of terawatt and petawatt peak power laser systems have attracted a heightened attention in recent years. It is caused by their important roles in the developing new areas of modern physics such as generation of electron and ion beams of high energy with record current density, fast ignition in inertial confinement fusion, generation of attosecond pulses in X-ray range, stimulation of nuclear reactions *etc*.

Presently, for achievement of terawatt and petawatt peak power level in a laser pulse, the solid-state only laser facilities with lamp or laser pumping are used. All these facilities require utilizing huge and expensive vacuum grating compressors after a final amplifier to recompress a femtosecond pulse preliminary stretched into the nanosecond time domain (CPA technique). The main bottleneck of the compressors is the low optical damage threshold (~0.2 J/cm^2) of gratings gold coating which makes difficult scaling ultra intense laser facilities to multipetawatt peak powers.

A photochemically driven XeF(C-A) gain medium is now considered as an alternative to existing solid state active media for femtosecond pulse amplifiers[1-4]. Due to gaseous nature of the active medium there is no physical limit for its scaling and one can operate in the regime of amplification of femtosecond pulses negatively-chirped into the subpicosecond time domain, whereas the final pulse recompression down to few tens of femtoseconds can be provided in the bulk material of the amplifier output window. It has a wide amplification band (~60 nm) in 480 nm range, which corresponds to the ~10 fs transform limited pulse. Moreover, XeF(C-A) active medium has a high saturation energy density of ~ 0.05 J/cm^2 and spectrally matches to the second harmonic of Ti:sapphire laser providing, along with its low ASE, achievement of temporal contrast as high as ~10^{10}.

The operating principle of the photolytically pumped XeF(C-A) amplifier considered in this presentation can be described briefly as follows[1-7]. The e-beam energy is deposited into pure xenon. Energy cascade processes lead rapidly to the formation of Xe_2^*, which radiates a fraction of the deposited energy in the continuum at (172±5) nm. This VUV radiation is transmitted through CaF_2 windows into the amplifier cell containing the mixture of XeF_2 vapour and N_2 buffer gas. When absorbs this radiation, XeF_2 molecules are photodissociated to form XeF^* molecules. The excited state produced in this way is primarily XeF(B1/2) which is then relaxed to the XeF(C3/2) state due to collisions with the N_2 buffer gas. The C state can then undergo spontaneous emission to the A state in a bound-free transition at (473±35) nm or stimulated emission with peak gain centered at 480 nm. Alternately, XeF^* can be quenched by XeF_2 or by transient products.

The multi-terawatt hybrid (solid state/gas) laser (THL-100) system on the basis of Ti:sapphire starting complex and photochemical XeF (C-A) amplifier with the aperture of 24 cm is now being built at HCEI SB RAS, Tomsk, Russia. These works are carried out in close collaboration with P. N. Lebedev Physical Institute, Moscow, Russia.

In this paper, the design and operating principle of hybrid laser system is presented and the results of numerical modeling of the active medium parameters, distribution of a small signal gain, fs-pulse amplification and first experimental results are discussed.

2 Hybrid femtosecond laser system design

Laser system consists of a Ti:sapphire starting complex and a photochemical XeF(C-A) amplifier with the aperture of 24 cm. "Start-480M" starter complex manufactured by Avesta-Project firm (Fig. 1) is used as a front end for the laser system. The complex is located on an optical table with size of 120 cm×260 cm and consists of the following components: Ti: sapphire master oscillator of femtosecond pulses with a continuous laser pumping (Verdy-8) at a wavelength of 532 nm, the stretcher of femtosecond pulse, regenerative and multipass amplifiers with a pulsed laser pumping at a wavelength of 532 nm, diffraction grating compression and the second harmonic generator (KDP). The complex has the following output parameters of the laser beam: pulse duration is 50 fs, the energy of radiation at the second harmonic (475 nm) is 5 mJ. The complex can operate in a single pulse mode and a frequency of 10 Hz.

