I R A M P
14(1), Jan 2023, pp. 13-17

ISSN: 2229-39-44

New Principles for Developing Gamma-Ray Directed Energy Sources Including Gamma-Ray Lasers

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ABSTRACT: Presented are advanced designs of gamma-ray sources of directed energy, including gamma-ray lasers. One concept is based on the self-channeling of a powerful optical laser in a gas within a metal tube. Another concept employs a direct excitation of a quadrupole nuclear level by a powerful optical laser. The third concept is based on the process of a high-order harmonic generation by an x-ray laser. All three concepts can be used for designing gamma-ray lasers that would have significant advantages over x-ray lasers. First, missile defense systems employing gamma-ray lasers would be weather independent. Second, the gamma-ray laser radiation can penetrate through the sand, which could be suspended in the air in a desert either naturally (due to strong winds) or artificially (as a protective "shield"). Besides, the first out of the three concepts can be employed for creating non-laser gamma-ray sources of directed energy to be used for detecting stored radioactive materials, including the radioactive materials carried by an aircraft or a satellite. Last but not least: these concepts can be also used for remotely destroying biological and chemical weapons as a preemptive strike or during its delivery phase, as well as for distinguishing a nuclear warhead from decoy warheads.

Kewords: gamma-ray lasers; directed energy sources; self-channeling; quadrupole nuclear levels; high-order harmonic generation

1. INTRODUCTION

Powerful x-ray lasers are available for quite some time [1]. They have found various civil applications [1], as well as limited military applications. The latter application are limited because x-rays do not penetrate through the clouds in the atmosphere, thus making weather-dependent any possible missile defense system based on them. Also, x-rays do not penetrate through the sand, which could be suspended in the air in a desert either naturally (due to strong winds) or artificially (as a protective "shield").

In distinction, the radiation of gamma-sources of directed energy, including gamma-ray lasers, would be free from these drawbacks. First, missile defense systems employing gamma-ray lasers would be weather independent. Second, the gamma-ray laser radiation can penetrate through the sand suspended in the air in the desert.

Besides, non-laser gamma-ray sources of directed energy can be used for detecting stored radioactive materials, including the radioactive materials carried by an aircraft or a satellite. Such sources can be designed for specific energies of gamma-quanta to cause a resonant nuclear photoexcitation of stored radioactive materials and to enable observing a characteristic time-delayed response of the stored media.

Also, gamma rays can penetrate through containers where biological or chemical weapons are stored and make these weapons ineffective. For biological weapons, the effect of gamma-rays is based on the fact that, when it kills one cell in a biological medium, all the neighboring cells will also die. (A weak gamma-radiation is already used for preserving corpses: it stops all cellular decay processes – just as it would stop all cellular reactions.) For chemical weapons, gamma rays can change the nuclear charge the nuclei inside the molecules of the chemical weapon. This change of the chemical formula can be such chosen that the new chemical substance would not be lethal.

Advanced gamma-ray directed energy sources can also destroy biological and chemical weapons during its delivery phase. Last but not least: these advanced sources can be designed such as to distinguish a nuclear warhead from decoy warheads – by causing a resonant nuclear photoexcitation in the warhead and observing a characteristic time-delayed response.

Concepts of gamma-ray sources of directed energy (including gamma-ray lasers) considered in the past were based ither on the Moessbauer effect or on the isomer scheme. However, these schemes were rather exotic and very far from practical implementations [2-4]. In the present paper we bring up more advanced concepts suitable for the practical design of gamma-ray sources of directed energy.

2. SELF-CHANNELING OF A POWERFUL OPTICAL LASER IN A GAS WITHIN A METAL TUBE

The propagation of a powerful radiation of an optical laser in a gas f light atoms (H, He, …) creates a plasma out of it and leads to the phenomenon of "self-channeling" [5].The ponderomotive force of the laser beam quickly removes free electrons from the channel area. The remaining ions start repelling each other. Due to the cylindrical symmetry, there begins the radial outflow of ions where the ions can reach energies up to tens of MeV inside the channel. The idea is to create this kind of the situation inside the metal tube and to use these accelerated ions as the projectiles to bombard metal atoms having short-lived (collective) excited states in their nuclei. The excitation mechanism is the well-known Coulomb collisions.

We consider, as ^{a9n} example, the nucleus ^{140}Ce, where the first quadrupole level 2+ (belonging to the first rotational band) of the energy 2.522 MeV would serve as the upper level for the gamma-lasing and the first octupole level 3- of the energy2.464 MeV would serve as the lower level for the gamma-lasing. The level 3- has a very low population rate by the Coulomb collisions from the ground state, because the latter is the dipole transition. Thus, these levels are well-suited for the gamma-lasing at the energy $\Delta E = 2522$ keV – 2464 keV = 58 keV.

