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High Repetition Rate P-P Lasers for Space Debris Elimination

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ABSTRACT

Studies show that the number of debris in Low Earth Orbit is exponentially growing despite future debris release mitigation measures considered. 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 which can remove at low expense and in a non-destructive way hazardous debris around selected space assets appear as a highly promising answer.

Introduction

For the lasers with a high average output power (GDL, HF/DF, COIL, Nd YAG) 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, 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 of laser versions with radiation self-injection into the paraxial resonator region. However, 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, 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 to play 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 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 1/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. 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. The injection beam energy should be high enough to exceed, after its arrival to the resonator axis, the saturation energy of the active medium.

P-P mode of operation was realized in two type of lasers theoretically and experimentally, in a gas-dynamic CO_2 and Nd YAG lasers [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 $\tau=0.92*10^{-4}$ s, the relaxation time $\tau_p=2.76*10^{-4}$ s, the total go-round resonator time $\tau_f=4.2*10^{-9}$ s, the luminescence lifetime τ_l =5 s, the resonator magnification factor M=1.45, the diameter of output laser aperture a=0.08 m. Nd YAG – laser was above of 1kW 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 4 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 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

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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. Theoretically P-P modes of regenerative amplification for high power lasers 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 below:

COIL P-P mode starts at frequencies > 20 kHz.
Depth of modulation -100% at frequencies > 100 kHz.
Pulse duration < 250 ns. Ratio P peak. / P aver. = 100 -1000.
HF/DF P-P mode starts at frequencies > 100 kHz.
Depth of modulation -100% at frequencies > 250 kHz.
Pulse duration < 100 ns. Ratio P peak. / P aver. = 100 -10000.
Nd YAG P-P mode starts at frequencies > 4 kHz.
Depth of modulation -100% at frequencies > 40 kHz.
Pulse duration < 250 ns. Ratio P peak. / P aver. = 100 -1000.
CO P-P mode starts at frequencies > 10 kHz.
Depth of modulation -100% at frequencies > 100 kHz.
Pulse duration < 250 ns. Ratio P peak. / P aver. = 100 -1000.

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 use for cleaning of the space from elements of space debris (ESD).These elements have collected over more than four decades of operation of space and created, in some cases, a big threat for 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 a diameter from 1 to 10 cm, the size nearby 8000 ESD exceed 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 maneuvering of SV. Experts estimate that splinters in diameter less than 1 cm do not represent special danger for existing SV. This is due to the presence of passive constructional protection although it makes SV considerably more heavy. 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 collision at the expense of maneuvering SV is impossible as on the radar screen such splinters are not visible.

In low orbits under the influence of atmosphere quickly enough there is their self-clearing as time of life ESD in orbits with height about 200 km averages about one week. In higher orbits in height their self-cleaning can occupy of 600 km 25 - 30 years, and at heights about 1000 km - 2 thousand years [5]. Our estimations have shown that the probability of collision SV in diameter of 10 m within one year of its operation makes 0,45 10-2 for ESD with a size 2 … 4 cm and 0,4 for ESD with a size < 0,4 cm, and frequency of collisions with the catalogued objects (≥10 cm) is at level of one collision for 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 SV is a real problem. For this purpose it is necessary to reduce speed of ESD`s movement. As it will be shown further, it is possible to reach at the expense of pulse irradiation ESD and reception on its surface of the plasma creating an impulse of return. Such impulse arising in a mode of laser ablation of ESD material, should reduce height of orbit ESD so that it has flown by SV or, finally, would enter into dense layers of atmosphere and has burnt down.

Several previous studies offered to use the Nd YAG ground based laser installations for space clearing, but such laser lacks connectivity with the passage of 1 mkm radiation of the big capacity through atmosphere that can lead to loss of optical quality of a bunch of radiation and occurrence of nonlinear effects They have small mobility, therefore number of ESD that can be influenced by radiation, will be limited. At 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 stoped by dense atmosphere. And the most important thing - requirements to 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 more. For these reasons for the most expedient arrangement of Nd YAG 100kW laser installation directly in space is recommended. Thus it is desirable, that such installation power consumption should be minimal. This condition satisfies Nd YAG with LD pumping, 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, which radiation propagation through the atmosphere is much more effective and the output power of existing systems (>1,5MW) and technology are more advanced.

