

LASER APPLICATIONS

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Elimination of space debris and objects of natural origin by laser radiation

V.V. Apollonov

Abstract. **We discuss the application of ground-based repetitively pulsed, high-frequency DF-laser systems and space-based Nd : YAG-laser systems for elimination of space debris and objects of natural origin. We have estimated the average power level of such systems ensuring destruction of space debris and similar objects.**

Keywords: *space debris, high-power laser, space vehicles, objects of natural origin, surrounding space.*

1. Introduction

Space debris (SD) is a collection of man-made objects and fragments in space, which no longer serve any useful purpose, and objects of natural origin, such as meteorites, asteroids, etc. From the point of their origin we can single out several categories of space debris:

(i) spent rocket stages and detached stages;

(ii) old satellites;

(iii) products of anti-satellite tests and debris formed due to collisions of satellites;

(iv) objects of natural origin.

Most space debris is less than 10 cm in diameter. The most significant contribution to the 'littering' of the near-Earth orbits have been made by anti-satellite missiles used to destroy worn-out satellites, which led to the formation of new fragments ranging from centimetres to several metres in size. Explosions and unintended collision in space are the most dangerous sources of space debris. To date, the problem of protecting actively functioning spacecrafts (SCs) from collisions with man-made debris and objects of natural origin has become crucial due to the greatly increased density of SD in low Earth orbit (LEO), particularly in the vicinity of regular orbits of SCs. Virtually the entire man-made SD is metal fragments of the former SCs moving in elliptical orbits around the Earth. By their size they are divided into four categories: small (less than 1 – 10 mm), medium (1 – 10 cm), big (larger than 10 cm for LEO and larger than 1 m for geostationary orbits) and microfragments (less than 1 mm). The distributions of SD in size and damage as well as the ways of struggling with it are presented in Table 1 [1, 2].

V.V. Apollonov A.M. Prokhorov General Physics Institute, Russian Academy of Sciences, ul. Vavilova 38, 119991 Moscow, Russia; e-mail: vapollo@kapella.gpi.ru

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Large SD fragments can be observed by ground-based tracking systems: Many of them are tracked and catalogued.

Due to the presence of different space debris categories and methods of debris removal by different laser systems, one can single out the following independent tasks which differ in formulation, criteria for space debris irradiation and, correspondingly, in the average power and the output repetitively pulsed radiation parameters:

1. Avoidance of collisions between controlled space debris and spacecraft.

2. Spacecraft protection from collisions with approaching space debris.

3. Removal of space debris from LEO and GEO.

The first two problems are directly related to the protection of a particular spacecraft from space debris, whereas the third one refers to the task of global LEO and GEO cleanup.

The principle of debris removal by high-power repetitively pulsed lasers is very simple: Radiation of a laser system rapidly heats the debris surface and removes part of the material owing to evaporation. As a result, depending on the absorbed energy and the exposure time, the space debris can break down into smaller fragments which do not threaten the spacecraft, or can change the flight trajectory due to a recoil momentum, and prevent a collision with the spacecraft. Complete evaporation of small fragments of space debris is also possible. In the case of a low pulse repetition rate laser and insufficient impact on the object, it is necessary to catalogue it again (with the new parameters of the orbit) and repeat the procedure in some time. A significant increase in the pulse repetition rate of the laser can simplify the task and use every time only a series of pulses, thereby removing the SD object from the catalogue. Thus, the aim of this paper is to

Table 1.

Size of SD fragments	Number of SD elements (thousands)	Consequences of collisions	Ways of preventing collisions
Large	14 (under observation)	Loss of a spacecraft	Mechanical removal, maneuvering, laser removal
Average	300	Serious damage	Irradiation with a power up to 500 kW
Small	$(70-80)\times10^3$	Significant damage	Architectural protection, hardening
Microfragments	$(10-100)\times10^9$	Surface erosion	Not necessary

assess the prospects of using high-frequency repetitively pulsed lasers for effective elimination of space debris.