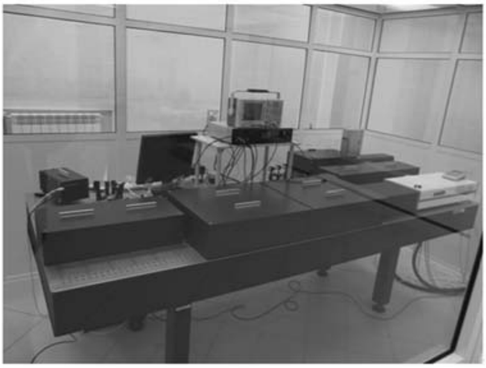
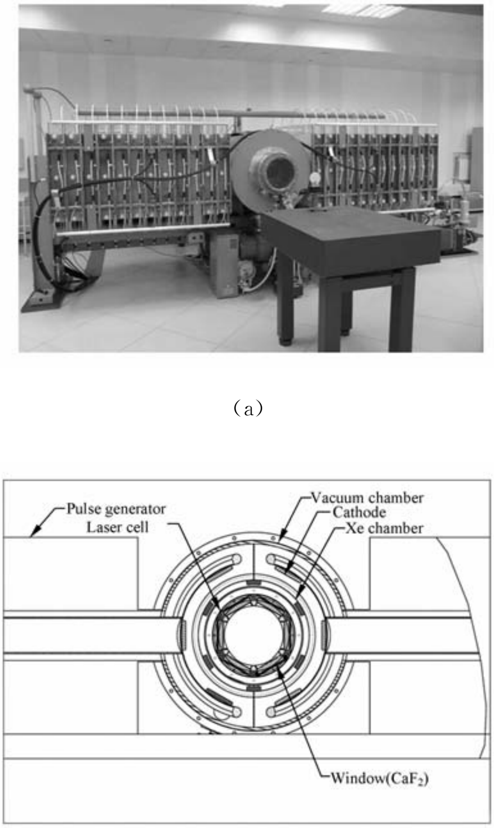


Fig. 1 Solid-state Ti:sapphire oscillator/amplifier front-end

It is planning that the seed pulse will be negatively stretched up to 1 ps using a prism pair arrangement before amplification in the photochemically driven XeF(CA) amplifier. There are two reasons for stretching seed pulse before amplification: one is to avoid nonlinear pulse distortion in the amplifier; the other is to exceed the rotational reorientation time of the XeF(C) molecules limiting energy extraction from the amplifier because this time estimated to be about 0. 5 ps, allows saturation of only a portion of the polarization distribution of the active medium gain if the seed pulse is linearly polarized.

Fig. 2 shows the cross sectional schematic diagram (a) and outside view (b) of the XeF(C-A) amplifier. The design of the e-beam accelerator is based on the unique technology developed at HCEI SB RAS.



(a)

(b)

Fig. 2　Cross sectional schematic diagram (a) and outside view (b) of the XeF(C-A) amplifier

It includes a two high-voltage pulsed generator (linear transformers), a vacuum diode with six cold explosive-emission cathodes, an electron beam injection system, a Xe filled chamber-converter and a laser cell. The high-voltage generator consists of 12 transformer stages and each of them involves eight capacitors (one is C=40 nF) and spark gaps. The capacitors can be charged up to a voltage of 100 kV. The central conductor which is the secondary turn for all 12 stages of the high-voltage pulse generator is connected to the cathode-holder of the vacuum diode. This construction permits to minimize the inductance of the supply circuit and weight of the accelerator. The distance between cathode and anode in the vacuum diode is 5 cm. The vacuum diode forms six 100 cm (long)×12 cm (wide) e-beams which are injected through 40 μm Ti foil into the Xe converter. The parameters of e-beam in the vacuum diode are the following: total current I is 320 kA, peak voltage U is 550 kV, pulse duration of e-beam power is about 150 ns (FWHM). The total energies of the electrons which pass through the foil into the Xe converter are 6. 5－7. 5 kJ in the 150－160 ns pulse (FWHM).

