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REVIEW PAPER

Shipborne Laser Beam Weapon System for Defence against Cruise Missiles

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ABSTRACT

Sea-skimming cruise missiles pose the greatest threat to a surface ship in the present-day war scenario. The conventional close-in-weapon-systems (CIWSs) are becoming less reliable against these new challenges requiring extremely fast reaction time. Naval Forces see a high energy laser as a feasible and effective directed energy weapon against sea-skimming antiship cruise missiles because of its ability to deliver destructive energy at the speed of light on to a distant target. The paper compares the technology and capability of deuterium fluoride (*DF*) and chemical-oxygen-iodine laser (COIL) in effectively performing the role of a shipborne CIWS against sea-skimming missiles. Out of these two lasers, it is argued that *DF* laser would be more effective as a shipborne weapon for defence against sea-skimming cruise missiles. Besides the high energy laser as the primary (killing) laser, other sub-systems required in the complete weapon system would be: A beacon laser to sense phase distortions in the primary laser, adaptive optics to compensate the atmospheric distortions, beam-directing optics, illuminating lasers, IRST sensors, surveillance and tracking radars, interfacing systems, etc.

1. INTRODUCTION

In the modern warfare, the greatest challenge faced by the surface ships is from the sea-skimming cruise missiles[1]. These missiles have low signatures at launch and during flight. They fly at low level, skimming a few meters above the sea surface at multiMach speeds. These missiles suddenly appear a few kilometers from the platform while performing evasive measures during the terminal run-in. Launch and impact sites cannot be derived simply by measuring the trajectory of these missiles.

This type of threat has significantly reduced the effectiveness of currently available missiles and essentially eliminated the naval gun systems from the role of ship's self-defence. Therefore, there is an urgent need to develop new technologies to defend the ships against such menacing threats. A high energy laser is one of the most effective close-in-weapon-system (CIWS) to meet such threats. The present article reviews capabilities of two lasers, viz., deuterium fluoride[2] (*DF*) and chemical-oxygen-iodine laser[3] (COIL), in effectively performing the role of a shipborne CIWS against sea-skimming missiles.

2. ADVANTAGES OF A LASER BEAM WEAPON SYSTEM

Some of the advantages[4-7] of a laser beam weapon system over conventional CIWS systems are:

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(a) Laser weapon system requires no conventional fire-control solution, since it delivers energy onto a distant target at the speed of light.

(b) Since the laser bullet has no mass, it is unaffected by any gravitational force, and hence no trajectory corrections are required.

(c) Once the beam director is locked onto a target, the system becomes insensitive to target manoeuvres.

(d) Laser beam weapon's high rate of fire as well as agility, coupled with precise aiming enable it to track a highly manoeuvreing target and shift from target-to-target on command.

(e) By tailoring the dwell time onto the target, the kill probability of a laser beam weapon system is nearly equal to one.

(f) The cost per kill of a laser system is significantly lower as compared to that of the conventional defence systems. This cost per kill is also negligible as compared to the cost of the target to be destroyed.

(g) The laser system is immune to electromagnetic interference.

3. ATMOSPHERIC PROPAGATION CHARACTERISTICS

The energy of a laser beam is attenuated in the atmosphere due to various factors, such as absorption, scattering, refraction, reflection, etc., and the total atmospheric path length. Another source of beam degradation is the atmospheric turbulence. Besides, in the case of propagation of high energy laser beams in the atmosphere, there are several nonlinear effects, such as thermal blooming that lead to the degradation of the phase-coherence, directionality, etc. All these parameters reduce the laser beam intensity onto the target. For a shipborne high energy laser, the major criterion is the selection of a suitable wavelength, such that the laser beam energy suffers the minimum possible attenuation in the highly humid sea environment.