By employing an optical laser of the energy 1 – 10 J in a pulse of 1 – 100 fs and using a Ce-tube of the inner radius ~0.1 mm and the outer radius ~ 0.2 mm, the length of the tube being L ~ 1 cm, one should b able to demonstrate the gamma-lasing gain $g = 3$ cm^{-1} and the gain-length product $gL = 3$.

Let us now compare the effect of such gamma-ray laser with the effect of a nuclear bomb explosion. The latter yields up to 10^{28} gamma-quanta (assuming 10^3 kg of the active medium in the nuclear bomb where each nucleus produces one gamma-quantum). This means that at the distance of 1 km, the nuclear bomb explosion creates the radiation density about 10^{17} gamma-quanta per cm^2, integrated over time.

In comparison, the radiation density of our gamma-ray laser will be about 10^9 gamma-quanta per cm^2 in a pulse of about 1 ns. Thus, the gamma-ray power density of our gamma-ray laser will be significantly higher than in the nuclear bomb explosion. This gamma-ray laser could have a repewould tition rate up to 10kHz depending on the pumping source.

Let us now evaluate how far this gamma-ray beam can propagate without a significant divergence. This distance can be estimated as

$$L \sim kd^2, \tag{1}$$

where k is the wavenumber of the gamma-radiation and d is the diameter of the gamma-ray beam. For the gamma-quanta of the energy ~ 1 MeV in the beam of the diameter ~ 0.1 mm, we get L ~ 100 km.

Thus, our gamma-ray laser not only would produce the gamma-ray power density than in the nuclear bomb explosion, but would also deliver this power density to significantly greater distances than the nuclear bomb explosion. Consequently, it could serve as a much better defensive destroyer than the nuclear weapon – for remotely destroying any biological weapon and to convert chemical weapons into non-lethal chemical substances. It would be also able to penetrate into warheads and make it possible to distinguish the nuclear warheads from decoys.

The same design can be employed for creating non-laser gamma-ray sources of directed energy to be used for detecting stored radioactive material, including those carried by an aircraft or a satellite. In this case, it would be necessary to have specific energies of gamma-quanta to cause the resonant nuclear photoexcitation of the stored radioactive materials and to enable observing a characteristic time-delayed response of the stored media. For this purpose the pumping laser could be of a significantly smaller energy than for the corresponding gamma-ray laser: a standard laser of the energy ~ 100 mJ in a 100 fs pulse would be sufficient.

3. GAMMA-LASING IN THE PROCESS OF THE HIGH-ORDER HARMONIC GENERATION (HHG) BY AN X-RAY LASER

The HHG resulting from the irradiation of a gas by a powerful optical laser has become a commonly accepted alternative to creating x-ray lasers (see, e.g., 1, 6-8]. As the harmonic number increases, the harmonic intensity first decreases, but the reaches a “plateau”, extending to harmonic numbers as high as ~ (40-50). Thus, the HHG is the way to increase the frequency of the output laser radiation (compared to the input laser radiation) by almost two orders of magnitude without too much loss of the intensity. In papers [9, 10] the authors found a way to further advance the process of the HHG by employing so-called “dipole media”.

Many mappers were devoted to explaining the plateau and other features of the HHG spectrum. Some authors used numerical solutions of the time-dependent Schrödinger equation [11], while others employed simpler analytical models (see, e.g., 12-20]).

Most theoretical works on the HHG considered the situation where diagonal matrix elements of the dipole moment operator are zeros. In other words, it was assumed that the atom does not possess Permanent Dipole Moments (PDMs). However, it was shown in a number of papers [20-28] that th response of a quantum system (atom/ion/molecule) to the external electromagnetic field can be significantly modified if the system possesses PDMs.

One of the examples of such systems is certain types of polar molecules (see, e.g., [22]). Another example is an atom/ion possessing PDMs induced by a static electric field.

In papers [9, 10] the authors focused at studying the dependence of the HHG spectrum on PDMs for a two-level atom interacting with a laser field tuned to a multiquantum resonance with the atomic transition. Two-level systems are extensively used in calculations of the HHG because these systems are simple and can give physical and mathematical insights of the problem, despite they cannot give the correct behavior of all the features of the emission. The HHG in a two-level system possessing no PDMs was studied, for example, in [12,13,15, 18]. A distinctive feature of the works [9, 10] is the application of the averaging method by Krylov-Bogliubov-Mitropolskii [28, 29] while solving the Schrödinger equation for an atom interacting with the laser field.

The authors of paper [9, 10] showed that the HHG by PDM systems results in a *significant extension of the plateau to higher frequencies and to a slower decline of intensities at the frequencies greater than the end of the plateau*. Moreover, there occurs a *substantial growth of the total, summary intensity of all components of the scattering spectrum*.

