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High power lasers for space debris elimination

APOLLONOV V V
(*Prokhorov General Physics Institute, Russian Academy of Sciences, Moscow* 119991, *Russia*)
* *Corresponding author, E-mail: vapollo@kapella.gpi.ru*

Abstract: A number of debris in low earth orbit is exponentially growing although future debris release and mitigation measures have been considered in human space activities. Especially, an already existing population of small and medium debris is a concrete threat to operational satellites. Ground-based DF laser and space-based Nd: YAG laser solutions appear as a highly promising answer, which can remove hazardous debris around the selected space assets at low expenses and in a non-destructive way. This paper introduces a research on the Space Vehicle(CV) protection and the orbit clearing from dangerous Elements of Space Debris (ESD) with diameters from 1 to 10 cm by means of a high-power and high repetition rate P-P Nd: YAG laser with an average power of 100 kW and a DF-laser with an average power about 1.5 MW.

Key words: DF laser; Nd: YAG laser; high power laser; space debris

用于空间碎片清除的高功率激光器

APOLLONOV V V
(俄罗斯科学院 普洛霍罗夫普通物理研究所,莫斯科 119991,俄罗斯)

摘要:虽然人类的太空活动已经考虑了尽量减少空间碎片的措施,但近地轨道碎片的数量仍呈指数增长,特别是中小型碎片的现有数量已对在轨卫星构成了实质性的威胁。作为具有较高期待的消除碎片办法,用地基DF激光器和空基Nd:YAG激光器消除碎片的方案令人关注,它们可以以低成本和非破坏性的方式清除空间轨道的危险碎片。本文介绍了使用平均功率为100 kW的高功率、高重复频率P-P Nd:YAG激光器和平均功率约为1.5 MW的DF激光器来保护在轨飞行器和清除直径为1~10 cm空间轨道危险碎片涉及的相关工作。

关 键 词:DF激光器;Nd:YAG激光器;高功率激光器;空间碎片
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1 High repetition rate P-P mode of laser operation

For the lasers with a high average output power (GDL, HF/DF, COIL, Nd:YAG), it is very common to use an unstable resonator configurations with a large cross section of the active medium. In the resonators of this type, externally-injected low-power beam may exert a significant effect on the characteristics of output radiation.

One way to realize the radiation control regime is the self-injection regime of radiation, which is extracted from the resonator and returned back to resonator as part of radiation after changing its spatial-temporal characteristics[1-2]. The transition to the transient lasing mode is impacted by the modulation of the self-injecting beam. Earlier, a study was made on laser versions with radiation self-injection into the paraxial resonator region. However, an analysis showed that the power of the beam injected into the paraxial beam region should be about the same value or comparable with the output laser power to efficiently control the resonator of a continuously pumped laser, which is unlike pure pulsed systems with regenerative amplification.

The self-injection of a part of output radiation through the resonator periphery is more efficient: on return to the paraxial resonator region, the injection power significantly rises due to a large number of passages, thus playing a dominant part in the formation of output radiation.

In the case of a traditional resonator, the role of waves converging to the resonator axis was found to be insignificant, because their source is a narrow region with a small relative area at the edge of the output mirror; accordingly, the power of the control wave injected into the resonator is low. This wave has a large divergence, and only its small part (of the order of NF, where NF≫1 is the Fresnel number) participates in lasing.

The effect of injection wave on the resonator characteristics can be enhanced by matching the beam phase with the resonator configuration and increasing the radiation power returned. In this case, the propagation direction and the wave front curvature of the injection beam should be matched with the resonator configuration. In this way, the injection beam concentrates after a relatively large number of passages through the resonator near the optical resonator axis, and transforms to a divergent wave that forms the output radiation. After its arrival to the resonator axis, the injection beam energy should be high enough to exceed the saturation energy of the active medium.

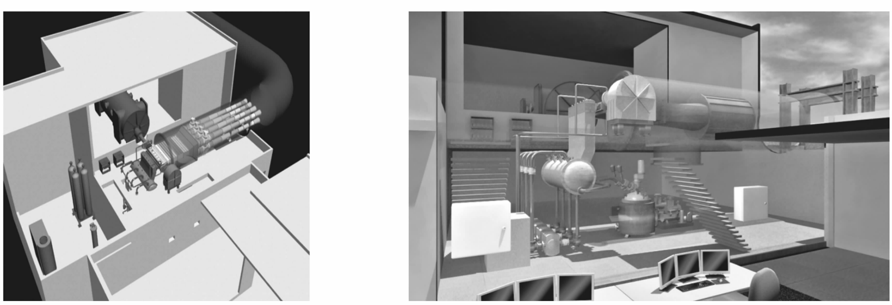
P-P mode of operation was realized in two types of lasers theoretically and experimentally, namely in a gas-dynamic CO_2 laser and Nd:YAG laser[3]. CO_2 laser had the following parameters: the length of the active medium $L_a = 1.2$ m, the unsaturated gain coefficient $g_0 = 0.6\ m^{-1}$, the time it takes the active medium to transit the resonator $\tau = 0.92 \times 10^{-4}$ s, the relaxation time $\tau_p = 2.76 \times 10^{-4}$ s, the total go-round resonator time $\tau_f = 4.2 \times 10^{-9}$ s, the luminescence lifetime $\tau_1 = 5$ s, the resonator magnification factor $M = 1.45$, the diameter of output laser aperture $a = 0.08$ m. Nd:YAG-laser was above 1 kW level, with two heads geometry.

The CO_2-laser resonator is made up of two spherical mirrors with rectangular apertures, which provided a geometrical amplification factor of 1.45. The active medium travels across the optical resonator axis. In what follows below all theoretical and experimental data are provided for a laser with the above parameters.

A part of the output laser radiation was diverted by an inclined metallic mirror to the injection beam formation system consisting of two spherical mirrors with conjugate focal planes. In the vicinity of the focal plane there formed the waist of the branched part of the laser beam, and a modulator was placed near the waist. The modulator location was selected so that the laser beam completely filled the aperture of the modulator. The maximal modulation frequency in our experiments has reached 50 kHz.