Based on the assessment of technology of potential weapon-class lasers in the present and near future, the following four types of laser are considered[3] for comparing their atmospheric transmission characteristics: Gas dynamic laser (GDL) emitting at 10.6 µm, hydrogen fluoride (*HF*) laser radiating on multiple lines between 2.640 µm and 2.954 µm, *DF* laser between 3.715µm and 4.046 µm, and COIL emitting at 1.315 µm. Previous references on experimental results of high resolution atmospheric transmission characteristics for the propagation of the above-mentioned four lasers simultaneously propagating in the same atmosphere to encounter targets at near-horizontal elevation angles do not provide complete information[8-11]. Another way is to make use of any of the currently available software packages, viz., Fascode, Modtran, Hitran, etc., to predict atmospheric propagation characteristics through simulation of the same atmospheric conditions.

HF laser beam transmits poorly through the atmosphere. Therefore, this laser can be considered only for a space-based laser weapon system where atmospheric propagation loss is not an issue. GDL (CO_2) laser has high attenuation in thick fog, rainy weather and highly humid sea environment, and therefore, this laser cannot qualify for a shipborne high energy laser beam weapon. Out of the remaining two lasers, viz., *DF* and COIL, the *DF* laser has higher transmission in the hazy, smoky, and highly humid sea environment. Although in very dense fog[2], the *DF* laser beam has high attenuation coefficient, it is still lower than that of COIL beam. Another encouraging factor is that the probability of occurrence of very dense fog is less than 2 per cent. Further, these adverse weather conditions pose a problem equally to both the attacker (the missile) and the defender (the ship). The typical values of attenuation coefficients in the highly humid sea environment, which would be used in the transmitter-power calculations in this paper, are 0.3 km^{-1} and 0.35 km^{-1}, for *DF* laser and COIL, respectively. Although these values have not been measured experimentally for the two lasers in the same atmospheric conditions at the same time, nevertheless, these are realistic values in the naval warfare environment of sea containing smoke and high humidity.

4. REQUIRED TARGET-DAMAGE IRRADIANCE OF LASER BEAMS

The laser beam does not vapourise or melt the missile's skin all the way through. Rather, it heats the skin until, whatever internal forces are present, cause the skin to fail. For calculating the damage threshold for a particular wavelength of the laser, corrections must be incorporated to account for the reflectivity of the laser beam from the surface of the target material and from the plasma created by its vapour. The other possibility is to point the killing laser beam on the fuel tank of the missile and heat it to a point where catastrophic structural failure occurs. Besides this, if the system could be designed to blind the missile optics or to cause malfunctioning of the missile's guidance system (soft targets), far less power density (irradiance) of the laser would be required to achieve this. Based on these observations, the irradiance (I_{tar}) values of the laser beam, on the target, range from 0.3 kW/cm^2 (soft targets) to 35 kW/cm^2 (hardened targets). For a typical sea-skimming missile (as a target), this value is 10 kW/cm^2.

The far-field beam divergence, α, to a reasonable approximation, is given by the expression[5]

$$\alpha \quad 2\lambda / D$$

where λ is the wavelength of the laser beam and D is the aperture of transmitter optics. The beam-spot diameter (d) on the target at a range R is given by

$$d = R\alpha \quad 2R\lambda / D \qquad (2)$$

If γ is the atmospheric attenuation coefficient of the given laser beam, the expression for the required power, P, of the laser transmitter can be easily derived and is given by

$$P \quad \frac{\pi I_{tar} R^2 \lambda^2}{D^2} e$$

Let the highest value of I_{tar} equal to 35 kW/cm^2 (which is far higher than 10 kW/cm^2 required for a typical sea-skimming missile) be considered for a range, R, of 5 km and a beam spot diameter of 2 cm on the missile. From Eqn (2), it is seen that, with this data, the required laser beam divergence is 4 μ rad. From this and Eqn (1), one can see that the required D of laser transmitter optics is equal to 1.9 m for a *DF* laser and 66 cm for COIL. As discussed earlier, if one takes the values of naval warfare sea environment attenuation coefficients for *DF* laser and COIL equal to 0.3 km^{-1} and 0.35 km^{-1}, respectively, one finally obtains [from Eqn (3)] the required powers as 492.8 kW for *DF* laser, and 632.8 kW for a COIL. However, an idealisation in the calculation of these power levels has been the assumption of diffraction-limited beams. If the laser produces a beam which is n times the diffraction-limited (as measured by the radius of the first Airy ring); the power levels of laser required would increase by a factor of n^2. Thus, there is a very strong incentive to achieve good beam quality in these lasers.

