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Laser Technology. General Aspects and Suitable Lasers for Ballistic Defense

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Abstract.

Laser light, due to the unique characteristics that demonstrates, has found an enormous variety of applications in every section of modern activities and of course in the military sector. Based on the laser medium, the operational wavelength and the peak power of the laser beam output, a description of the operational principles of high energy laser systems has been made. Gas ($CO_{2)}$, chemical (DF, HF and I), eximer and free electron lasers are generally described in this paper additionally with their capabilities and disadvantages. Finally, an analysis has been made, to the effects of the propagation of a high energy laser beam in the atmosphere (atmospheric turbulence and thermal blooming).

Keywords: Laser, high energy lasers, CO_2 lasers, chemical lasers, DF lasers, HF lasers, I lasers, eximer lasers, free electron lasers, atmospheric turbulence, thermal blooming, scattering, atmospheric transmittance.

1. Laser Theory

1.1 Introduction

The concept of using lasers for ballistic defense has been initiated during the period of "Cold War". In 1962 U.S. Pentagon proposed their use in order to confront the nuclear threat. In 1979, a tremendous advance in the specific field has been achieved with the U.S.'s SDI (Strategic Defense Initiative) program, widely known as "Star Wars". Nowadays, the wide spread of weapons of mash destruction led U.S.A in the development of the ballistic defense program called NMD (National Missile Defense). Laser technology was the base for the development of the required technological innovations in the scientific field of directed energy weapons.

A crucial factor in the design of a laser weapon system is the evaluation of the exact laser's energy that is necessary for the destruction of the enemy's missile. In order to destroy a ballistic missile with a laser beam, an over-heat, melting or

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evaporation of its' outer casing is needed. In order for this to happen, the laser system must concentrate the energy of the laser beam in specific spots of the missile and retain the aim and focusing of the laser beam stable for enough time so as to heat the material until the point of failure. The laser's effectiveness depend on the power of the beam, the duration of the pulse, the wavelength, the atmospheric pressure and temperature, the material of the missile, the velocity of it and the thickness of the outer material.

1.2 Basic Elements of a Laser

A laser is basically consisted of a pump, an amplifying medium and a resonator (Figure 2).

The pump is an external energy source that is responsible for the population inversion in the laser medium [1]. The amplifying medium is the laser medium which can be a gas, liquid or solid. This medium determines the operation wavelength of the laser radiation. The resonator is an optical device that directs photons back and forth through the amplifying (laser) medium. Normally the resonator is consisted of two perfectly aligned plane or curved mirrors. One of them reflects almost 100% of the incident photons and the other one allows a small part of the incident photons to escape and create by this way the desired laser beam.

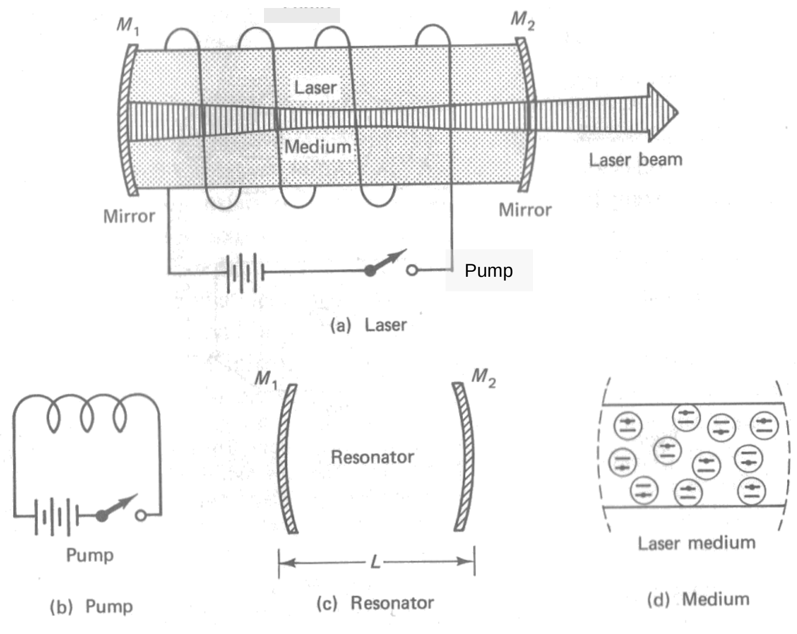

Figure 1. Basic elements of a laser, (a) laser device, (b) Pump, (c) Resonator, (d) Laser medium, ([1])