The above important features can be physically interpreted as follows. The wave function of a two level atom possessing PDMs and subjected to the driving laser firl, is modulated in time in such a way that the modulation has both low-frequency component and high-frequency components. The temporal modulation of the wave function leads to the temporal modulation of the averaged dipole moment D(t). Two factors can cause the high-frequency modulation of D(t). The first factor (existing also for atoms/ions possessing no PDMs) is the oscillatory nondiagonal matrix element of the interaction with the driving field. The second factor (specific only for atoms/ions possessing PDMs) is the oscillatory difference of the diagonal matrix elemens of the interaction. *For sufficiently large values f the PDMs, the second factor can dominate and cause both the extension of the plateau to higher frequencies and the slower decline of the intensities at frequencies greater than the end of the plateau.*

The above advances make it possible to consider the following concept of a gamma-laser. Let an x-ray laser irradiate a plasma medium. Due to the process of the HHG, the output laser radiation would have a frequency about two orders of magnitude greater than the x-ray frequency, thus corresponding to the gamma-ray range. The efficiency of the HHG in this case can be also significantly enhanced by using the methods suggested in papers [9, 10].

Compared to the HHG under an optical laser radiation, there are several novel features of this design, as follows.

1. In the conventional design, the ratio of the size r of the atomic scatterer to the laser wavelength λ was $r/\lambda << 1$. In distinction, in the present design, this ratio could be in the range $0.1 \leq r/\lambda < 1$. Therefore, in the latter design, the electric-quadrupole radiation should be taken into account in addition to the dipole radiation.
2. For the same reason ($0.1 \leq r/\lambda < 1$), the propagation of the radiation n the scattering medium can differ from the conventional HHG.
3. It is known that the plateau in the harmonic spectrum ends at the energy

$$E \approx I + 3.17U, \tag{2}$$

where I is the ionization potential of the scatterers and U is the ponderomotive energy of electrons in the laser field. Therefore, there are two ways to increase the cutoff energy E and thus the efficiency of the HHG in this design:

A) to use scatterers of a high nuclear charge $Z \sim 90$ for increasing I;

B) to work with scatterers of smaller values of Z ($1 \leq Z < 30$), but to employ a higher power of the input laser for increasing U.

4. DIRECT EXCITATION OF A QUADRUPOLE NUCLEAR LEVEL BY A POWERFUL OPTICAL LASER

In this concept, the idea is a circularly-polarized radiation of a powerful optical laser to produce a collective excitation of a quadrupole nuclear level. In this case, the nucleus can be thought of as receiving an additional dipole moment. Therefore, it could be interpreted as a so-called "giant resonance" [30].

For widely available intensities of the optical lasers, the quadrupole nuclear excitations would be possible if the nonharmonic part of the nuclear potential is relatively small. Therefore, the best candidates would be nuclei having quasi-equidistant spectra of the lowest quadrupole states, such as, for example, ^{128}T. However, experimentally it would be better to deal with a gas rather than a metal. Nuclei of gaseous media, having quasi-equidistant spectral of the lowest qudrupole states, are ^{40}Ar, ^{132}Xe, and ^{134}Xe.

The most prospective candidates are ^{132}Xe and ^{134}Xe. Indeed, the 2+ qudrupole state of these nuclei have energies $\Delta E = 668$ keV and $\Delta E = 847$ keV, respectively. By employing a Nd-laser of the energy ~1 J in a pulse of ~ 1 ps, thus producing the power density ~ 10^{18} W/cm^2, one could excite $N \sim 2x10^6$ of ^{132}Xe or $N \sim 1x10^6$ of ^{134}Xe nuclei per shot. Each excited nucleus emits one gamma quantum of the corresponding energy. Therefore, the total number of gamma-quanta coincides with the above values of N. The angular distribution is expected to be $1 + \cos^2\theta$, where θ is the angle between the wave vector of the optical laser and the direction of the observation.

5. CONCLUSIONS

We discussed novel advanced concepts suitable for the practical design of gamma-ray sources of directed energy. One concept is based on the self-channeling of a powerful optical laser in a gas within a metal tube. Another concept employs a direct excitation of a quadrupole nuclear level by a powerful optical laser. The third concept is based on the process of a high-order harmonic generation by an x-ray laser. All three concepts can be used for designing gamma-ray lasers that would have significant advantages over x-ray lasers. First, missile defense systems employing gamma-ray lasers would be weather independent. Second, the gamma-ray laser radiation can penetrate through the sand, which could be suspended in the air in a desert either naturally (due to strong winds) or artificially (as a protective "shield"). Besides, the first out of the three concepts can be employed for creating non-laser gamma-ray sources of directed energy to be used for detecting stored radioactive materials, including the radioactive materials carried by an aircraft or a satellite. Last but not least: these concepts can be also used for remotely destroying biological and chemical weapons as a preemptive strike or during its delivery phase, as well as for distinguishing a nuclear warhead from decoy warheads. Thus, the defense capabilities of the proposed gamma-ray lasers can save numerous lives.

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