It may be mentioned that the same power levels of these lasers can also be used to create larger beam spot diameters on the target. In that case, the weakest node (seeker optics or the electronic guidance system, for example), requiring far less levels of irradiance, would be incapacitated. This technique would result in shortening the kill time. This approach would also lead to easing of the focussing requirements and to a relaxation of the jitter and beam quality requirements. Further, the larger spot on the target would also require a smaller aperture of the transmitter optics. This would also require smaller number of actuators for the correction of wavefront distortions due to atmosphere. As an example, for a beam spot diameter of 10 cm on the missile, the beam divergence would be 20 μ rad, the diameter of transmitter optics would be 38 cm for *DF* laser, and 492.8 kW *DF* laser would be able to give an irradiance of 1.4 kW/cm^2 on the missile, which is sufficient to disable the optics or the electronic guidance system of the missile. Similarly, within a range of 13 km, the same 492 kW DF laser would be able to produce a beam spot of 5.2 cm diameter and an irradiance of 402 W/cm^2 on the missile which should be capable of disabling the optics or the guidance system of the missile.

5. DEUTERIUM FLUORIDE LASER

The continuous wave *DF* laser of interest is a combustion-driven supersonic mixing laser. A combustor is used to generate atomic fluorine by thermal dissociation of an appropriate fluorine compound, typically F_2 or NF_3, burnt at a few hundred torr and at about 1600 K. It should be noted that NF_3 is less toxic as compared to F_2. Helium gas is also introduced as a diluent, the thermal conductivity of which helps to maintain low operating temperature (~ 300 K) in the cavity that increases the efficiency of the laser. The supersonic flow is established by a fine array of nozzles, alternately injecting the combustor-derived atomic fluorine and D_2-bearing streams. The basic chemical reaction in this laser is as follows[2]:

$$F + D_2 \rightarrow DF \quad + 31.7 k-cal/mol$$

$$DF^* \rightarrow DF \quad \text{Laser beam}$$

An optical resonator transverse to the flow direction extracts the laser beam. Unstable resonators are commonly used because they can provide fundamental mode extractions from large volume gains. Present designs of high power lasers use silicon, silicon carbide, or molybdenum mirrors. Typical wavelengths emitted are between 3.715μm and 4.046 μm.

TRW (USA) has demonstrated a 2 MW power-level shipborne *DF* laser, viz., mid infrared advanced chemical laser (MIRACL) for the US Navy to test against cruise and ballistic missiles[12]. The associated sea-lite beam-director (SLBD) successfully tracked the exhaust plume, rocket motor and the rear of the body, then offset the aim point to the nose, allowing the laser to detonate the warhead, resulting in the catastrophic destruction of a Mach 2.2 Vandal missile, on 23 February 1989. This system had 1.8 m aperture telescope to produce a beam spot of 1.8 cm on the target. The shipborne SLBD differs from the other beam director in that a fluoride glass watertight window has been used as the laser beam exit aperture. The MIRACL/SLBD system has been installed at the high energy laser test facility (HELSTF) at the White Sands Missile Test Range, New Mexico. Encouraged by the success of these trials, the US Navy is now preparing to develop a high energy laser weapon system based on MIRACL/SLBD onboard ship.

It has been shown by the US Navy that the shipborne MIRACL/SLBD can be repackaged as a complete high energy laser weapon system (HELWS) to fit into the equivalent volume occupied by a 127 mm gun mount and its associated magazine[2]. Further, it was projected that replacing the gun system with this HELWS package would result in a 15 per cent reduction in weight and 5 per cent improvement in ship stability because of the weight redistribution.

