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Laser Technology and Weapons

By Apollonov V. V
Prokhorov General Physics Institute, Russian Federation

Abstract- The experience of designing strategic laser systems in the previous years and a strong belief in the attainability of the goal - the development of high-power laser weapons - help to significantly accelerate the pace of work in the field of new technologies. World press has recently published the articles where it was suggested that the anti-missile airborne laser project suffers cost overruns and delays and may fall victim to budget cuts. Just after that mass media immediately reported that the Pentagon refuses to develop combat lasers. As a result, there has appeared an epic set of myths about combat lasers. The task of this paper is to consider the most ridiculous statements and to reject them by sufficient analysis. An additional goal is to focus the interests of laser physics community to the mono-module disk laser geometry, which is possible now for implementation.

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LASERTECHNOLOGYANDWEAPONS

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Laser Technology and Weapons

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I. Introduction

The Wall Street Journal has recently published an article in which it was suggested that the anti-missile airborne laser (ABL) project suffers cost overruns and delays and may fall victim to budget cuts. Mass media have immediately happily reported that the Pentagon refuses to develop combat lasers. However, this euphoria seems very misleading, if not tougher.

Today, chemical lasers are being widely replaced by solid-state diode-pumped lasers. It is these lasers that the Pentagon counts on, because they are more compact, simpler and cheaper to use than chemical lasers. Besides, they are reliable, easily compatible (without any transformation of the output voltage) with nuclear and solar energy, allow for further scaling of output parameters and the efficiency of their operations is significantly higher. Northrop Grumman Corporation has already presented a 105-kW solid-state laser and intends to significantly increase its output power [1]. According to data from U.S. laboratories work is on the way to develop a prototype of a 500-kW laser. Subsequently, 'hyperboloids' will be truck-mounted [high energy laser technology demonstrator (HEL TD) program], ship-mounted [maritime laser demonstrator (MLD) project], and airborne [high energy liquid laser air defense system (HELLADS); a laser for F-35, B-1, CH-47 aircrafts). Another direction is largely supported by Raytheon, which stakes on fiber systems. A 50-kW laser weapon system (LaWS) will be integrated with the Phalanx Close-In Weapons System (CIWS) against anti-ship missiles and its land based version of Centurion C-RAM. In addition, the officials in the U.S. have recently reported on the progress of works on a combat free electron laser. At the same time, we should not forget about "Alpha" system (a laser with an output power of 4.5 MW), lying on the ground and waiting for the decision to be launched.

Anti-missile airborne laser

Brining solid-state lasers to megawatt powers takes time and considerable resources. However, the experience of designing strategic laser systems in the previous years and a strong belief in the attainability of the goal - the development of high-power laser weapons – help to significantly accelerate the pace of work in the field of new technologies. It should be noted, however, that tactical laser systems with lower power outputs have already been tested in the U.S. and now find applications in the army. All this testifies that the Pentagon experts clearly do not think about cancelling the promising laser programs. We are talking here about an effective system of disinformation. Last year's report 'Technology Horizons' by the Pentagon refers to the global changes in the 'rules of the game' after the proliferation of 'high energy weapons', which will turn the traditional symbols of military power into outdated stuff like cannonballs and cavalry... And while the U.S. develops laser programs, many other counties show 'laser apathy.' Incompetent bloggers and pseudoscientific workers, who had something to do with the laser program thirty years ago, speculate that 'lasers are a bluff.' As a result, there has appeared an epic set of myths about combat lasers. Consider the most ridiculous of them.

II. Ten Myths

a) *Myth 1. 'Combat lasers have been developed for four decades with no progress in sight.'*

Let us quote one of the Russian papers: "In the 1970s the Americans took a 150-ton Boeing-707 and 'stuck' a laser to it, which successfully burned small rockets. In the 2000s, they took a 350-ton Boeing-747 and 'stuck' a heavier and more powerful laser, which

Author: Prokhorov General Physics Institute, Russia.
e-mail: vapollo@kapella.gpi.ru

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successfully burned larger size rockets. In 20 years they will buy in Ukraine a decommissioned "Antonov AN-225 Mriya" (640 tons), and here it is, the Death Star [2]. Yes, probably it will be able to shoot down a "Scud", and even a "Taepodong". However, only at the site, and once, no more."