1.3 General Laser Operation

In order to study the principles of laser's operation we can see step by step the phenomena that take place inside a laser whose medium has atoms in more than four energy states (Figure 3).

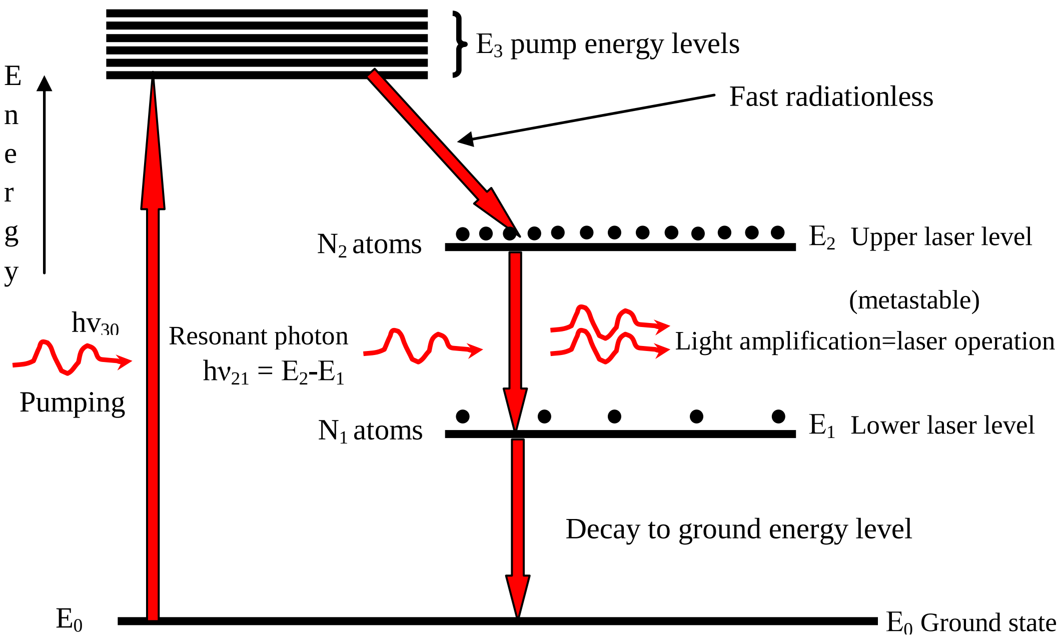

Figure 2. Basic operation procedures in a laser whose medium has atoms in four energy levels ([1] and[2])

Initially, energy is coupled into the laser medium from an appropriate pump. Due to this energy, a large number of atoms are transferred from the energy level E_0 to energy level E_3. Physically, the excited atoms decay spontaneously in order to return to their initial energy level E_0. A large number of them decay from pump energy level E_3 without usually radiating to a state with energy level E_2. This is an energy level named as "upper laser level" due to the fact that is a metastable energy level. It has the long lifetime of the order of 10^{-3} s [2]. So atoms decay from energy level E_3 and the majority of them are gathering in the metastable upper laser level E_2 resulting in a large population of N_2 atoms. When atoms decay from energy level E_2 they go to a state with energy level E_1 with a resulting spontaneous emission. Energy level E_1 is an ordinary energy level which is named as "lower laser level".

[2] All the other energy levels have a decay time of the order of 10^{-8} s.