The fuels used for the *DF* laser are not hypergolic and do not result in fire by virtue of their mixing. Fuel storage for the MIRACL/SLBD requires a cryogenic tank. Filament-wound, composite-construction high pressure tanks should be used. Some advantages of the shipborne system are that the fuel and oxidiser are physically separated in standardised tanks. The tanks should be designed to a leak-before-rupture requirement. If punctured due to any reason, including attack on the platform, these tanks should be designed to vent or leak instead of exploding. *HF*, which is toxic, is one of the combustion byproducts of *DF* laser. To vent the gas from the laser's low pressure interior, HF is mixed with a large amount of steam to raise the pressure of the exhaust as a whole and slightly higher than that of outside atmosphere. The only comparable effluent in the shipboard environment is the missile exhaust. Several facts make the laser effluent safer than the missile exhaust. Firstly, the pressure recovery pump in the laser system directs the exhaust upward. The exhaust will travel up and pass over the ship's superstructure. Unlike onboard missile's exhaust which tends to envelop the ship, the laser exhaust is safer to handle as compared to a missile. Secondly, in terms of hazardous components viz., *CO*, *HCl*, *DF* and *HF*, the laser's exhaust is much more benign than a missile's exhaust. A comparison between the laser and missile exhaust components[2] is shown in Table 1.

Recently, the US Army has sponsored the advanced concept technology demonstration (ACTD) using a tactical high energy laser (THEL), viz., MIRACL, for use against close-in air threats[13-14]. The US Army, Israeli Defence Ministry, and California-based TRW Space and Electronics Group successfully tested this laser, but airborne, against an unguided, operational 122 mm artillery rocket. This was the first destruction of a short range rocket on 09 February 1996 with a live warhead by a laser at HELSTF, New Mexico, under the US-Israel Joint Nautilus Programme[15].

Table Exhaust plume mass flow (kg/s)

Hazardous components	DF laser	Typical missile
CO	3.7	21.1
CO_2	36.2	1.0
HF	12.2	–
HCl	–	22.2
Inert	187.9	59.8

6. CHEMICAL-OXYGEN-IODINE LASER

Another potential weapon class laser is the COIL. It is the only shortest wavelength (1.315 µm) high energy chemical laser in existence today to operate on an electronic transition rather than on rotational or vibrational transitions. It was first demonstrated at the USAF's Weapon Laboratory in 1978. In COIL, singlet, oxygen generators produce oxygen atoms. The process involves blowing chlorine gas past a basic hydrogen peroxide and *KOH* solution. Chlorine migrates into the liquid and reacts to produce excited oxygen atoms. This chemical reaction is shown as[16]

$$Cl_2\,(g) + H_2O_2\,(l) + 2KOH\,(l) \rightarrow O_2^*\,(^1\Delta_2) + 2KCl + 2H_2O$$

The upper level of oxygen has a lifetime of 45 min which makes it a potential candidate to efficiently transfer its energy to iodine. But due to this long lifetime, oxygen has a small gain coefficient and, therefore, cannot be lased directly. Excited oxygen then escapes from the solution and is mixed downstream with molecular iodine. The iodine molecules are broken up and individual iodine atoms are excited by a nearly resonant reaction with oxygen in multiple reactions. The last transfer of energy leaves atomic iodine in an inverted population and this takes place between the mirrors of laser resonator. As the excited iodine atoms relax, they release the laser beam[17] at 1.315 µm.

The US Air Force's Combat Command hopes to deploy a fleet of seven Boeing 747-400 freighter aircraft carrying airborne laser (ABL) weapon system by 2008 at a cost of $5 billion[18-19]. The aircraft, cruising at 12.0-13.5 km would engage targets after they have cleared the clouds, from ranges of about 450 km by means of COIL with an output power of about 3 MW and with a beam divergence of less than a micro-rad. The ABL laser will focus on the fuel tank of the missile and heat it to a point where catastrophic structural failure occurs[20-21]. The sudden release of pressure from the fuel tank will destroy the missile.