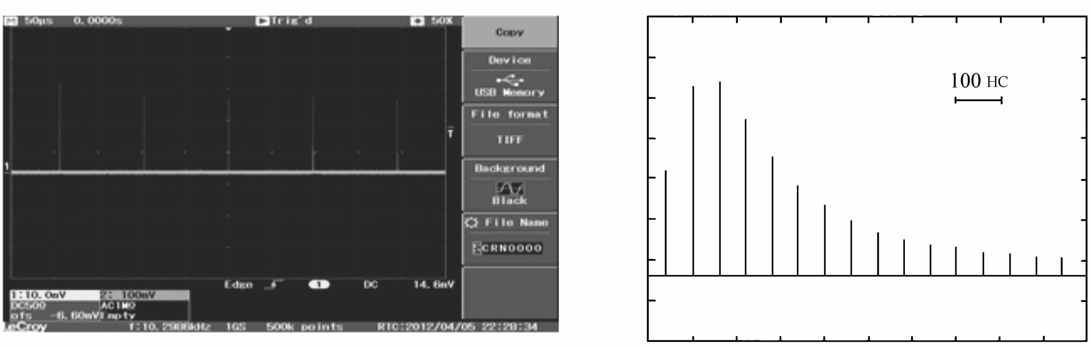
A mirror focused the radiation onto the calorimeter. The duration of an individual pulse was about 100 – 150 ns. We emphasize that the recorded pulse duration was limited by the measuring path bandwidth which is equal, as noted above, to 50 MHz. The amplitudes of individual pulses exceeded the average value of output power by factor ~10. The average output power was measured with a calorimeter cooled with running water. It is noteworthy that the average output power in the pulse-periodic mode was equal to the output power in the CW laser-operating mode. Good agreement between the experimental and theoretical data for frequencies ranging up to 25 – 50 kHz testifies to the adequacy of the proposed model and the possibility of employing this method at higher frequencies to convert a CW laser to the operating mode similar to the Q-switching mode.

HF/DF-laser and COIL are waiting for the experimental efforts to be applied. Fig. 1 is the simulated setup diagram of HF/DF laser with active media. Theoretically, P-P modes of regenerative amplification for high power lasers (Fig. 2) have been investigated and modeled by computer. The output parameters are dependable on parameters of media, way of pumping and resonator geometry. The summary of the radiation temporal structure is presented in Tab. 1.



(a) Top view　　(b) Side view

Fig. 1　Simulated setup diagram of HF/DF laser with active media: $L = 135$ cm, $H = 40$ cm



(a) Gain switch pulse　　(b) CW mode of operation

Fig. 2　Train of pulses for regenerative amplification

Tab. 1 Summary of the radiation temporal structure

Parameters	Lasers			
	COIL	HF/DF	Nd:YAG	CO
Frequencies at the starup of P-P mode/kHz	>20	>100	>4	>10
Frequencies at the modulation depth of 100%/kHz	>100	>250	>40	>100
Pulse duration/ns	<250	<100	<250	<250
Ratio(P_{peak}/P_{aver})	100 – 1 000	100 – 10 000	100 – 1 000	100 – 1 000

2 New application for high repetition rate P-P lasers

In previous years an increasing attention has been given to the study of possibility of lasers using for cleaning of the elements of space debris(ESD) from the space. These elements have collected over more than four decades of operation of space and in some cases, created a big threat to space vehicles(SV). Experts estimate that by 1996 about 3.5 million ESD was traced in the size less than 1 cm, more than 100 thousand splinters in the size of diameters from 1 to 10 cm, and nearby 8000 ESD in the size of exceeding 10 cm[4-6]. Large ESD with a diameter more than 10 cm are found out by modern watch facilities and are brought in special catalogues. The most effective method of protection from such ESD is the maneuvering of SV. Experts estimate that splinters in a diameter less than 1 cm do not represent a special danger for existing SV. This is due to the presence of passive constructional protection although it makes SV considerably heavier. The most unpleasant diameter of splinters is 1 – 10 cm when the necessary degree of passive protection does not manage to be carried out because of its unacceptably big weight. To avoid the collision at the expense of maneuvering SV is impossible, as such splinters are not visible on the radar screen.

In low orbits under the influence of atmosphere quickly enough, there is the EDS self-clearing, as the time of life of ESD in orbits with a height of about 200 km averages about one week. In higher orbits in height of 600 km, their self-cleaning can occupy 25 – 30 years; and at the height of about 1 000 km, their self-cleaning can occupy 2 thousand years[5]. Our estimations have shown that the probability of collision with SV in diameter of 10 m within one year of its operation makes 0.45 for EDS, 10^{-2} for ESD with a size of 2 – 4 cm and 0.4 for ESD with a size of <0.4 cm; and frequency of collisions with the catalogued objects(≥10 cm) is at the level of one collision per 30 years. And every year, the number of ESD is increasing. The reality of a collision of SV with ESD is very clear.

As a result, the withdrawal of ESD from an orbit to protected the SV is a real problem. For this purpose, it is necessary to reduce the speed of ESD′s movement. As it will be shown further, it is possible to reach at the expense of ESD pulse irradiation and the reception on its plasma surface to creat an impulse of return. Such impulse arising in a mode of laser ablation of ESD material should reduce the height of ESD orbit so that it has flown by SV or, would finally enter into dense layers of atmosphere and get burnt down.

Several previously offered studies use the Nd:YAG ground-based laser installations for space clearing, but such laser lacks connectivity with the the passage of 1 μm radiation of the big capacity through the atmosphere, which can lead to the loss of optical quality of a bunch of radiation and the occurrence of nonlinear effects. They have small mobility and therefore the number of ESD that can be influenced by radiation will be limited. At the influence of laser on ESD from the earth surface, the return impulse will be directed upwards and the apogee of orbit ESD will be increased, but the perigee is going to be decreased and stopped by dense atmosphere. And the most important thing is that the requirements for power of the land-based laser should be increased in comparison with the space laser, as the distance from a terrestrial surface to ESD is much longer. For these reasons, the most expedient arrangement of Nd: YAG 100 kW laser installed directly in space is recommended. Thus it is desirable that the power consumption for such installation should be minimal. This condition satisfies Nd: YAG with LD pumping, so that it is capable to work independently in P-P mode of operation with very small expenses of power for the system service control. But for the case of the ground-based laser, we have suggested the DF-laser, whose radiation propagation through the atmosphere is much more effective and whose output power of existing systems(>1.5MW) and technology are more advanced.