2. Ground- and space-based laser systems

Currently, chemical DF lasers are the most suitable for the task [3–5]. When a beam passes through the atmosphere, it is preferable to use a DF laser system (wavelength $\lambda_{DF} \sim 3.8 \times 10^{-4}$ cm). A necessary requirement to the laser system is a high quality output, providing the beam divergence, which is close to the diffraction limit. When a spaceborne laser system is used, advantage can be taken of a solid-state diode-pumped laser ($\lambda_{YAG:Nd} \sim 1.06 \times 10^{-4}$ cm). To remove efficiently the space debris, it is proposed to use high-power, high-frequency DF lasers and a solid-state laser. In this case, the peak values of the radiation intensity incident on the space debris increase by orders of magnitude as compared to the cw regime. The time between pulses is determined by the change of the active medium or by restoring the population inversion of a medium (in the case of a solid-state laser). Experiments performed at the A.M. Prokhorov General Physics Institute of the Russian Academy of Sciences showed that the optimal (in terms of the maximum energy output and effective overcoming of the plasma screen) modulation frequency of a DF laser is ~100 kHz, and the excess of the peak power over the average output power is 2–3 orders of magnitude [6, 7]. The pulse duration in both cases lies in the range of 10^{-7}–10^{-8} s. The ratio of the DF-laser powers in the cw and repetitively pulsed regimes was determined by taking into account vibrational kinetics. Radiation at various vibrational–rotational transitions in this regime was calculated using the equations for a free-running and Q-switched laser resonator. At low pulse durations (less than 100 ns) nonequilibrium distribution of emitting molecules over the rotational levels of the generation process was taken into account.

To solve the above-mentioned problems, use can be made of various laser systems, both with a ground-based and a space-based power plant: a stationary ground-based laser system (GBLS) ensuring beam focusing and pointing on a space debris fragment, and a standalone space-based laser system (SBLS) also ensuring beam focusing and pointing on a space debris fragment.

The space debris fragments that represent a threat to the spacecraft and the time of a possible future collision are well known. To remove the threat of a collision, it is needed to change the trajectory of the space debris so that the spacecraft is not hit by the fragment, or the threat of the next collision with the fragment is postponed indefinitely. Due to collision threat warning technology, there is an opportunity to remove a fragment many orbits before the collision. This problem can be solved with the help of ground-based DF lasers, which irradiate SD fragments from a mountain that is 2.5–3.5 km high. It is also possible to use mobile airborne laser systems that can be transported in the right spot at the right moment [8, 9]. However, this approach in comparison with the first two seems less effective.

A stationary GBLS is used to destroy SD fragments moving at a low orbit over the laser. The beam impact is effective in the sector with a full opening angle of ~30° with respect to the vertical, and the region of interaction at a height of 300 km is a circle with a diameter of ~160 km. When flying over the Earth, the space debris leaves a spiral 'footprint' with a width of 160 km, making 16 orbits a day, which are spaced at a distance of about 2.5 thousand km from each other. Thus, ~5200 km of the circumference of the Earth is covered each day, and the entire circumference will be covered within 8 days on average. Therefore, stationary lasers are not always applicable to the task of removing SD threat; they can be used only when the global early warning system tracks a fragment in advance and the laser itself is mounted in the right place. However, in the case of a high-frequency repetitively pulsed regime there can arise a situation when the space debris fragment is destroyed per one orbiting over the stationary GBLS.

As a result of the beam action, the debris fragment and the spacecraft become spatially separated by the size of the interaction region. In the case of non-coplanar orbits, this region is on the order of the spacecraft size. In the case of close-to-coplanar orbits the interaction region is much larger with the borders of this region being within the distance of the spacecraft size. For estimates we consider the following example. Let a space vehicle with characteristic dimensions $L_{SV} \sim$ 100 m move along a circular orbit at a height of $H = 300$ km at a speed $v = \sqrt{\gamma M/(R_E + H)} \sim 7.73 \times 10^5$ cm s^{-1} (where γ is the gravitational constant; and M and R_E are the Earth mass and radius, respectively) and an orbital period $T = 2\pi(R_E + H)/v \sim 5.42 \times 10^3$ s ≈ 90 min. Let the fragment move along the same trajectory. We shall consider the impact of the laser pulse at the fragment instantaneous, which increases its speed by Δv. Then, it is easy to obtain that the orbiting period will change by $\Delta T = 3T\Delta v/$. During one orbiting of the fragment the travelled distance will change by $\Delta S = 3T\Delta v$. To reach $\Delta S > L_{SV}$ it is needed to change the speed of the SD fragment by $\Delta v > L_{SV}/3T = 6$ mm s^{-1}. If irradiation has been performed during N orbits before the collision, the necessary change in the speed is reduced by N times. For example, with the fragment irradiated prior to 100 orbits before the collision, the 100-m spatial separation between the debris and the spacecraft is achieved at $\Delta v \sim 0.06$ mm s^{-1}. Therefore, one must first choose the number of orbits before the first irradiation, the recoil momentum and the number of pulses needed to remove the space debris fragment from the spacecraft trajectory [1–5].