7. ADAPTIVE OPTICS & BEACON LASER

The distortions of the laser beam by the turbulent atmosphere can be compensated almost completely by adaptive optics techniques[22]. It means that if the medium is distorting the beam, the reverse propagating beam heals itself of the distortions occured during the forward propagation. To launch a primary (killing) laser beamfrom the ship to the target, first a beacon laser beam is needed to propagate through the atmosphere. Each pulse of the beacon laser (usually a pulsed *Nd:YAG* laser) beam arrives at the missile slightly ahead of the target spot and just before the next adjustment to the killing laser beam. A reflection of the beacon laser beam from the missile records the atmospheric distortions on its return journey to the shipborne laser transmitter. The phase distortions across the aperture of the incoming beacon laser beam are sensed by a wavefront sensor (a detector array) and this information is used to deform the surface of a flexible (deformable) mirror. The deformation is achieved by means of actuators. Each actuator causes local deformation in the reflecting (flexible) membranes. The killing laser beam emerges as a plane wave from the transmitter and is incident on to deformed mirror, where it is imparted the compensatory phase. The minimum number (*N*) of phase sensors (also the number of actuators) is equal to the area of the transmitter aperture divided by the atmospheric area of coherence. That is

$$N = (D/r_0)^2 \qquad (4)$$

where *D* is the diameter of transmitting optics and r_0 is the lateral coherence length which depends on the wavelength, range and the value of Cn^2 (refractive structure parameter of the turbulent atmosphere). Taking a value of 5 km for the range, and $Cn^2 = 2 \times 10^{-13}$ $m^{-2/3}$, the value of coherence length is approximately equal to 3.2 cm for the 1.9 m diameter exit aperture of *DF* laser and 0.8 cm for the 66 cm diameter exit aperture of COIL. Using Eqn (4), one gets the required number of actuators approximately equal to 3525 in *DF* laser and 6806 in COIL. A single deformable mirror is actually composed of a large number of small mirrors (for example, 3525, in the case just discussed). Tiny pistons or actuators, attached to the back of each small mirror move these mirrors in such a way so that the deformable mirror, as a whole, imparts the required phase to the killing laser beam. Because the atmospheric profile changes rapidly, the faster the sampling by the beacon laser beam, the better it is. A prf of about 500 of the beacon laser would be adequate for this purpose.

8. ACQUISITION, TRACKING & DISCRIMINATION

A complete engagement involves detection, acquisition, tracking, classification, cueing and firing initiation. Missile tracking can be cued by input from reconnaissance assets[23]. Airborne surveillance radars could achieve this. The initial search and tracking could also be performed by several IRST sensors in a 360° field-of-view placed in the aircraft, helicopter, unmanned airborne vehicle or aerostat. In addition to the killing (primary) laser and the beacon laser, there are a number of ancillary infrared lasers (normally 50-100 Hz rep-rate pulsed *Nd:YAG* lasers) illuminating the missile. Besides locking onto the target, these illuminating lasers form the image of the missile on the imaging/tracking system. Switching over from passive tracking of the missile's exhaust plume by the IRST sensors to the active laser illumination should take minimum time. The main mirror of the transmitter should also play the role of a tracker besides focussing the primary and beacon laser beams[24,25]. In future, laser radar onboard ship will be able to take over the target from the surveillance radar and provide acquisition and tracking capabilities for multiple targets through narrow, directive beams from suitable lasers in the IR spectrum. Laser radar has the excellent angular and range resolutions for high energy laser beams to track and destroy targets. Finally, the verification that the target has been killed is to be considered. If a guidance electronics has been disabled, the deviation from the normal extrapolated trajectory should be readily detectable by the same tracking system that was used to acquire the target in the first place. For determining the onset of catastrophic destruction of hardened target, the IRST sensors could monitor the hot spot produced by laser radiation. This would also be essential for keeping the laser beam on the target. A sudden discontinuity in the radiative emission on burn through the target could be detected by the infrared detectors.

9. COIL vs *DF* LASER

Table 2 gives the comparative performance of COIL and *DF* laser as a shipborne CIWS against sea-skimming missiles and clearly establishes that advantages of a *DF* laser outnumber those of a COIL as a shipborne CIWS for defence against sea-skimming cruise missiles.