In the reference [5], the most possible variants of rapprochement of ESD flying as a rule on elliptic orbits with various SV and moving on circular orbits at heights of 200 – 700 km have been analyzed. Two variants when SV moves on a circular orbit at a height of 400 km have appeared to be the worst, i. e. ESD flying on elliptic orbits whose heights of apogee are 2 000 km and 4 000 km. In this case, in a perigee there are areas where the planes of orbits SV and ESD coincide, and the speed of their rapprochement is maximum; and in this area, vectors of speed SV and ESD lie along the same direction, *i. e.* by influence of the laser radiation it is impossible to give ESD a lateral component of speed, as it is in more opportunity for an inclination of planes of orbits SV and ESD under the relation to each other.

The maximum speeds of rapprochement calculated for these two variants have been accordingly –395 m/s and –2 463 m/s. For circular orbits with height of 200, 400 and 700 km, the speeds of EDS flying on circular orbits in approchement with SV do not exceed 343 m/s, therefore these variants can be neglected.

Let's consider the process of rapprochement of ESD which is catching up with SV, after the influence on ESD of the laser radiation. Before the laser influence, the force of an attraction of the Earth and the centrifugal force are equal:

$$\frac{mv_0^2}{R+H} = \gamma \frac{mM}{(R+H)^2}, \tag{1}$$

Where: v_0 – speed of movement ESD on a trajectory before the influence of a laser impulse, R – radius of the Earth, H – height of ESD over the earth, M – weight of the Earth, γ – a gravitational constant, m – weight of ESD. After such influence on ESD, this balance will be broken; then the reduction of ESD speed Δv will force the normal acceleration into the direction towards the centre of the Earth:

$$a_{\mathrm{H}} = -\frac{\gamma M}{(r+H)^2} + \frac{(v_0 - \Delta v)^2}{R+H}, \tag{2}$$

Where: Δv – change of ESD speed after laser pulse influence(typical value of Δv is ~200 km/s[7]). After simple transformations from (1), we will receive:

$$a_{\mathrm{H}} = \frac{-2 \cdot v_0 \cdot \Delta v + \Delta v^2}{R+H}, \tag{3}$$

Through the time – t the radius-vector of ESD orbit will be changed:

$$\Delta H = \frac{a_{\mathrm{H}} t^2}{2} = \frac{\Delta v \cdot (\Delta v - 2v_0)}{R+H} t^2. \tag{4}$$

By knowing the initial distance – L from SV to ESD and a tangential component of rapprochements speed of ESD to SV after the influence of a laser pulse:

$$t = \frac{l}{v_{\mathrm{T}}} = \frac{l}{v - \Delta v}. \tag{5}$$

Then for the change of size of a radius-vector of ESD orbit, we will receive the following expression:

$$\Delta H = \frac{\Delta v \cdot (\Delta v - 2v_0)}{R+H} \frac{l^2}{(v - \Delta v)^2}. \tag{6}$$

From here, it is possible to find the distance between ESD and SV when it is necessary to start the influence on ESD by laser:

$$l = (v - \Delta v) \sqrt{\frac{\Delta H \cdot (R+H)}{\Delta v \cdot (\Delta v - 2v_0)}}. \tag{7}$$

Proceeding with the SV dimensions, we will set the size $\Delta H = 30$ m. Then for the first variant of ESD rapprochement to SV at $v_{rapp} = 395$ m/s, $\Delta v = 200$ m/s, $v_0 = 8$ km/s, $H = 400$ km, $R \approx 6\ 300$ km, the distance between them will make 4.1 km. This way will be passed in the time of ~20 s. Then for metal ESD at typical values of $C_m^{\text{ОПТ}} = 4$ dyn · s/J and $S/m = 0.15\ \text{cm}^2/\text{g}$, we will receive $\Delta v = 6$ cm/s, and the necessary number of pulses for the value $\Delta v = 200$ m/s will make 3 300 pulses at a 3 000 Hz frequency of high repetition rate Nd:YAG laser. Necessary time of influence is 1.1 s, which is much less than the time of rapprochement to SV found before (20 s). It shows that with the same laser, it is possible to reject ESD from SV with rapprochements having much greater speed.

For more exact calculations at the high speeds of rapprochement, it is necessary to consider the dynamics of change of values Δv and the current distance between ESD and SV after the influence of each laser pulse of P-P irradiation on ESD.

For the second variant with very great speed of rapprochement $v_{rapp} = 2\ 463$ m/s at $\Delta v = 200$ m/s and with a much bigger distance of 20 km, the rejection is possible as well. However, maintenance of Δv at the distance of 20 km will meet some changes of parameters due to the bigger size of the focal point on such a distance.

The problem of ESD withdrawal from SV orbit where ESD has flown by SV has been considered above. The other problem is also important, that is, to create such impulse of return to achieve decline in ESD to an orbit in height of 200 km at the expense of the further braking in atmosphere of particles of ESD, so that ESD will be burned down and the space will be cleared from ESD. In other words, a SV with laser installation will carry out a role of "cleaner" of the most used orbits. If the particle ESD has decreased to 200 km over the Earth surface, its speed needs to be reduced by a certain value Δv which will allow it to pass from a circular orbit on elliptic orbit whose exact value can be calculated as follows:

$$\Delta v = v_{apogee} - v_{start}, \tag{8}$$

Where: v_{apogee} – ESD speed in the apogee of a transitive elliptic orbit, v_{start} – speed of ESD in an initial circular orbit. Speed in the apogee is:

$$v_{apogee} = \sqrt{\frac{2 \cdot \gamma \cdot M \cdot R_{start}}{r_{200} \cdot (r_{200} + R_{start})}}, \tag{9}$$

Where: r_{200} – radius of a circular orbit in height of 200 km, R_{start} – radius of an initial orbit. ESD speed in an initial circular orbit is defined as:

$$v_{start} = \sqrt{\frac{\gamma \cdot M}{R_{start}}}. \tag{10}$$

On the basis of given data by ref. [5], the graphic dependence of demanded reduction of speed ESD in the apogee of an elliptic orbit from the height of an initial circular orbit has been constructed. The similar dependence has been resulted in the work of ref. [5] without explanations. It is clear that ESD, being in the orbit with height of ~900 km, will decrease to the height of 200 km if reducing the speed by 200 m/s.