Under the '150-ton Boeing-707,' to which a laser was 'stuck,' is apparently meant a 137-ton Boeing KC-135 stratotanker based on the" 707 "of the first), modified in 1973 into NKC-135ALL [airborne laser laboratory (ALL)]. In 1983, a laser mounted on the aircraft shot down several Sidewinder air-to-air missiles at a distance of 5 km and some other 'little' things. What has changed since then? According to the above quotation – only the size of the aircraft.

Airbased military laser

But what about the reality? Even the so-called 'megawatt' CW lasers of the 1980s did not emit light at megawatt power levels, they consumed more power. The 2.2-megawatt Miracle laser system, which later in the combat version was called a tactical high energy laser (THEL) ('MIRACLE' with the 'SEALITE' guidance system) did not possess a supernatural power [3]. What to say about the earlier and five times weaker ALL. Has there been any progress since then? An ABL has a power of 1.1 MW and it is not the power to be consumed; this is the power in the beam. Thus, a 'more powerful' (50 times) laser was 'stuck' to a 350-ton Boeing... However, it should be understood that the actual capabilities of the laser rely not on the power as such, but on the concentration of the radiation, i.e., the ability of the 'guns' to emit not only a powerful, but also a narrow beam. The ALL had the level of the radiation concentration equal to 10^{13} J/(sr·s). An ABL has the level of about 10^{18} J/(sr·s) – that is, 10 thousand times higher. These achievements are made up not only of the straight-line growth in the power. The last 30 years have seen a period of extremely rapid development of adaptive optics to compensate for the effects of atmospheric turbulence and laser path on the transmitted beam. In addition, the lasers of the same class are radically reduced in size. The first version of a THEL weighed 180 tons and could be hardly installed into six trailers. The laser used a hydrogen–fluoride mixture which is very unfriendly to the environment. The second generation of advanced tactical lasers (ATLs) relies on oxygen–iodine mixtures [so called chemical oxygen–iodine lasers (COILs)] and is more compact. Finally, a new solid-state laser of Northrop Grumman weighs 1.5 tons, including the cooling system. In the future its weight is expected to be reduced to 750 kg. As a result, the land based version of the system consists of a heavy expanded mobility tactical truck (HEMTT A3), command post on a high mobility multipurpose wheeled vehicle and a towed single-axle trailer with the AN/MPQ-64 radar. At the same time, the U.S. works hard to convert the CW regime of the lasers in the pulse-periodic one, which will dramatically increase their range of actions.

Mobile laser system

Talks about the fact that "combat lasers have been developed for forty years and so they are hopeless," only show ignorance in technical matters. Breakthrough technologies are first tested for a few decades before the entry into a phase of maturity. Thus, aircrafts at the time of the first flight had almost 60 years of history – the first flying models were built in 1840 and the attempts to build full-size airplanes date back to 1868. It is, in fact, a classical scheme of development of any technology using new physical principles: First, a long 'incubation period' with no apparent practical results, and only then a 'great leap forward.'

b) *Myth 2. "Lasers cannot be used for a long time, usually they work several seconds."*

It is not so! In fact, chemical and solid-state combat lasers ensure continuous wave operation for minutes and tens of minutes. The next step in the development of high-power laser systems, of course, will be the implementation of a variable temporal structure of radiation in order to raise the peak radiation power for the ablation mechanism and to eliminate the effect of the screening of the target by plasma [4].

c) *Myth 3. "Energy of laser weapons is negligible compared to the fire arms."*

For comparison, the power of a 76.2-mm F-22 divisional gun (1936) is at 150 MW. This power is 150 times higher than that of the ABL! Besides, we ignore here the energy of the explosive in the shell, which is the same. Ponder upon this simple fact: A small ancient gun of the Second World for the price of scrap metal is hundreds of times more powerful than the ultramodern 'combat' laser weighing tens of tons and valued at over five billion USD. Only one shot from the ABL costs millions of dollars. And this shot comparable in energy with the burst of a machine-gun fire.

Such a comparison of the power achieved in 0.01 s with the power of CW light, and the 'proof' of inferiority of 'long-play' weapons (by using this comparison) contradicts even the school physics course. Let us try to compare everything in the correct way, i.e., by counting the energy sent to the target.