Table 2. COIL vs *DF* laser

Parameter	COIL (1.315 μm)	*DF* laser (3.8 μm)	Remarks
Diameter of beam directing optics for the same beam divergence	Smaller (66 cm)	Large (1.9 m)	COIL has an advantage over *DF* laser.
Operating temperature inside plasma tube	Low (250-300 K)	High (1600 K)	This makes COIL more efficient. Although the combustion temperature for *DF* laser is 1600 K, its operating temperature in the cavity can be reduced to 300 K by adding *He* as a diluent.
Operating pressure inside plasma tube	Few Torr	200 Torr	Due to less turbulence in plasma tube of COIL, beam quality of COIL is better.
Toxicity of laser	Less	High	In sea environment, toxicity of *DF* exhaust gases can be controlled. Moreover, toxicity of *DF* laser is less than that of a typical ship-borne missile.
Weight and size for the same output laser power	Smaller	Larger	Whereas weight and volume are stringent requirements for ABL, it is not a very big constraint onboard ship. For example, replacement of 127 mm naval gun by a *DF* laser weapon system resulted in 15 per cent reduction in weight and 5 per cent improvement in ship stability.
Design and engineering problems to discharge laser's exhaust gases to atmosphere	More difficult (due to low pressure of gases)	Less difficult (due to high pressure of gases)	*DF* laser has an advantage over COIL in this aspect.
Maximum beam irradiance incident on output mirror of laser for equal divergence	High (due to smaller diameter of mirror)	Lower (due to larger diameter of mirror)	*DF* laser mirror can withstand eight times the irradiance as compared to COIL mirror.
Beam pointing accuracy and stabilisation of platform	More difficult (due to smaller mirror)	Less difficult	This aspect is critical in the case of a laser onboard ship in rough sea environment.
Attenuation coefficient (humid sea environment)	0.35 km^{-1}	0.3 km^{-1}	In ABL, minimum height of aircraft is 12 km due to poor transmission of COIL in clouds.
Effect of turbulence in the atmosphere	More Pronounced	Less pronounced	Beam quality would be affected more severely in COIL than in *DF* laser
Number of actuators required in the adaptive optics (R = 5 km, a = 4 μrad, $Cn^2 = 2 \times 10^{-13}$ $m^{-2/3}$)	6806	3525	Challenges in design and engineering of deformable mirrors are less stringent in *DF* laser than in COIL.
Power levels required (R = 5 km, α = 4 μrad, catastophic damage of missile) (highly humid sea environment)	≅ 600 kW	≅ 500 kW	Less power is required in the case of *DF* laser than that of COIL.
Technology Status	Several hundred kW of power levels yet to be reported	As high as 2-3 MW of power levels have been generated in *DF* laser.	Technology to achieve required power levels in *DF* laser already existing.
Demonstration of feasibility of HELWS onboard ship	Not yet demonstrated	US Navy demonstrated it onboard ship (1989).	*DF* laser as a CIWS has already been demonstrated onboard ship.

10. CONCLUSIONS

The following conclusions are drawn

- Alaser beam weapon system has several advantages over currently available defence systems onboard ship against sea-skimming missiles. Although a HELWS can perform as a stand-alone CIWS, yet it is not suggested that it should replace the existing naval guns or any other weapon performing a similar role. HELWS can form a part of the integrated defence system.

  DF chemical laser has an advantage over other lasers as a shipborne CIWS against sea skimming missiles and other low-flying targets.

  Detailed and high resolution atmospheric studies are needed to determine the transmission characteristics of COIL and *DF* laser beams simultaneously in different sea environment conditions. Software packages may also be used for this study. Similarly, studies should also be conducted to determine the laser damage threshold energies for the materials of various soft and hard targets.

- The laser system should become operational in a very short time after the switch-on command.

  The size, weight and layout of the laser system onboard ship should take care of the stability of the ship along with a good beam pointing accuracy.

- Safety and leak-proof storage of laser chemicals as well as the laser beam safety aspects for the personnel onboard ship and in its vicinity should also be taken care of.

- In addition to the above parameters, the laser source should be capable of integrating with beam directing optics, low power pulsed illuminating laser, beacon laser and adaptive optics, autotracking system, and fire control system.

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