The change of ESD speed Δv after the influence of laser radiation pulse with the energy density E (J/cm^2) on ESD is defined from the following expression:

$$\Delta v = C_m ES/m, \tag{11}$$

Where: S – the interaction area, m – weight of ESD, C_m [dyn · s/J] – proportionality factor between Δv and E, depending on the ESD type. Characteristics of the most widespread of them are presented in the Tab. 2[5]. Such ESD are formed as a result of SV explosions or their collisions with ESD. Spheroids of Na and K are formed after destruction of reactors. Splinters of phenol-carbon plastics and fragments of "plastics-aluminum" are the fragments of thermal protection; splinters of aluminum-based materials can appear after explosion of tanks and covers of SV; steel bolts are the fragments of connecting block armature.

Tab. 2 C_m(opt) and S/m for different ESDs

	Type of ESD				
	Na(K)	"C" based materials	Organics-based materials	"Al" based materials	"Fe"-based materials
Angle/(°)	65	87	99	30	82
Apogee/km	930	1 190	1 020	800	1 500
Perigee/km	870	610	725	520	820
$(S/m)/(cm^2 \cdot g^{-1})$	1.75	0.7	2.5	0.37	0.15
Size/cm	1.0	1×5	0.05×30	1×5	1×10
Reflectivity	0.4	0.02	0.05/0.7	0.05/0.7	0.5
$C_m^{opt}/(dyn \cdot s/J)$	(6±2)	(7.5±2)	(5.5±2)	(4±1.5)	(4±1.5)

High-power high repetition rate P-P laser should generate a temporally and spectrally effective pulse designed for high transmission through the atmosphere as well as for efficient ablative coupling with the target.

The space-based Nd:YAG laser with output power less than 100 kW that we propose is the best tool for fast re-entering of the ESD into the dense layers of atmosphere.

The DF ground-based laser system that we have proposed is capable to get a rapid engagement of targets whose orbits cross over the site, with potential for kill on a single pass. Very little target mass is ablated per pulse so the potential to create additional hazardous orbiting debris is minimal.

The laser system would need to be coupled with a target pointing and tracking telescope with guide-star-like wave-front correction capability.

Tab. 3 presents the LEO/MEO ESD removal data for Nd:YAG laser. ESD have a size of 1 – 10 cm and fly below the 300 km altitude. C_m = 4 dyn·s/J in average is for polymer and "Al"-based materials response. Typical S/m data for ESD, namely NaK-1.75, Al-0.37, and Fe-0.15, are taken from the Tab. 1. For $I = 3.0$ J/cm^2, S/g = 0.15 cm^2/g, we need N = 7 000 laser pulses for ESD re-entry. Nd:YAG-laser operating at 3 000 Hz can re-enter small object from the gap 1 – 10 cm in 2.3 s. Such a level of average output power (360 kW) for CW/P-P Nd:YAG lasers has not yet been demonstrated up to now. To get such effective results for clearing, we not only need the laser but also a 30-m-diameter telescope to deliver the laser pulses to a target at 300 km range or more within 10 ns time duration.

Tab. 3 LEO/MEO ESD removal data for Nd:YAG laser

λ	τ	D_b	W	f	$\langle P \rangle$	d_s	Z	I
1.06 μm	10 ns	30 m	60 J	3 000 Hz	360 kW(0.5)	5.2 cm 2Dif	300 km	3.0 J/cm^2

Tab. 4 presents the LEO/MEO ESD removal data for DF laser. ESD have the same size of 1 – 10 cm and fly below the 300 km altitude. C_m = 4 dyn-s/J in average is for the same materials: polymer and aluminum. With $I = 0.6$ J/cm^2, $t = 10$ ns, $S/g = 0.15$ cm^2/g, we need N = 3 5000 pulses for ESD re-entry. Ground-based 1.5 MW DF-laser operating at 10 kHz can re-enter any small object from the gap of same size in 3.5 s. This operation requires a 30 m-diameter telescope to deliver 2 J/cm^2 ($C_m = 0.2\ C_m^{opt}$) to a target at 300 km range with a 10 ns pulse at 3.8 μm. Here is important to note that with one minute delay for retargeting, all objects of this height and below can be re-entered during

0.5 year only. It should be also noted that the level of output power for CW regime had already been demonstrated and the technology is mature enough. The realization of P-P mode of operation for this type of laser is the question of time. Motivation is completely available. New tasks for high repetition rate high-power lasers generated during the last few years are very much important[7-9] and definitely should be solved in the near future.

Tab.4 LEO/MEO ESD removal data for DF laser

λ	τ	D_b	W	f	$\langle P\rangle$	d_s	Z	I
3.8 μm	10 ns	30 m	150 J	10 kHz	1.5 MW	18 cm 2Dif	300 km	0.6 J/cm^2

3 Conclusion

This paper presents the SV protection and the orbit clearing from dangerous ESD with diameters from 1 to 10 cm by means of a high-power and high repetition rate P-P Nd:YAG laser with an average power of 100 kW and a DF-laser with an average power about 1.5 MW.

The paper examines the possibility of applying the installations mentioned above not only for dangerous ESD withdrawal from SV orbit, but also for planned clearing of the most maintained orbits from such ESD when these installations will carry out a role of a "cleaner" for these orbits. For this purpose, under the influence of radiation, it is necessary to translate ESD from a circular orbit to elliptic one, whose perigee is in the dense atmosphere beds where ESD should be burned down. As a result of the decision of a ballistic problem, dependence of necessary reduction of speed of ESD from the height of their orbit over the Earth is received. Our paper finds that for orbits with heights of up to ~300 km, the demanded influence can be provided by 1.5 MW DF-laser installation with a 30 m-diameter telescope within the pulses duration of about ten nanoseconds.