This energy level has a small decay time to the ground state E_0 and as a result the number of atoms N_1 cannot be large enough. So due to the fact that $N_2 > N_1$ we have the desired population inversion. With this condition achieved, a photon of resonant energy $h\nu_{21} = E_2 - E_1$ interacts with any one of the N_2 atoms and can initiate the stimulated emission and as a result the laser amplification begins. The same energy's photon can also stimulate the absorption from energy level E_1 to energy level E_2. Now the rate for stimulated emission exceeds that of stimulate absorption. So, the laser is in an operational mode. The number of incident resonant photons is increasing and the operation of laser can continue. The atoms that drop from energy level E_2 to energy level E_1 due to the stimulated emission process, decay rapidly to ground energy level E_0. If the operation of pumping is continues, laser operation is cycling. For all of these reasons LASER stands for Light Amplification by Stimulated Emission of Radiation.

1.4 Characteristics of Laser Light

The characteristics of laser light that make it so unique are the following:

Monochromaticity

The light emitted by a laser is almost characterized by a single wavelength. When radiation is produced by non-thermal excitation, it is called fluorescence ([1]). The fluorescence is created due to the decay of atoms between two well-defined energy levels E_2 and E_1.

In Figure 4 below we can see the graph of spectral radiant exitance vs wavelength. The emitted light has a wavelength spread $\Delta\lambda$ about a center wavelength λ_0 where

$$\lambda_0 = \frac{c}{\nu_0} \text{ and } \nu_0 = \frac{E_2 - E_1}{h}.$$

From this plot we can understand that light is not monochromatic due to the fact that there there is a wavelength spread given by $\lambda_0 \pm \frac{\Delta\lambda}{2}$ where the dominating factor is the linewidth $\Delta\lambda$.

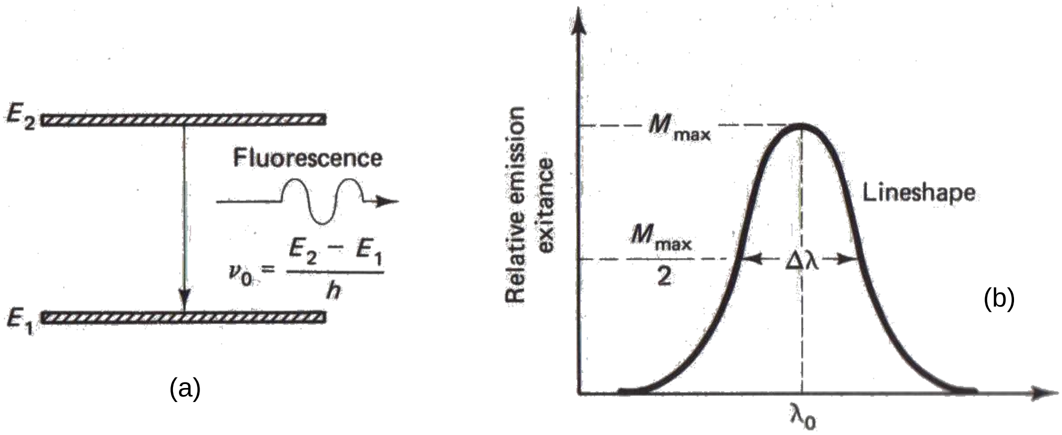

Figure 3. Fluorecence due to the decay between two well-defined energy levels in an atom, (a) spontaneous emission, (b) lineshape and linewidth for this spontaneous emission ([1])

In the lasing process the stimulated emission narrows the band of wavelengths emitted during spontaneous emission. In Figure 5 below we can see that $\Delta\lambda$ is very small and the result of this is light emission of high degree of monochromaticity.