The muzzle energy of a 12.7-mm heavy machine gun is 15 – 17.5 kJ at a rate of 80 – 100 shots per minute. In other words, a 100-kW laser can be 'replaced' by three and a half heavy machine guns (6000 kJ/min vs. 1750). But let us return to the gun. The muzzle energy of F-22 is 1.35 MJ, while the power of the ABL is 1.1 MW, i.e., 1.1 MJ every second. Thus, the laser shoots 48 'shells' per minute. By converting the MW power to the TNT equivalent, we will obtain 240 grams of explosives per second and 14.4 kg per minute, which corresponds to the content of 18 high-explosive shells from the same gun. However, the actual 'value' of the laser is higher. The matter is that even with accurate firing of firearms, most of the 'energy' goes not to the enemy, but dissipates. The reason for that includes a dozen factors (wind, fluctuations in humidity, air pressure and temperature, the Coriolis force, etc.), making the bullet or shell spread inevitable. A steady flux of photons flies to where it was sent, excluding the huge amount of unnecessary loss.

d) *Myth 4. "Efficiency of lasers is a few percent."*

In fact, the efficiency of combat lasers is about 20.6%, and this is not the limit. According to the RELI program, the efficiency is planned to be raised up to 25%. Fiber lasers, which are adapted by Raytheon for military applications, now have an efficiency of about 30%. The efficiency of firearms is 20%–40%. At the same time, the efficiency of (smaller but steadily growing in power) solid-state diode-pumped systems is more than 50%, and soon it will approach its physical limit of about 85%.

e) *Myth 5. "The laser beam has a huge diffraction divergence."*

Here we deal a physically insuperable law of diffraction, which states that the laser beam always diverges with an angle proportional to the ratio of the wavelength to the diameter of the beam. If we take a specific combat IR laser with a wavelength of 2 μm (this wavelength is typical of combat THELs, etc.) and a beam diameter of 1 cm, we obtain a divergence angle of 0.2 mrad (this is a small angular divergence; for example, standard laser pointers/rangefinders have a divergence angle of 5 mrad and higher). However, because of 0.2-mrad divergence the beam

spot diameter will increase from 1 cm to 3 cm at a distance of 100 meters. That is, only 100 meters away the beam density will decrease (proportionally to the area of interaction) by 7 times. At a distance of a kilometer the density of the beam falls by 300 times.

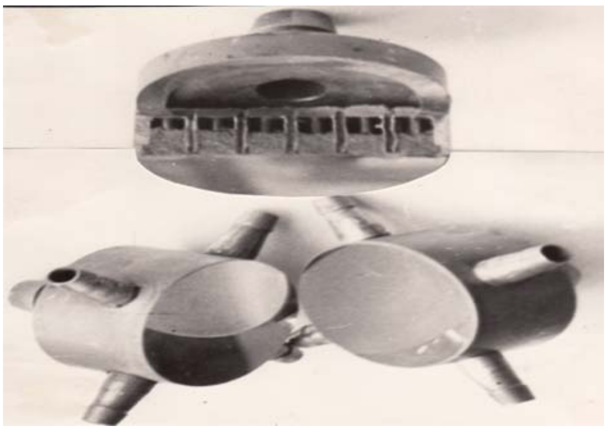
Actually, a combat laser emitting a beam with the initial diameter of 1 cm is a fruit of an unhealthy imagination, not burdened with some knowledge in this area. In fact, when using the focusing optics the diffraction divergence is about λ/D, where λ is the wavelength, and D is the diameter of the mirror and also the initial beam diameter, tapering due to focusing as the beam approaches the target; a large beam diameter (meters in this case) provides a low diffraction divergence. In the case of the ABL the wavelength is 1.315 μm, and the diameter of the mirror is 1.5 m; by dividing one by the other, we obtain the divergence of about 10^{-6} rad. In other words, at distance of only one kilometer the laser beam from the Boeing diverges by (oops!) 1 mm. At a distance of 200 km, the diffraction divergence will be 20 cm. The actual ABL beam divergence exceeds the diffraction limit by only 1.2 times.

f) *Myth 6. "One can easily be protected from laser weapons using, for example, an aluminum mirror."*