Consider the mechanism of irradiation of a metal space debris fragment. Metals are good absorbers of radiation in the mid-IR range. It is known that radiation in metals is absorbed in the skin-layer. During radiation absorption at a depth of 0.05–0.1 μm, the melting and evaporation zone is localised. In this case, because of a drastic metal expansion in the interaction zone, a part of the melt is removed in the form of droplets. In the absence of gravity, this effect is most pronounced: liquid droplets are quickly destroyed by heating, because the internal pressure overcomes the surface tension before the process of intense evaporation and the melt cannot be kept on the surface. Thus, the task is to provide the conditions for intensive evaporation of the SD material. In this case, using a pulse train we should 'pump' the required energy into a thin surface volume before thermal expansion throughout the entire volume of the material, which ensures the destruction of the SD surface and formation of a mechanical recoil momentum [10, 11].

At a power density $I > 10^5$ W cm^{-2} and high-frequency (above 10^4 Hz) irradiation, the debris material is fairly intensively evaporated. For fusible materials the threshold intensity is lower. The irradiation of the debris can be called 'soft.' Since the recoil momentum of each pulse is small enough, the addition of pulses at a high frequency of the repetitively pulsed regime leads to significant mechanical interaction [12–14]. We have carried out assessments for a laser system based on a DF laser. For the altitude of the orbit in question, when the diameter of the telescope is D = 3 m, I_{th} = 100 KW cm^{-2}, and the laser spot diameter on the target is d = 2.8 m, the DF-laser average powers P_{av} at pulse durations τ = 10 and 100 ns and pulse repetition rates f = 10 and 100 kHz are as follows: P_{av} = 120 MW (τ = 100 ns, f = 100 kHz), 25 MW (100 ns, 10 kHz), 25 MW (10 ns , 100 kHz) and 6 MW (10 ns , 10 kHz).

At the required powers the beam divergence equal to three diffraction limits at the laser output, $\Delta\theta \sim 3\theta_d$, seems to be sufficient to solve the problem. Moreover, propagation in the atmosphere introduces additional beam distortions and absorption losses. When the light spot is circular, the divergence (full angle) $\Delta\theta$ will be $\sim 3\theta_d \approx 2.44\lambda_{DF}/D \approx 9\times10^{-6}$ rad. When focusing laser light on a target at a height H = 300 km, the spot diameter is $d = H\Delta\theta \simeq 2.8$ m. Therefore, to ensure the emission intensity $I_{peak} = 10^5$ W cm^{-2} on the target, an average peak pulsed power at the output telescope mirror (excluding losses during the beam propagation) must be equal to $P_{peak} = 10^5\pi d^2/4 \approx 6\times10^9$ W. Let us now estimate the expected time-averaged power of the DF laser with a pulse duration of ~ 100 ns. Because the characteristic time of energy accumulation in the active medium is ~10 μs, then at a characteristic pulse duration of ~100 ns (duty cycle is equal to 100), the average power of the repetitively pulsed DF laser should be equal to 60 MW. However, due to strong relaxation in the medium at the moments when lasing is absent, transition from continuous operation to the repetitively pulsed regime is accompanied by a substantial energy loss, which is ~50% of the average output power. Therefore, at a pulse duration ~100 ns and the beam divergence $3\theta_d$ an average power of ~120 MW is required. At ~10 ns and f = 100 kHz, the peak power of the laser pulse can exceed the average power of the laser in the repetitively pulsed regime by virtually 10^3 times. However, in the absence of rotational equilibrium of emitting molecules, the laser power relative to the equilibrium case further decreases. The necessary level of the average laser power in the repetitively pulsed regime decreases with the rotational equilibrium taken into account by approximately 3–4 times as compared to the cw laser and at the divergence $3\theta_d$ will be equal to ~25 MW.

For comparison, we have estimated the average laser power at a pulse repetition rate of 10 kHz for two pulse durations – 100 and 10 ns. However, the values of the average laser power in these cases (25 and 6 MW, respectively) prove unreasonable. Consideration of irradiation regimes at higher repetition rates in this case does not make any sense, since the required average powers turn to be considerably larger.