It is shown that, for the worst variant, in case of influence on metal ESD with the greatest speed of ~2.5 km/s in their rapprochement with SV, the condition that angular divergence of radiation of space-based 100 kW Nd:YAG laser should not be worse than two diffraction limits at the use of a telescope in which diameter of main mirror $D=1$ m is admissible.

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Author's biography:

Apollonov V V(1945—), male, Doctor of physics and mathematics, Professor, Academician of RANS and AES. He is the leading specialist in the area of basic principles of creation and development of high power laser systems and high power radiation interaction with a matter. He is the member of European and American Physical Society, SPIE, AIAA, American Society for QE and the member of specialized scientific council of Russia. He is a full member of Russian Academy of Natural Science and Academy of Engineering Sciences, a laureate of State Prize of USSR(1982) and of Russia(2001). E-mail:vapollo@ kapella. gpi. ru

译文参考:

1　激光器运行的高重复率 P-P 模式

对于具有较高平均输出功率的激光器(GDL、HF/DF、COIL、Nd:YAG)来说,采用具有大横截面激活介质的非稳腔配置是很常见的。在这类谐振腔中,从外部注入的低功率激光束可能会对输出光的特性产生重要的影响。

一种实现辐射控制机制的方法是辐射光的自注式机制,即光从谐振腔中被提取出来,然后在改变其时空特性后作为辐射光的一部分返回到谐振腔[1-2]。进入瞬态激光模式的过渡阶段要受到自注光束调制的影响。早期人们曾做过一项激光器型式的研究,并将辐射光以自注方式注入近轴谐振腔区域。但分析表明,注入近轴光束区域的光束功率应当与输出激光功率值大致相同,以有效控制连续激励式激光器的谐振腔,这与具有再生放大功能的纯脉冲系统不同。

将部分输出辐射光以自注方式注入谐振腔外围则更加高效:在返回近轴谐振腔区域时,由于流量大,注入光的功率明显增强,从而在输出光束形成过程中起到了主导作用。

在使用传统谐振腔时,发现光波会聚于谐振腔轴线的作用并不明显,因为波源是一块狭窄的区域,其面积在输出镜的边缘相对较小;因此注入谐振腔的控制波功率也相应较低。该光波具有较大的发散性,而且只有一小部分(为 1/NF 级,其中 NF 为菲涅尔数,NF≫1)参与激光的形成。

通过使光束相位与谐振腔匹配以及增加返回的辐射功率,可以增强注入波对谐振腔特性的效应。在这种情况下,注入光束的传播方向和波前曲率应当与谐振腔构型相匹配。这样,大面积的注入光束进入谐振腔后就会集中在该腔光轴附近形成汇聚光束而输出。而在谐振腔光轴上,注入光能量应该足够高以至于超过激活介质的饱和能量。

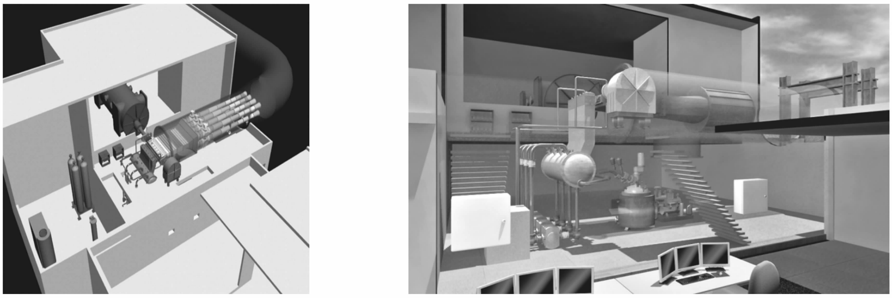
在理论和实验上,P-P 运行模式是通过两类激光器实现的,即气体动力 CO_2激光器和Nd:YAG激光器[3]。CO_2激光器具有下列参数:激活介质的长度 $L_a = 1.2$ m;非饱和增益系数 $g_0 = 0.6$ m^{-1};激活介质经过谐振腔的时间 $\tau = 9.2 \times 10^{-5}$ s;弛豫时间 $\tau_p = 2.76 \times 10^{-4}$ s;返回谐振腔的时间 $\tau_f = 4.2 \times 10^{-9}$ s;荧光寿命 $\tau_1 = 5$ s;谐振腔的放大系数 $M = 1.45$;激光器的输出孔径 $a = 0.08$ m。Nd:YAG 激光器输出功率高于 1 kW,并具有双头几何外形。

CO_2激光器谐振腔由带矩形孔的两块球面镜组成,球面镜的几何放大系数为 1.45。激活介质穿过光学谐振腔轴线。下面提供了与上述参数的激光器有关的所有理论数据和实验数据。

输出光的一部分经倾斜的金属镜面反射后,转向具有带共轭焦面的两块球面镜组成的注入光束形成系统,在焦面附近形成了激光束分支束腰,在束腰附近放置一个调制器。调制器位置的选取应保证让激光束完全充满调制器孔。实验中最大调制频率达到50 kHz。

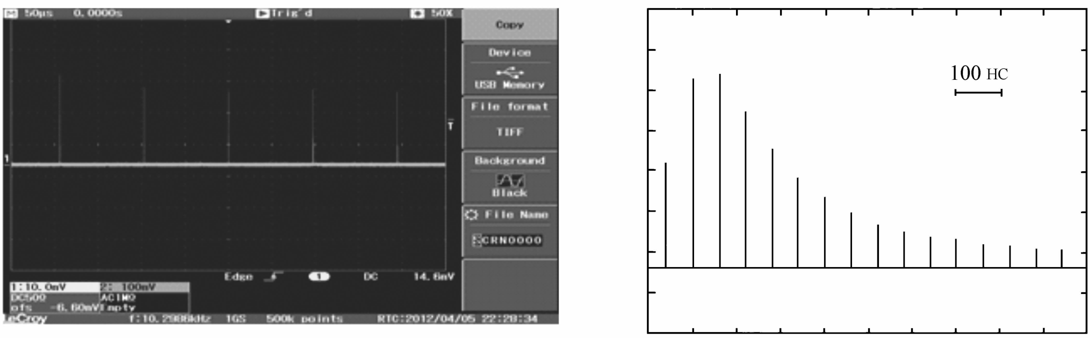
球面镜将辐射聚焦到热量计。单个脉冲的持续时间约为 100 ~ 150 ns。需要强调的是所记录的脉冲持续时间受到了测量路径带宽的限制。如上所述,测量路径带宽为 50 MHz。单个脉冲的幅度超过输出功率平均值约 10 倍。平均输出功率由经过水冷的热量计测定。值得注意的是脉冲周期模式下的平均输出功率等于连续波(CW)激光器运行模式下的输出功率。在 25 ~ 50 kHz 频率范围的实验数据和理论数据的高度一致性证实了该模型的充分性以及在较高频率下用此方法转化 CW 激光器的运行模式,使之接近于 Q 开关模式的可能性。