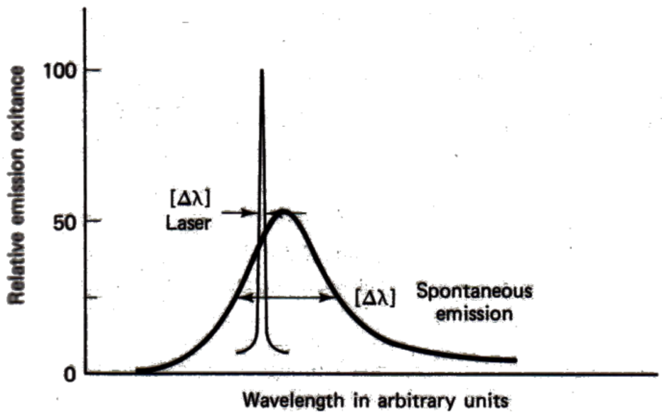

Figure 4. Comparison between laser’s emission linewidth and that of spontaneous emission ([1])

Coherence

Coherence is a measure of the degree of phase correlation that exists in the radiation field of a light source at different locations and times ([1]). A laser source ensures both a narrow-band output and a high degree of phase correlation.

Directionality

Laser light has a very high degree of directionality. This is due to the geometrical design of the laser cavity, the high monochromaticity and coherence that we have already described. In Figure 6 below we can see the laser's optical cavity and the output laser beam.

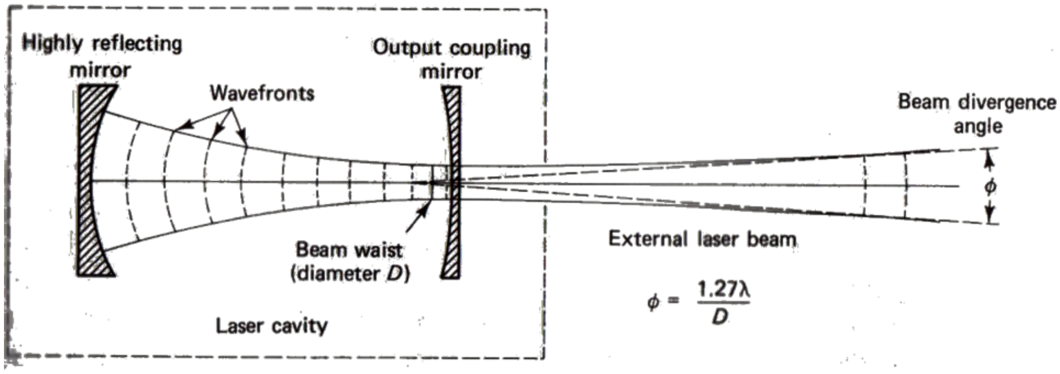

Figure 5. Internal and external laser beam for a given optical cavity ([1])

Laser Source Intensity

Laser light's intensity is number of orders of magnitude greater than that of any other light source. In order to understand better this capability we must make a quantitative analysis. Lets for example take a gas laser with power output $1mW$and an average energy of $10^{-19}J$ per visible photon ($E = hV$), then the photon output rate

$$\frac{P}{hV}\ 10^{16}\,\frac{photons}{s}.$$

For a thermal source with a radiating surface equal to that of a beam waist of $1mW$ laser that we used earlier in this analysis, having a diameter of $0.5mm$

$$\frac{thermal\ photons}{s} \approx 10^{9}\,\frac{photons}{s}$$

The great difference in intensity between laser and other light sources is described schematically also in the following figure (Figure 7). The output photon rate in the hot thermal source is almost 7 orders of magnitude less than the equivalent output rate of the laser. It should be noted also that the laser emits all of the photons in a small solid angle $(2 * 10^{-6}sr)$ compred with the $2\pi\ sr$ solid angle of the hot thermal source. If we calculate the photon output rate of the hot thermal source that are emitted into the solid angle of the laser $2 * 10^{-6}sr$ then we see that this rate is equal to only $320\,\frac{photons}{s}$.