Yet another malapropism. Indeed, some metals may have near-100% reflection coefficients. First, however, these coefficients are not equal 100%. Thus, at a wavelength of 1 μm the reflection coefficient drops to 75% for most structural metals. A real missile after its launch will be also significantly contaminated with combustion products. Meanwhile, modern 'hyperboloids' emit light in the vicinity of 1 μm (the ABL has a wavelength of 1.315 μm). In this case, 25% of hundreds of kilowatts will be sufficient even in the cw regime to heat up and melt down the thin skin layer of the missile. Thus, reflectivity will decrease because the absorption of laser radiation increases rapidly with increasing temperature, and abruptly jumps after the start of melting. In the pulse-periodic regime the situation is even more favorable.

i. *Water cooled mirrors*

Besides, there arises also a 'childish' question: If the laser beam can be focused and directed by a mirror, why cannot the same mirror protect us from the laser beam? In lasers use is usually made of multilayer dielectric mirrors that can reflect very much – but in a very narrow range and only under strictly defined angles [5]. In addition, they are cooled, which is impossible to do with the entire surface of the target. In other words, simple, effective and affordable protection from high-power lasers does not exist.



Mirror with porous cooling system

g) *Myth 7. "The problem of overheating of lasers cannot be solved."*

Four megawatts of heat, which can heat red-hot an aircraft and burn to the ground, are generated per each megawatt of laser power. The cooling system with the gas flow rate of 1800 m/s (de Laval nozzle) is unable to release the generated heat from the fuselage.

In reality, the 'disposal' of the amount of heat in the megawatt units is quite trivial. Has anyone seen a red-hot diesel locomotive? Meanwhile, a decent diesel engine with a capacity of 2 MW releases more than 1 MW of heat into in the oil and cooling system. Far less easy is the problem of heat release from the limited volume of the laser weapon. In the case of a chemical ABL, the heated reaction products are simply blown out of the cavity by the well-known de Laval nozzle, and then liquid ammonia is used for cooling. Fairly cumbersome is the system with cryogenic components; however, it really is able to 'recycle' a very impressive amount of heat. Tactical solid-state lasers, which need more than 400 kW of heat to be released, do well without cryogenic 'refrigerators.' Thus, the HELLADS makes use of a unique cooling technique; the circulation of a liquid releases excess heat outside the 'laser cannon.' Remarkable also is General Atomics' advanced thermal energy storage device capable of cooling directed energy weapons. Heat is stored in the 35 kilogram module by melting a wax-type phase change material. As a result, the HELLADS provides for the interception of missiles within two minutes at the specified cw power followed a thirty- second break.

h) *Myth 8. "High-power and compact energy sources for combat lasers do not exist."*

This is partially true: It is not yet possible to mount a 100-kW solid-state laser on anything less than a truck because of the need to have at hand a 500-kW generator and suitable capacitors. In fact, this is a real problem, which has nothing to do with fantasy. In practice, the hybrid version of the HEMTT (HEMTT A3), even in the basic version has a 350-kW generator, which can provide up to 200 kW. When the engine power is increased up to 505 hp, HEMTT A3 can produce 400 kW of continuous exportable power. A nice addition is the 1.5-MJ capacitor bank. In other words, where the bloggers fancy an electric power plant, in fact, there is a high-tech truck. However, the issue of energy in the space can be solved by other, more efficient ways.

For example, well developed are nuclear power sources, solar energy, with its unlimited possibilities.

Mobile laser system

i) *Myth 9. "Every shot a laser is worth millions of dollars."*

In fact, one shot of the ABL costs 10 thousand USD, whereas the domestic 16 million rubles are the propaganda and exaggeration. This is comparable with the cost of a Fagot anti-tank guided-missile system. More complex anti-tank guided-missiles cost tens of thousands of dollars; for example, a Maverick air-to-ground missile for hitting targets ranging from a distance of a few thousand feet to 13 nautical miles at medium altitude costs 154 thousand USD, a Patriot missile – 3.8 million USD. The cost of a shot from tactical lasers is less than from the ABL. Even in a hydrogen fluoride THEL it was 2-3 thousand USD; in this case, the laser used not hydrogen but deuterium which is quite expensive.