HF/DF 激光器和 COIL 激光器正处于试验准备阶段。图 1 为 HF/DF 激光器装置模拟图。从理论上来说,高功率激光器的再生放大 P-P 模式(如图 2所示)已经用计算机进行过研究、建模,其输出参数在介质参数、激励方式和谐振腔几何尺寸方面是可靠的,表 1 列出了辐射时间结构。



(a) 俯视图　　(b) 侧视图

图 1　HF/DF 激光器装置模拟图($L=135$ cm,$H=40$ cm)



(a) 增益开关脉冲　　(b) 连续运行模式

图 2　高功率激光器的再生放大 P-P 模式模拟装置

表 1　辐射时间结构

参数	激光器			
	COIL	HF/DF	Nd:YAG	CO
P-P 模式的初始频率/kHz	>20	>100	>4	>10
调制深度为 100% 的频率/kHz	>100	>250	>40	>100
脉冲宽度/ns	<250	<100	<250	<250
$P_{峰值}/P_{平均值}$	100 ~ 1 000	100 ~ 10 000	100 ~ 1 000	100 ~ 1 000

2　高重复率 P-P 激光器的新用途

前些年,人们将越来越多的注意力投向用激光器清除空间碎片(ESD)的可能性研究上。在 40 多年的太空飞行器运行过程中,这些碎片已经聚集并在某些情况会下对太空飞行器(SV)造成极大的威胁。专家们估计,1996 年前,探测到的直径小于 1 cm 的 ESD 数量已达到约 350 万,直径为 1 ~ 10 cm 的碎片数量超过 10 万,而直径大于 10 cm 的 ESD 数量将近 8000[4-6]。直径超过 10 cm的大 ESD 是通过现代观测设备发现的,这些 ESD 已被列为特殊种类。通过操纵 SV 可有效避免这些 ESD。专家们认为直径小于 1 cm 的碎片并不会对现有 SV 有严重威胁,这是因为出现了 SV 的被动结构防护,虽然这使得 SV 重量明显增加。当直径为 1 ~ 10 cm 的碎片因为重量过大而无法进行必要的被动防护时,这种碎片尺寸便成为了最让人头疼的事情。在这种情况下,全凭操纵 SV 来避免与这类碎片碰撞是不可能的,因

为在雷达屏幕上这些碎片是看不见的。

在受大气影响足够快的高度内(约 200 km 低轨道),ESD 具有自动清理特性,ESD 的平均寿命约为 1 周。在更高的轨道内,ESD 的自动清理会花费很长的时间:如在 600 km 高度的轨道内需要 25 ~30 年,而在约 1000 km 的高度则需要 2000 年[5]。通过估算表明,在 SV 的一年运行过程中,直径为 10 m 的 SV 与 ESD 碰撞的可能性为 0.45 次,其中与直径为 2 ~4 cm 的 ESD 碰撞的可能性为 10^{-2} 次,而与直径 <0.4 cm 的 ESD 碰撞的可能性为 0.4 次。与特殊类物体(≥10 cm)碰撞的频率为 1 次/30 年。ESD 的数量每年都在增加,SV 与 ESD 碰撞的可能性也变得越来越大。

因此,将 ESD 从轨道中移除以保护 SV 成为当务之急。为此,有必要降低 ESD 的运动速度。正如进一步显示的,可以通过对 ESD 的脉冲辐照及其等离子表面的吸收产生反冲力来达到这一目的。在 ESD 材料的激光烧蚀模式下,产生的冲力应当能降低 ESD 轨道的高度,让 ESD 随着 SV 飞行,或最终进入大气致密层后烧毁。

前几次研究采用了 Nd:YAG 地基激光装置进行太空清理,但这些激光器缺乏与大体积 1 μm 辐射光通道的连通性。当这些辐射光穿过大气时,辐射光束的光学质量会变坏,同时发生非线性效应。这些激光器的可移动性很小,因此受辐射影响的 ESD 数量将会受到限制。在 ESD 受到来自地球表面的激光影响时,反冲力的方向将向上,轨道 ESD 的远地点距离将增加,但其近地点距离将减少并受到致密大气层的阻止。重要的是与天基激光器相比地基激光器的功率应当增加,因为从地表到 ESD 的距离相比之下要大得多。出于这些原因,建议直接将 Nd:YAG 100 kW 激光器安装在太空中。因此理想的情况是,此类安装方式应当具有最低的功率消耗。这种条件要求 Nd:YAG 以激光二极管(LD)泵浦,使之能在 P-P 运行模式下独立工作,系统服务控制所消耗的功率极低。但对于地基激光器,建议采用 DF 激光器,这种激光器在大气层中的辐射传播要有效得多,而且其现有系统的输出功率(>1.5MW)和技术也更加先进。

文献[5]分析了 ESD 接近 SV 最可能的情况。这些 ESD 通常在椭圆形轨道上飞行,而各种 SV 在 200 ~700 km 高度的圆形轨道上运动。当 SV 在 400 km 高的圆形轨道上运动时,两种 ESD 运动情形是最不好的,那就是在 2000 和 4000 km 远地点高度的椭圆形轨道上飞行的 ESD。这种情况下,在近地点存在 SV 和 ESD 的轨道平面恰好重合的区域,而且它们的接近速度最大。在此区域,SV 和 ESD 的速度矢量位于相同的方向,也就是说,在激光辐射的影响下,不可能给 ESD 一个横向速度分量,因为在双方的相关性作用下,SV 和 ESD 的轨道平面更可能发生倾斜。