The stainless steel Xe converter has a diameter of 45 cm. It is fitted with a high vacuum pump port and gas flow inlet and outlet port. We used Xe of 99. 999 7% purity. In experiments the fresh xenon was filled to converter from a cylinder without preliminary purification. After some work when amplification of active medium decreased the xenon was cleaned by online gas recycling system, consisting of a pump and Sircal MP-2000 purifying system. Activating the recycling system brought the VUV output of Xe converter and active medium gain back up to approximately the initial value.

Laser cell closed by CaF_2 windows is installed in the centre of Xe converter. The 8 cm distance between Ti foil and CaF_2 windows was chosen to assure that the electrons were stopped in the cell at the xenon operating pressure of 3 bar. The VUV window interfaces between the xenon and laser cells consist of arrays of 9 rectangular CaF_2 windows, each 2 cm thick and 12 ×12 cm wide. The clear aperture of the 113 cm long hexahedral laser cell is 24 cm. The laser cell is filled with XeF_2/N_2 mixture at pressure of 0.25—1 bars.

The laser cell is sealed by two windows of fused quartz with a diameter of 30 cm and was designed for use with internal mirrors that provided optical access to the entire cross-section of the active medium. The multipass mirror system is inserted and adjusted inside the laser cell. The mirrors are mounted in flanges that bolted to the end flanges on the laser cell. The mirror substrates have diameters from 2 cm up to 10 cm and were fabricated from polished with two sides fused quartz. The mirrors provide a broad-band high reflection ($\rho=99.5\%$ for 460 nm$<\lambda<$500 nm) for XeF(C-A) laser transition. The reflectivity at the 351 nm for XeF(B-X) laser transition is 8%. The dielectric mirrors have protective coating of Al_2O_3 with ionic treatment in order to avoid the etching of the surface due to chemical attack by XeF_2 and by photo-dissociation products of active medium (presumably F_2). The mirror system allows to amplify the femtosecond laser beam on 33 passes through the active medium of the XeF(C-A) amplifier. The seed beam has a diameter of 1.5 cm at the entrance to the amplifier and up to 10 cm at the exit. Increasing the laser beam diameter during the amplification permits more efficiently to extract energy radiation from the XeF(C-A) amplifier.

3 Simulation and experimental results

In this paper, we conducted experimental and computational studies of the gain. In the experiments, the gain was measured using a continuous laser at a wavelength of 488 nm. Fig. 3 shows the behavior of the gain in time synchronously with the current a vacuum diode. It is seen that the gain pulse duration of the active medium is 200 ns (FWHM).

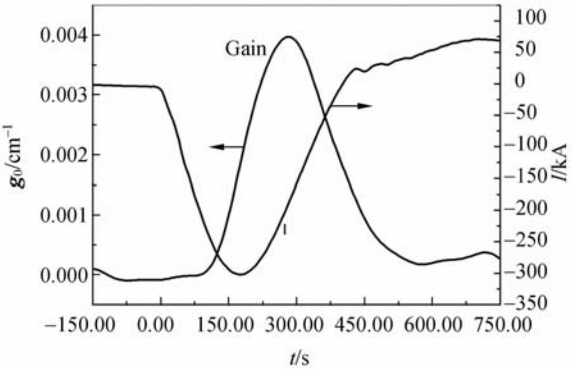


Fig. 3 Experimental measurement of small signal gain (near of window) and diode current in time

For simulation of femtosecond pulse amplification in XeF(C-A) active medium of a hexahedral pumped laser chamber with gases XeF_2/N_2 mix by VUV radiation was developed the computational model. This model was used for preliminary calculation of the active medium parameters and femtosecond pulse amplification. An interaction of the pumping radiation with XeF_2 molecules result in formation of XeF(B) and XeF(C) molecules at high vibration levels in this model. Pumping of lower vibrational levels was occurred in a process of VT relaxation these molecules in collisions with atoms of buffer gas. The model takes into account a processes of B-C exchange, dissociation of excimer molecules in the ground states and XeF(B-X) and XeF(C-A) spontaneous emissions.