In principle, one could try to further reduce the laser pulse duration down to 1 ns. All other things being equal, it would enable us to decrease the average power of the DF laser by one more order of magnitude, which at the divergence $3\theta_d$ will be equal to ~2.5 MW. However, we should keep in mind that it is virtually impossible to obtain at these ultrashort pulses a beam divergence, which is close to the diffraction limit (for such a short time the mode structure of the radiation field in a cavity does not have time to form – the round-trip time for light in the cavity is ~10^{-8} s at the time of the pulse existence ~10^{-9} s). A solution to the problem by shortening the master oscillator pulse is limited by a threshold condition for lasing. Moreover, the weak power of the master oscillator requires a significant lengthening of the active medium of the amplifier, which further complicates the solution of problems related to the amplified spontaneous emission suppression.

The above estimates are consistent with a minimum achievable recoil momentum in the laser radiation–refractory target surface interaction. It is assumed that this is sufficient when the onset of irradiation is appropriately chosen in order to remove a space debris fragment from the interaction region of the spacecraft's and debris fragment's orbits. For more fusible materials requirements to the average laser power are less stringent. It is clear that the increase in the average power of a laser source simplifies the solution to this problem, thereby making it possible to use fewer pulses and to eliminate the need to catalogue space debris.

3. Protection of spacecrafts from collisions with space debris

Protection of a spacecraft from collisions with space debris or objects of natural origin is needed when a spacecraft is subjected to the possibility of being hit by approaching uncontrolled space debris fragments or meteoroid particles, or by controlled fragments when their trajectories coincide with those of a spacecraft at some orbit. In this case, the fragment can be destroyed or removed from its orbit using a standalone space-based solid-state diode-pumped laser system, mounted directly on the protected spacecraft, or running along the same orbit near the spacecraft [13]. The laser must have sufficient electrical power to operate continuously in orbit. Effective irradiation of the space debris target becomes possible if the time of its detection does not exceed much the total time of target tracking, preparation of the device to shoot, power beam pointing, and duration of a pulse train. To remove the threat of a collision requires endowing the space debris fragment with such an amount of energy that the fragment will start braking and lag behind the spacecraft or its trajectory will change so much that it will miss the spacecraft. It is clear that the net effect on the target, compared to the stationary problem, should be much more powerful. This is accompanied by intense evaporation of the space debris material; therefore, ionisation of vaporised molecules and plasma formation are also possible.

To evaluate the braking effect, there exists a semi-empirical formula, which shows that under the action of the laser pulse, the fragment velocity Δv, associated with the absorbed pulse energy, changes due to the expansion of the plasma produced: $\Delta v = C_m E/m$, where E is the absorbed energy; m is the mass of the target; C_m is a coefficient determining the efficiency of the radiation energy used for evaporation and to a large extent depending on the type of target material, the radiation intensity I_{peak} and pulse duration τ [8]. Below we present the experimental data on the optimal (with maximum C_m) peak intensity I_{peak} as a function of τ. Thus, when τ = 100 ns, $I_{peak} = 2\times10^8$ W cm^{-2}, and when τ = 10 ns, $I_{peak} = 6\times10^8$ W cm^{-2}, i.e., $I_{peak} \sim 1/\sqrt{\tau}$. When the intensity deviates from the optimal value, the laser action decreases rapidly; therefore, we assume that the peak intensity is optimal. It is well known that the power density of ~10^8 W cm^{-2} is widely used for laser drilling and cutting of materials under sublimation or ablation. This irradiation regime compared to that previously discussed can be called 'hard.' In the interval between two successive pulses at a repetition rate of ~ 100 kHz the plasma expanding into vacuum has time to travel a sufficient distance in order to prevent the absorption of the next laser pulse energy away from the target. Assessment of the impact of molecular absorption on the efficiency of the laser radiation passing through the atmosphere shows the advantage of the DF-laser radiation over the Nd : YAG-laser radiation. The integral attenuation coefficient in the case of the DF laser is two times lower in comparison with that of the Nd : YAG laser. The average powers P_{av} of a repetitively pulsed solid-state laser with a mirror diameter $D = 3$ m, operating at $f = 100$ and 10 kHz in the case of optimal irradiation of the SD at a distance $L = 100$ km to the object and at a divergence θ_d for the pulse durations $\tau = 100$ and 10 ns are as follows: in the 'hard' regime ($D = 3$ m, $I_{th} = 1$ GW cm^{-2} , $d = 0.08$ m) $P_{av} = 1200$ MW ($\tau = 100$ ns, $f = 100$ kHz), 120 MW (100 ns, 10 kHz), 120 MW (10 ns, 100 kHz) and 12 mW (10 ns, 10 kHz); in the 'soft' regime ($D = 3$ m, $I_{th} = 10$ MW cm^{-2} , $d = 0.08$ m) $P_{av} = 12$ MW (100 ns, 100 kHz), 1.2 MW (100 ns, 10 kHz), 1.2 MW (10 ns, 100 kHz) and 120 kW (10 ns , 10 kHz).