经计算这两种情况下的最大接近速度分别为 395 和 2463 m/s。对于高度分别为 200、400、700 km的圆形轨道,ESD 在这些圆形轨道上飞行时接近 SV 的速度≤343 m/s,因此这些情况可以忽略。

让我们考虑一下当 ESD 受到激光辐射的影响后,ESD 追上 SV 时的接近过程。在受到激光影响前,ESD 的地球引力和离心力是相等的:

$$\frac{mv_0^2}{R+H} = \gamma \frac{mM}{(R+H)^2}\,, \tag{1}$$

式中:v_0 为在受到激光脉冲影响前,ESD 在轨道上的运动速度;R 为地球的半径;H 为 ESD 在地表上方的高度;M 为地球的重量;γ 为引力常数;m 为 ESD 的重量。当 ESD 受到激光影响后,此平衡将会被打破;ESD 的速度减量 Δv 会在地心方向上产生法向加速度:

$$a_H = -\frac{\gamma M}{(r+H)^2} + \frac{(v_0 - \Delta v)^2}{R+H}\,, \tag{2}$$

式中:Δv 为 ESD 受到激光脉冲影响后的速度变化量(Δv 的典型值约为 200 km/s[7])。经过式(1)的简单变形,得到:

$$a_H = \frac{-2 \cdot v_0 \cdot \Delta v + \Delta v^2}{R+H}\,. \tag{3}$$

经过时间 t,ESD 轨道的矢径将发生变化:

$$\Delta H = \frac{a_H t^2}{2} = \frac{\Delta v \cdot (\Delta v - 2v_0)}{R+H} t^2. \tag{4}$$

通过 SV 到 ESD 的初始距离 l 以及在受到激

光脉冲影响后 ESD 接近 SV 的速度切向分量,可求出 t:

$$t = \frac{l}{v_T} = \frac{l}{v - \Delta v}. \quad (5)$$

对于 ESD 轨道的矢径尺寸变化,将得到下列表达式:

$$\Delta H = \frac{\Delta v \cdot (\Delta v - 2v_0)}{R + H} \frac{l^2}{(v - \Delta v)^2}. \quad (6)$$

由此就可求出通过激光器对 ESD 实施影响时,ESD 和 SV 之间的距离:

$$l = (v - \Delta v)\sqrt{\frac{\Delta H \cdot (R + H)}{\Delta v \cdot (\Delta v - 2v_0)}}. \quad (7)$$

利用 SV 的尺寸,得到 $\Delta H = 30$ m。对于 ESD 接近 SV 的第一种情况,如果 $V_{rapp} = 395$ m/s,$\Delta v =$ 200 m/s,$v_0 =$ 8 km/s,$H = 400$ km,$R \approx 6\ 300$ km,则 ESD 与 SV 之间的距离为4.1 km。这段距离将在约 20 s 内被通过。对于金属 ESD,当典型值 $C_m^{OIIT} = 4$ dyn·s/J 且 $S/m = 0.15$ cm^2/g 时,得到 Δv =6 cm/s;当高重复率 Nd:YAG 激光器处于 3 000 Hz 频率时,如果 $\Delta v = 200$ m/s,脉冲数将达到 3 300 个,影响时间将是 1.1 s,这比前面发现的 ESD 接近 SV 的时间(20 s)要短得多。这表明,对于相同的激光器,当接近速度较大时就可能使 ESD 避开 SV。

要想得到高速接近时的更精确计算结果,就有必要考虑速度值变化量 Δv 以及在受到每种 P-P 辐射激光脉冲的影响后 ESD 与 SV 之间的距离。

对于第二种情况,如果在 $\Delta v = 200$ m/s 时接近极高速度 $v_{rapp} = 2\ 463$ m/s,而且 ESD 和 SV 之间的距离大得多——达到 20 km,那么 ESD 也可能避开 SV。但由于在 20 km 距离上的焦点尺寸更大,因此要在这个距离上保持 Δv 值不变就需要对参数做出修改。

前面已经研究了 ESD 从 SV 轨道上清除的问题——ESD 曾与 SV 一起在 SV 轨道上飞行。另一个问题也很重要,即创建一种反冲力,使 ESD 在 ESD 粒子大气层中通过进一步制动以使其下滑到高度为 200 km 的轨道上,从而使 ESD 烧毁,并从太空中清除。换句话说,安装有激光器的 SV 将为最常用的轨道扮演“清洁工”的角色。如果粒子 ESD 已下降到地表上方 200 km 处,其速度需要减去特定数值 Δv,让 ESD 能穿过椭圆轨道上面的圆形轨道 。Δv 的精确数值可利用如下公式计算:

$$\Delta v = v_{apogee} - v_{start}, \quad (8)$$

式中:v_{apogee}为 ESD 在过渡性椭圆轨道的远地点上的速度;v_{start} 为 ESD 在初始圆形轨道上的速度。远地点上的速度为:

$$v_{apogee} = \sqrt{\frac{2 \cdot \gamma \cdot M \cdot R_{start}}{r_{200} \cdot (r_{200} + R_{start})}}, \quad (9)$$

式中:R_{200}为 200 km 高度处圆形轨道的半径;R_{start}为初始轨道的半径。ESD 在初始圆形轨道上的速度定义为:

$$v_{start} = \sqrt{\frac{\gamma \cdot M}{R_{start}}}. \quad (10)$$

由文献[5],当 ESD 处于初始圆形轨道高度上的椭圆轨道远地点时,所需 ESD 速度减量的图形相关性已经绘制出来。在文献[5]中也得到了类似的相关性,但没有说明。很明显,如果速度降为 200 m/s,那么位于约 900 km 高度处轨道内的 ESD 将降到 200 km 高度。

受到激光辐射脉冲的影响后,ESD 的速度变化量 Δv 将随着 ESD 能量密度 E(J/cm^2)的变化而变化:

$$\Delta v = C_m ES/m, \quad (11)$$

式中:S 为交互区;m 为 ESD 的重量;C_m(dyn·s/J)为 Δv 和 E 之间的比例因子,取决于 ESD 的类型。ESD 的最普遍特性见表 2[5]。这些 ESD 是由于 SV 爆炸或 SV 与 ESD 碰撞后形成的。球状 Na、K 是在反应堆被毁后形成的,苯酚碳塑料碎片以及“铝塑”碎片是热防护装置的碎片;铝基材料的碎片会在 SV 机盖爆炸后出现;钢制螺栓则来自连接块支架的碎片。