The amplification of the injected pulse was described in frame of a noncoherent model, using a one-dimensional transport equation for laser photon flux. The photon flux was injected in the active medium in fixed point of resonator. After going of photons from one mirror to the other, the flux was came back in the active medium in another point and so on. According to our estimation, the model may be used for simulation laser pulse amplification with pulse length down to *t* about (100-150) fs. More accurate border of application of this model will be specified after comparing the simulated data with experimental results and with results of simulation by a coherent model. The rate equations and transport equations were solved using Gear methods and method of Runge-Kutta accordingly.

In the calculations, quadrilateral[5,7] and cylindrical methods were used. In the first case, the correlation of calculated parameters of an active medium with real hexahedral geometry was realized by a geometrical factor value of absorbed VUV energy. In the second case, the distribution of active particles assumed to be symmetric over the azimuthal angle and the length of the active region. Power VUV radiation pumping at each point of the active region was calculated in accordance with the spatial distribution of XeF_2 molecules and radiation pump power at the outer edge of the active region in each time moment.

According to the data presented in Ref. [57] and [7], the fluorescence efficiency of e-beam pumped xenon was taken to be $\eta_{pumpXe}=30\%$ and the VUV coupling efficiency, which is the product of CaF_2 windows transmission and the solid angle factor, was estimated to be $\eta_w=15\%$. In this case, the VUV photon flux density at the internal surface of CaF_2 windows was calculated to be $F_R=\eta_{pumpXe}\cdot\eta_w\cdot(P_{pumpXe}/S)/\hbar\omega=2.0\times10^{23}\ cm^{-2}s^{-1}$, where S is the area of the laser-cell side-face. Experimental measurement of VUV photon energy density inside laser sell shown that it equals 34 mJ/cm² and total pump energy — 240 J near the window. It gives the pump photon flux density $F_R=1.6\times10^{23}\ cm^{-2}\cdot s^{-1}$ which was used in our simulations. The value of absorbed VUV energy by XeF_2 depends from the molecules concentration and geometrical factor η_{geom}. The average cross section of XeF_2 photo absorption at 172 nm weighted by the xenon intensity distribution is $\sigma(XeF_2)=1.6\times10^{-17}\ cm^2$[3].

Our model allows calculating the XeF(C) molecules concentration in active medium in case of pumping by VUV radiation. The spatial distribution of molecules concentration in an active medium depends essentially of XeF_2 vapour pressure. The product of this molecules concentration on the cross section of stimulated emission $\sigma=9\times10^{-18}\ cm^2$[5] gives the value of the gain. Its behavior for the different vapour pressures is clearly illustrated in our simulations, as is shown in Fig. 4. The choice of pressure value was caused by the two factors: a sufficiently uniform distribution of excimer molecules in active medium and a sufficiently high gain. As shown in the picture of a rather uniform gain distribution in the active medium, its value could be obtained at XeF_2 pressure of 13.33～26.66 Pa.

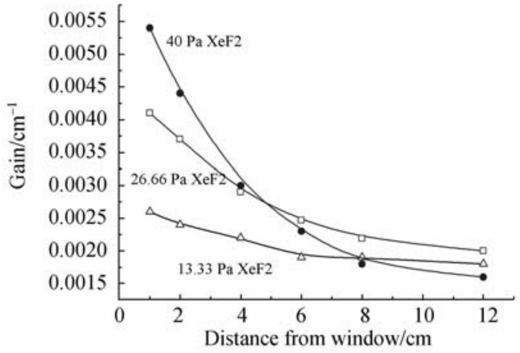


Fig. 4 Distribution of a small signal gain from center of window surface (0) to laser sell center (12 cm) for different XeF_2 pressures (simulation)

Experimental distribution of a small signal gain in the laser sell is presented in Fig. 5. It could see a good agreement of the gain value with the simulation results. The temporal behavior of small signal gain conforms practically the pump pulse but it has a time delay of maximum point about 40-50 ns. This delay increases when the XeF_2 vapour pressure decreases.