Thus, space-based diffraction-limited repetitively pulsed solid-state diode-pumped lasers with an output power of 100–1000 kW and a pulse duration $\tau \sim 10-100$ ns will provide in the 'soft' regime the necessary impact on a space debris fragment at an aiming distance of 100 km. The light spot on the fragment at this distance will be within 8 cm.

The use of ground-based DF lasers for the spacecraft protection is possible when a receiving mirror is installed on the spacecraft. However, this variant is suitable only when the point of collision of a spacecraft with a space debris fragment lies in the region of the GBLS action, which is a highly unlikely event. However, we note that in this case the receiving mirror mounted on the spacecraft needs to be large enough to intercept the entire radiation beam. Estimates show that the required diameter of the receiving mirror, depending on the beam divergence, must be several meters. The use of a fully terrestrial laser system for 'hard' irradiation of the space debris fragment by a DF laser directly from the Earth would require a laser system with high average powers.

In the 'hard' regime ($D = 30$ m, $I_{th} = 10$ MW cm^{-2}, $d = 0.28$ m, DF laser, radiation divergence $3\theta_d$) the power $P_{av} = 60$ MW ($\tau = 100$ ns, $f = 100$ kHz), 24 MW (100 ns, 10 kHz), 6 MW (10 ns, 100 kHz) and 2.4 MW (10 ns, 10 kHz); in the 'soft' regime ($D = 30$ m, $I_{th} = 100$ kW cm^{-2}, $d = 0.28$ m, DF laser, radiation divergence $3\theta_d$) $P_{av} = 600$ kW ($\tau = 100$ ns, $f = 100$ kHz), 250 kW (100 ns, 10 kHz), 60 kW (10 ns, 100 kHz) and 25 kW (10 ns, 10 kHz).

From these estimates it is clear that effective elimination of the SD fragment is quite possible, since the required level of the average power of chemical lasers has been already reached and we only need to use them in the repetitively pulsed regime with a minimum loss of the average power of the system.

4. Orbital debris clearing

Clearing orbital debris with lasers is possible through the use of a standalone space-based DF laser with a focusing and beam pointing systems. To speed up the fall of a space debris fragment to the atmosphere requires the fragment braking and transfer to a lower altitude with a shorter 'lifetime.' It is known that the dwell time ('lifetime') of a space debris fragment in orbit is highly dependent on the height of the orbit. According to the data available in the literature, the lifetime of a fragment at an altitude of 1000 km is about 2000 years, at an altitude of 600 km it is ~25–30 years, at an altitude of about 200 km – about a week. In the altitude range of 100–1000 km the dependence of the space debris fragment lifetime on the height above the Earth can be approximated in accordance with these data as $t \sim h^7$. With such a strong height dependence even a small deceleration and a decrease in orbit leads to a significant reduction in SD lifetime. Thus, the lifetime decreases from 120 to 6 days with decreasing orbit from 300 to 200 km.

The estimates of the efficiency of SD elimination require special modelling and calculations for each particular orbit and space debris type. Theoretically, in the entire range of laser irradiations (from 'soft' to 'hard'), the fall of space junk on the Earth is accelerated. As follows from the estimates, in the 'hard' regime a train of high-power laser pulses (when a fragment flies over the stationary laser) can lower the orbit of a space debris fragment to the required level. If this fragment enters the upper atmosphere ($h \sim 100$ km), it slows down and burns out during 1–2 orbits, i.e., the problem is solved. However, this formulation seems excessive, because it is quite often sufficient to lower the fragment's orbit, so that its orbit is below that of the spacecraft.

Based on the available literature data, we can assert that the space-based laser power of about several tens of kilowatts is sufficient to significantly reduce the lifetime of a small SD fragment. Naturally, the further increase in the laser power further reduces the lifetime, i.e., increases the effectiveness of the fragment entry to the atmosphere; therefore, near-Earth space debris can be rather rapidly cleared using a standalone SBLS with an output power of several hundred kilowatts. The number of laser shots will be determined by the accuracy of direct hits and the time needed for a space-based laser to become operational again.