In the paper [5] the most possible variants of rapprochement ESD, flying, as a rule, on elliptic orbits, with various SV, moving on circular orbits at heights 200 - 700 km have been analyzed. Two variants when SV moves on a circular orbit at height of 400 km have appeared the worst, and ESD fly on elliptic orbits with height of apogee - 2000 km and - 4000 km. In this case in a perigee there are areas where planes of orbits SV and ESD coincide, and 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 to ESD a lateral component of speed, as in more opportunity of 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 made accordingly - 395 m/s and - 2463 m/s. For circular orbits with height 200, 400 and 700 km settlement of rapprochement ESD speeds, flying on circular orbits, with SV do not exceed 343 m/s, therefore these variants can be neglected.

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

$$\frac{m\upsilon_0^2}{R+H} = \gamma\frac{mM}{(R+H)^2},$$

Where Vo - speed of movement ESD on a trajectory before influence of a laser impulse, R - radius of the Earth, H - height ESD over the Earth, M - weight of the Earth, γ - a gravitational constant, m - weight ESD after such influence on ESD this balance will be broken; then the reduction of ESD speed □□

will force the normal acceleration in the direction to the centre of the Earth:

$$a_{\text{H}} = -\frac{\gamma M}{(R+H)^2} + \frac{(\upsilon_0 - \Delta\upsilon)^2}{R+H}$$

Where Δυ - change of ESD speed after laser pulse influence (typical value Δυ makes ~ 200 km/s [7]). After simple transformations from (1) we will receive

$$a_{\text{H}} = \frac{-2\cdot\upsilon_0\cdot\Delta\upsilon + \Delta\upsilon^2}{R+H}.$$

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

$$\Delta H = \frac{a_{\text{H}}t^2}{2} = \frac{\Delta\upsilon\cdot(\Delta\upsilon - 2\upsilon_0)}{R+H}t^2$$

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

$$t = \frac{\lambda}{\upsilon_{\text{т}}} = \frac{\lambda}{\upsilon - \Delta\upsilon}$$

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

$$\Delta H = \frac{\Delta\upsilon\cdot(\Delta\upsilon - 2\upsilon_0)}{R+H}\frac{\lambda^2}{(\upsilon - \Delta\upsilon)^2}$$

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:

$$\lambda = (\upsilon - \Delta\upsilon)\sqrt{\frac{\Delta H\cdot(R+H)}{\Delta\upsilon\cdot(\Delta\upsilon - 2\upsilon_0)}}$$

Proceeding of the SV dimensions, we will be set by size *ΔH* = 30 m. Then for the first variant of rapprochement ESD to SV at V rapp. = 395 m/s, Δυ = 200 m/s, Vo = 8 km/s, *H* = 400 km, R ≈6300 km the distance between will make 4,1 km. This way will be passed in time ~ 20 s. Then for metal ESD at typical values $C_{\text{m}}^{\text{опт}}$ = 4 din-s/J and *S/m* = 0,15 sm2/g we will receive Δυ = 6 cm/s, and the necessary number of pulses for the value Δυ = 200 m/s will make 3300 pulses at frequency of high repetition rate Nd YAG laser - 3000 Hz necessary time of influence 1,1s, which is much less than 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 big speeds of rapprochement it is necessary to consider dynamics of change of values Δυ and current distance between ESD and SV after influence of each laser pulse of P-P irradiation of ESD.

For the second variant with very great speed of rapprochement V rapp = 2463 m/s at Δυ = 200 m/s and much bigger distance - 20 km the rejection is possible as well. However, maintenance of Δυ at the distance - 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 that ESD has flown by SV has been considered above. Other problem is also important - 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 will be burned down, and the space will be cleared from ESD. In other words, SV with laser installation will carry out a role of "cleaner" of the most used orbits. That particle ESD has decreased to 200 km over the Earth surface, its speed needs to be reduced by certain value Δυ which will allow it to pass from a circular orbit on elliptic which exact value can be calculated as follows:

$\Delta\upsilon = V_{apogee} - V_{start}$,

Where Vapogee - ESD speed in apogee of a transitive elliptic orbit, V start - speed ESD in an initial circular orbit. Speed in apogee is:

$$V_{apogee} = \sqrt{\frac{2\cdot\gamma\cdot M\cdot Rstart}{r_{200}\cdot(r_{200} + Rstart)}},$$

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:

$$V_{start} = \sqrt{\frac{\gamma\cdot M}{Rstart}}.$$

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

Change of ESD speed Δυ after the influence of laser radiation pulse with energy density *E* [J/cm2] on ESD is defined from the following expression:

Δυ =Cm E S/m;

Where *S* - the interaction area, *m* - weight of ESD, Cm [din s/J] - proportionality factor between and *E*, depending on the ESD type . Characteristics of the most widespread of them are presented in the Table 1 [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 - fragments of connecting blocks armature.

Table 1. Cm(opt) and S/m for different ESD

	Type of ESD				
	Na (K)	"C"-based materials	Organics-based materials	"Al"-based materials	"Fe"-based material
Angle, (degre.)	65	87	99	30	82
Apogee, (km) Perigee, (km)	930 870	1190 610	1020 725	800 520	1500 820
S/m, (cm^2/g) size, (cm)	1,75 1,0	0,7 1×5	2,5 0,05×30	0,37 1×5	0,15 1×10
Reflectivity	0,4	0,02	0,05/0,7	0,05/0,7	0,5
$C_m^{opt}, \left(\frac{Din\ s}{j}\right)$	(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 100kW that we propose is the best tool for fast re-entering of the ESD to 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.

Table 2 presents the LEO / MEO ESD removal data for Nd YAG laser. ESD have a size 1 - 10 cm and fly below 300 km altitude. Cm = 4 dyn-s/J in average for polymer and "Al"- based materials response. Typical S/m data for ESD: NaK-1,75; Al-0,37;Fe-0,15 are taken from the Table 1. For I= 3.0 J/cm2, S / g= 0,15cm2 /g, we need N =7000 laser pulses for ESD re-entry. Nd YAG - laser operating at 3000 Hz can re-enter small object from the gap 1-10cm in 2.3 s. Such a level of average output power (360kW) 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 in diameter telescope to deliver the laser pulses to a target at 300 km range or more with 10 ns time duration:

Table 2. LEO / MEO ESD removal data for Nd YAG laser

λ	τ	D_b	W	f	<P>	d_s	Z	I
1.06 μm	10 ns	30 m	60 J	3000 Hz	360 kW (0,5)	5,2 cm 2Dif	300 km	3,0 J/cm 2

Table 3 presents the LEO / MEO ESD removal data for DF laser. ESD have the same size 1 - 10 cm and fly below 300km altitude. Cm = 4 dyn-s/J in average for the same materials: polymer and aluminum. With I = 0.6 J/cm2, t=10ns, S/g= 0,15cm2 /g, we need N = 35000 pulses for ESD re-entry. Ground based 1,5MW DF - laser operating at 10 kHz can re-enter any small object from the same size gap in 3,5 s. This operation requires a 30 m in diameter telescope to deliver 2 J/cm2 (Cm = 0,2 Cm opt) to a target at 300km range with a 10 ns pulse at 3.8 mkm: 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.

Table 3. LEO / MEO ESD removal data for DF laser

λ	τ	D_b	W	f	<P>	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

Conclusion

1. This paper presents SV protection and orbit clearing from dangerous ESD with diameter from 1 to 10 cm by means of high power high repetition rate P-P Nd YAG with an average power of 100kW and DF-lasers with an average power of about 1,5 MW;

2. The paper examines the possibility of applying 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" of these orbits. For this purpose under the influence of radiation it is necessary to translate ESD from a circular orbit to elliptic, which 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 height of their orbit over the Earth is received. Our paper finds that for orbits with heights up to ~300 km the demanded influence can be provided by 1,5MW DF-laser installation with a telescope with a diameter of -30m and duration of pulses about ten nanoseconds;

3. It is shown that for the worst variant in case of influence on metal ESD with the greatest speed of their rapprochement with SV ~2,5 km/s angular divergence of radiation of space based 100kW Nd YAG laser should not be worse than two diffraction limits at use of a telescope with diameter of main mirror D = 1 m is admissible.

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