Sketch space based laser system

j) *Myth 10. "All the problems that can be solved with laser weapons, are easier and cheaper to solve by traditional means."*

This conclusion has already been proven to be ineffective; see, for example, at Israel's attempts to defend against missile attacks by Hamas missiles (the Iron Dome system). One interception costs 30-40 thousand USD. The cost of a rocket for a Grad multiple rocket launcher system is about 1 thousand USD, the cost of a Qassams rocket does not exceed 200 USD. Thus, the interception will be 40-200 times more expensive than the rocket launched by the enemy. In this connection Tariq abu Nazar, the Hamas spokesman, once said "if every rocket launch of our missilemen costs tens of thousands of dollars for Israelis, we will assume that the goal is achieved." As a result, some newspaper people accuse not developers of laser systems but those who are responsible for termination of the Israeli-American program. The Centurion missile defense system has not found wide application because of the short-range and great ammunition consumption.

III. Legends

Of course, this is not a complete list of the legends about lasers. Most of them are built on the same principle: either outrageous lie or painstaking making of a mountain out of a molehill. In fact, lasers on the battlefield are real and the army, which possesses such weapons, will receive an impressive advantage. Thus, the air force, able to actively defend against anti-aircraft and air-to-air missiles, will be much less vulnerable to air defenses. Thus, the development of laser technology is critically important not only for well developed countries. Combat lasers are an obvious asymmetrical response to the superiority of the precision weapons. The 'ideology' of the latter in a very rude manner is to ensure that instead of a dozen of shells, a guided munition (though much more expensive) is used to precisely hit a specific target, and to minimize collateral damage. However, such a scheme is particularly vulnerable to laser defense systems, which make no difference between an archaic shell for two hundred dollars or an expensive high-tech device or military equipment. The number of targets is not so great, and their cost is ten times higher than that of the most expensive laser 'shot.'

IV. Disk laser

It is already evident that the world has entered a new round of technological race. It does not depend on our wishes, it is the willing of time. Most developed countries, based on their technological advantages, are spending billions of dollars to develop high-tech next-generation lasers [6]. According to Japanese media U.S. invested up to now more than 100 billion USD in the development of semiconductor laser pumping of solid-state lasers.

The mono-module disk laser concept is one of the most effective design for diode-pumped solid-state lasers, which allows the realization of lasers with super-high output power, having very good efficiency and also excellent beam quality. Since the first demonstration of the principle in 1966 [7] the output power of mono-module disk has been increased to the level of few kW in continuous wave (CW) mode of operation. "Zig-Zag" disk laser geometry does not look like as a perspective one for further output parameters growing. The scaling laws for mono-module disk laser design show that the limits for CW mode of operation is far beyond 100 kW for output power and the energy can be higher than 100 J in pulsed mode of operation. Due to the efficient porous cooling technology and possibility of amplified spontaneous emission (ASE) suppression the operation of the mono-module disk laser geometry is possible in CW and pulse-periodical (P-P) modes at extremely high output power.

This is due to the indisputable advantages of the disk geometry in terms of the minimal thermal lens in the active media and the high radiation resistance of the disk in the P-P regime because of the large area of the optical surface to couple out the radiation. So, the necessity to find a solution to the problem of the ASE suppression along the diameter of the disk was the major problem (matter of patent). In our case, the size of the disk at a multi-megawatt level of the average power output should be at least 50 cm, i.e., at least hundred time bigger the size of the disk that is used today in the existing systems. Radiation from such a laser, obtained during generation in the active medium of a single disk, does not require additional phase-locking. At the same time, such a laser in a mono - module geometry will be very well combined with a large-diameter telescope for ensuring high peak power density of the laser pulse on space debris. It is known that the disk geometry of a laser was proposed 51 years ago; however, to this day, the solution to the problem of the ASE suppression with increasing transverse dimensions of the active medium in the mono-module disk geometry is found! Thus, the prospects of new versions of the mono-module disk laser creation for new class of cutting edge problems are open!

V. Conclusion

The need to accelerate the development of high technology is the major topic of many political leader speeches. It is important to note the opinions of Western experts, who say that today laser technology is one of the most effective ways to gain technological superiority in the world. And today, laser technology makes it possible:

- to provide a new level of development of industry, science and technology for your country, the revival of scientific and technological strength of the country on the basis of modern high-techs;
- to make your country a leader in the field of technical, scientific and technological progress;
- to revive a large number of enterprises in many sectors of industry, which are well known for their developments in previous years;
- to strengthen your country leading position in space and to ensure strategic and geopolitical priorities in the modern world;
- to derive benefit from the sale of a wide range of laser programs, which is today comparable to the benefit from the sale of traditional products and resources.

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