When use is made of a ground-based laser system with a receiving mirror installed on a spacecraft, the energy loss during the passage of radiation through the atmosphere and the mirror loss will require a much more powerful installation (apparently, several megawatt). The number of laser shots is determined by the number of passes of the mirror over the ground-based laser (on average no more than once every 8 days) and the probability of the fragment location within the laser hitting range in these periods. In this case, less laser shots are needed compared to the case when use is made of a standalone SBLS. However, possible is an alternative of simultaneous maintenance of many SD objects, but then the problem is complicated by the need for constant cataloguing of such objects.

Finally, we note that a more detailed study of the problem presented, in particular, the effect of the pulse repetition rate and duration, relative velocities of the space junk, laser power, etc. on the space debris destruction should rely on a more accurate mathematical modelling of generation processes in a high-frequency repetitively pulsed laser, radiation propagation in LEO at different altitudes, effectiveness of repetitively pulsed radiation action on space debris of different origin, etc. Different variant of laser systems discussed in this paper can find application not only in the problems associated with SD, but also in other research projects. In particular, their application is expedient in designing and fabricating laser rocket engines, in wireless transmission of energy over long distances, in cleaning the surface of water from the oily products, in cleaning long and complex surfaces from dirt, in protecting the most valuable and ecologically dangerous objects from lightning, and in some special applications.

5. Conclusions

1. Repetitively pulsed laser systems with a high repetition rate are an important tool in solving the problem of efficient elim-

ination of space debris and objects of natural origin or their removal to a safer orbit.

2. The problem of advance protection from space debris can be solved with the help of ground-based high-frequency repetitively pulsed DF lasers directly irradiating the debris from the Earth in the 'hard' regime, when the size of the telescope mirror is 30 m. At $\tau \sim 10$ ns and $f = 10$ kHz the laser system should generate an output no less than ~2.4 MW. In the 'soft' regime, the average output power of the laser system is lower, i.e., no more than 600 kW.

3. The problem of protecting the spacecraft from space debris or meteor particles can be most effectively solved with the help of a standalone space-based high-frequency repetitively pulsed solid-state laser system mounted on a spacecraft, or near it. In the 'soft' regime the spacecraft can be reliably protected at a distance of ~100 km. When the size of the telescope mirror is about 3 m the average output power of a Nd:YAG laser system lies in the range 100 kW to 1 MW, depending on the pulse repetition rate and duration.

References

1. Phipps C.R., Michaelis M.M. *Proc. SPIE Int. Soc. Opt. Eng.*, **3092**, 728 (1997).
2. Campbell I.W. *Project «ORION//NASA: Techni. Memorandum»*, 108522 (1996).
3. Apollonov V.V., Vagin Yu.S. RF Patent No. 2400005 (May 20, 2009).
4. Apollonov V.V., Alcock A.J., Baldis H.A. *Opt. Lett.*, **5**, 333 (1980).
5. Apollonov V.V., Kijko V.V., Kislov V.I., Suzdaltsev A.G. *Kvantovaya Elektron.*, **33** (9), 753 (2003) [*Quantum Electron.*, **33** (9), 753 (2003)].
6. Bashkin A.S., Gurov L.V., Katorgin B.I. *Kvantovaya Elektron.*, **38** (5), 429 (2008) [*Quantum Electron.*, **38** (5), 429 (2008)].
7. Apollonov V.V., Pletnev N.V. *Progr. Symp. ISBEP-7* (Ludwigsburg, Germany, 2012) p. 17.
8. Phipps C.R., Luke J.R., Funk D.J., Moore D.S., Glownia J., Lippert T. *Proc. SPIE Int. Soc. Opt. Eng.*, **5448**, 1201 (2004).
9. Kuznetsov L.I., Savitchev V.Yu., Tikhonov N.N. *Kvantovaya Elektron.*, **25** (4), 372 (1998) [*Quantum Electron.*, **28** (4), 361 (1998)].
10. Apollonov V.V., Kijko V.V., Kislov V.I., Tischenko V.N. *Proc. SPIE Int. Soc. Opt. Eng.*, **5777**, 1011 (2005).
11. Apollonov V.V., Grachev G.N., Gulidov A.I., Tishchenko V.N. *Kvantovaya Elektron.*, **34** (10), 941 (2004) [*Quantum Electron.*, **34** (10), 941 (2004)].
12. Apollonov V.V., Kijko V.V., Kislov V.I. *Progr. Symposium HPLS@A-2012* (Istanbul, 2012) p. 25.
13. Apollonov V.V. *Laser Phys. J.*, **23**, 1 (2013).
14. Apollonov V.V. *Chinese Opt.*, **1**, 1 (2013).