Simulation of output energy of amplified pulse was carried out for the following conditions: input energy of 3 mJ, pulse duration of

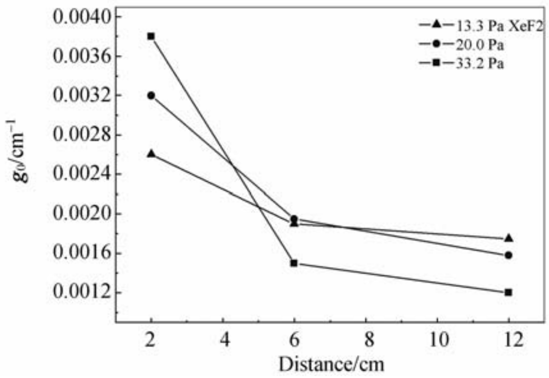


Fig. 5 Experimental distribution of a small signal gain from center of window (0) to laser cell center (12 cm) for different XeF_2 pressures

500 fs (FWHM), laser beam input diameter of 1 cm, output diameter of 6 cm, the trips number through an active medium of 30. Output energy near 2 J was obtained for 26.66 Pa XeF_2 vapour pressure and 0.23 bar on N_2. The increase of a XeF_2 vapour pressure up to 40 Pa (i. e. gain rise) and number trips up to 33 allows getting the output energy in range of 3 J.

4 Conclusions

In this paper, the multiterawatt hybrid (solid/gas state) laser (THL-100) system on the basis of Ti:sapphire starting complex and photochemical XeF(C-A) amplifier with the aperture of 24 cm which is now being built at HCEI SB RAS, Tomsk, Russia is presented. Pumping amplifier scheme begins with the e-beam excitation of xenon to produce Xe^* fluorescence at 172 nm which photodissociates XeF_2 vapours in a laser cell to form XeF(C3/2) excited state radiating on the (C-A) transition centered at 480 nm. Frequency doubling conversion of a 50 fs seed pulse of 0.1 TW power from a Ti:sapphire laser system to match spectrally the amplification band of the XeF(C-A) amplifier is used.

According to the numerical modeling of the XeF(C-A) amplifier and the first measurement of gain, it allows to obtain up to 2—3 J output energy. It means that the out peak power has been up to 40—60 TW in a 50 fs pulse. The laser system will provide high temporal contrast up to 10^9-10^{10}. Realization of this approach will pave a new avenue for the development of high-contrast multiterawatt and sub-petawatt laser systems.

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作者简介：

Valery Losev (1950), male, was born in Alma-Ata, Spain. Now, he is a professor and head of Laboratory in High Current Institute SD RAS; He received his M. S. degree from Tomsk Polytechnic Institute (1973) and Ph. D. degree from Tomsk State University (1980) and Doctor of phys. -mathem. sciences from Tomsk State University (2000); professor in Tomsk Polytechnic University (2010). Now, he is mainly engaged in laser physics, gas discharge, plasma physics, optics, nonlinear optics, excimer lasers, fs-laser systems, high quality laser beams, laser technologies, electron beams, high voltage pulse generators. E-mil: losev@ogl. hcei. tsc. ru

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●下期预告

水平式激光发射系统指向误差的修正

薛向尧[1,2]，高云国[1]，姜伟伟[1,2]，张文豹[1]，于　萍[1]
(1. 中国科学院 长春光学精密机械与物理研究所，吉林 长春 130033;
2. 中国科学院 研究生院，北京 100039)

为修正由轴系误差引起水平式激光发射系统的指向误差，借鉴经纬仪视轴指向误差的修正方法——单项差法、坐标变换法，建立了激光发射系统指向误差的修正模型，由此掌握了轴系误差在激光发射光路中的传递规律。在介绍该系统光机结构及建模理论的基础上，得出反射镜的作用矩阵。通过建立水平式跟踪架笛卡尔坐标系，将激光光束看作空间内一单位矢量，并借助矢量旋转与坐标变换，得到了各单项误差解析式，通过线性叠加得出激光发射系统指向误差的修正模型，结合电视跟踪系统所测量的激光束指向误差，采用最小二乘法拟合得出修正模型中各待定系数。实验结果表明：指向误差经修正后，系统在某两轨道上和天顶区域的指向精度可达到 3.1″和 9.7″，达到了系统设计的精度要求。