表 2　不同 ESD 的 C_m^{opt} 和 S/m

	钠(钾)	碳基材料	有机物基材料	铝基材料	铁基材料
角度/(°)	65	87	99	30	82
远地点/km	930	1 190	1 020	800	1 500
近地点/km	870	610	725	520	820
$(S/m)/(cm^2 \cdot g^{-1})$	1.75	0.7	2.5	0.37	0.15
尺寸/cm	1.0	1×5	0.05×30	1×5	1×10
反射率	0.4	0.02	0.05/0.7	0.05/0.7	0.5
$C_m^{opt}/(dyn \cdot s/J)$	(6±2)	(7.5±2)	(5.5±2)	(4±1.5)	(4±1.5)

高功率高重复率 P-P 激光器可产生专门用于高速穿越大气层以及与目标物高效烧蚀耦合时谱的有效性脉冲。

输出功率低于 100 kW 的空基 Nd:YAG 激光器是使 ESD 快速进入致密大气层的最佳工具。

DF 地基激光系统能够与飞行轨道上经过该处的目标物快速耦合,并具有在单次行程中清除 ESD 的潜能。在每个脉冲内,只有很小的目标物质被烧蚀,因此生成其它危险性轨道碎片的可能性也最小。

激光系统需要与具有导星类波前校正能力的目标定位跟踪望远镜连接。

表 3 给出了 Nd:YAG 激光器的 LEO/MEO ESD 清除数据。ESD 的尺寸为 1 ~ 10 cm,在 300 km高度下飞行。对聚合物和铝基材料 C_m 值约为 4 dyn·s/J。ESD 的典型 S/m 数据 NaK-1.75、Al-0.37、Fe-0.15 均取自表 1。对于 $I=3.0$ J/cm^2 且 $S/g=0.15$ cm^2/g 的情况,需要$N=7\ 000$ 个激光脉冲使得 ESD 再次进入。在3 000 Hz下运行的 Nd:YAG 激光器能在 2.3 s 内从 1 ~10 cm 的间隙再次进入小物体。迄今为止,还未能证实 CW/P-P Nd:YAG 激光器的平均输出功率能达到 360 kW。为得到有效的清除结果,不仅需要激光,还需要直径为 30 m 的望远镜,以便在 10 ns 的持续时间内将激光脉冲传送到 300 km 射程的目标物处。

表 3　Nd:YAG 激光器的 LEO/MEO ESD 清除数据

λ	τ	D_b	W	f	$\langle P \rangle$	d_s	Z	I
1.06 μm	10 ns	30 m	60 J	3 000 Hz	360 kW(0.5)	5.2 cm 2Dif	300 km	3.0 J/cm^2

表 4 给出了 DF 激光器的 LEO/MEO ESD 清除数据。ESD 的尺寸为 1 ~10 cm,在 300 km 高度下飞行。平均值 $C_m=4$ dyn·s/J 仍适于相同的材料:聚合物和铝。当 $I=0.6$ J/cm^2, $t=10$ ns, $S/g=0.15$ cm^2/g 时,需要 $N=35\ 000$ 个脉冲使得 ESD 再次进入。在 10 kHz 下运行的地基 1.5MW DF 激光器能在 3.5 s 内从相同尺寸的间隙再次进入任何小物体。此操作需要一台直径为 30 m 的望远镜,以便在一个 10 ns 的脉冲内(3.8 μm)将 2 J/cm^2 ($C_m=0.2C_m^{opt}$)激光传送到 300 km 射程的目标物处。此处值得注意的是如果存在 1 min的重定位延时,激光器将只能在半年内再次进入在此高度及低于此高度的所有物体。还应当注意的是:CW 系统的输出功率水平已经过证实,而且技术已足够成熟。要实现这类激光器的 P-P 运行模式只是时间的问题,目前时机已完全成熟。在过去几年里研制高重复率高功率激光器的新任务非常重要[7-9],一定要在不久的将来解决。

表 4　DF 激光器的 LEO / MEO ESD 清除数据

λ	τ	D_b	W	f	$\langle P\rangle$	d_s	Z	I
3.8 μm	10 ns	30 m	150 J	10 kHz	1.5 MW	18 cm 2Dif	300 km	0.6 J/cm^2

3　结　论

利用平均功率为 100 kW 的高功率高重复率 P-P Nd:YAG 激光器和平均功率约为 1.5MW 的 DF 激光器使 SV 避免与直径为 1 ~ 10 cm 的危险 ESD 碰撞,并将这些 ESD 从轨道中清除。

分析了利用上述装置将危险 ESD 从 SV 轨道中移出并在这些装置扮演着轨道“清洁工”角色时,有计划地将这些 ESD 从最常维护的轨道中清除的可能性。为此,在辐射影响下,有必要将 ESD 从圆形轨道转移到椭圆形轨道。椭圆形轨道的近地点处于致密大气层中,ESD 可在那里被烧毁。由弹道问题的解决方案可知,ESD 需要从地表上空的 ESD 轨道高度处进行必要的减速。对于高度约为300 km的轨道,可通过安装有 $D = 30$ m 望远镜的 1.5MW DF 激光装置在约为 10 ns 的脉冲宽度内提供所需要的激光辐射能量。

如果与 SV 间最大接近速度约为2.5 km/s的金属 ESD 受到激光辐射的影响,那么在 ESD 最坏情况下的可接受条件是当使用主镜直径 $D = 1$ m 的望远镜时,空基 100 kW Nd:YAG 激光器的辐射角散度应当不次于两个衍射极限。

作者简介:

Apollonov V V(1945—),男,物理与数学博士,教授,俄罗斯自然科学院和工程科学院院士,高功率激光系统以及高功率辐射线 - 物质相互作用领域首席专家,欧美物理学会、SPIE、AIAA、美国量子电子学会会员,俄罗斯专业科学委员会会员,曾获得苏联国家奖章(1982 年)、俄罗斯国家奖章(2001 年)。E-mail:vapollo@ kapella. gpi. ru