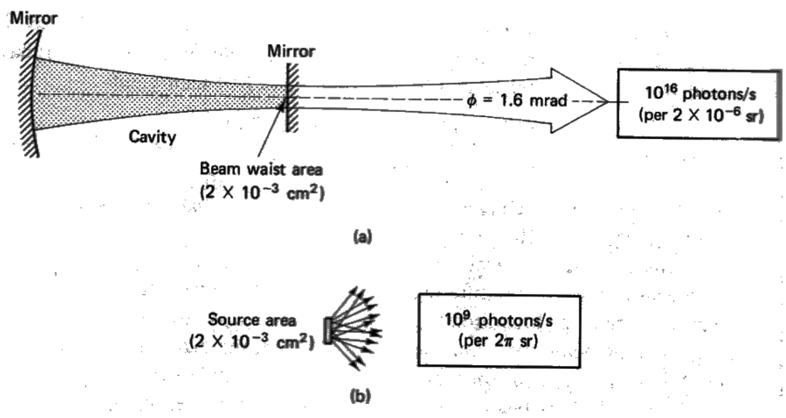

Figure 6. Photon ouput rates between a hot thermal source and a low-power He-Ne gas laser ([1])

Focusability

If we have an ordinary light source it is very difficult to focuse the ordinary light to a tiny spot due to the combination of a non-point source and the incoherent characteristics of the specific type of light. The laser emits coherent light from a "point-like" source. The difference between the focusing capability of laser vs ordinary light is shown in Figure 8 below. In Figure 8(a) we can see the incoherent radiation from a non-point thermal source that is focused to a demagnified image of size $h_i\ \lambda$. In Figure 8(b) the laser beam is coherent and is focused to a diffraction-limited spot of diameter $d\ \lambda$.

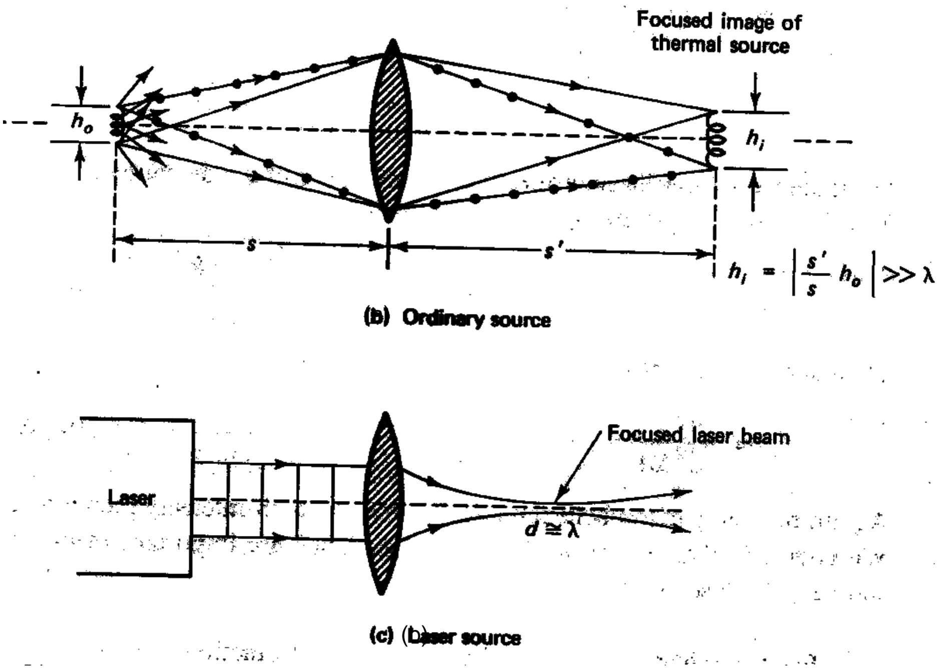

Figure 7. Focused beam from (a) ordinary thermal source, (b) laser point source ([1])

1.5 Laser Types in Spectral Regions

The lasers that are candidates for high power weapon applications fall into the near infrared to near ultraviolet region of the spectrum (except for the X-ray laser which was contemplated for Space-Defense-Initiative application). Figure 10 below shows the electromagnetic spectrum and the various application regions.

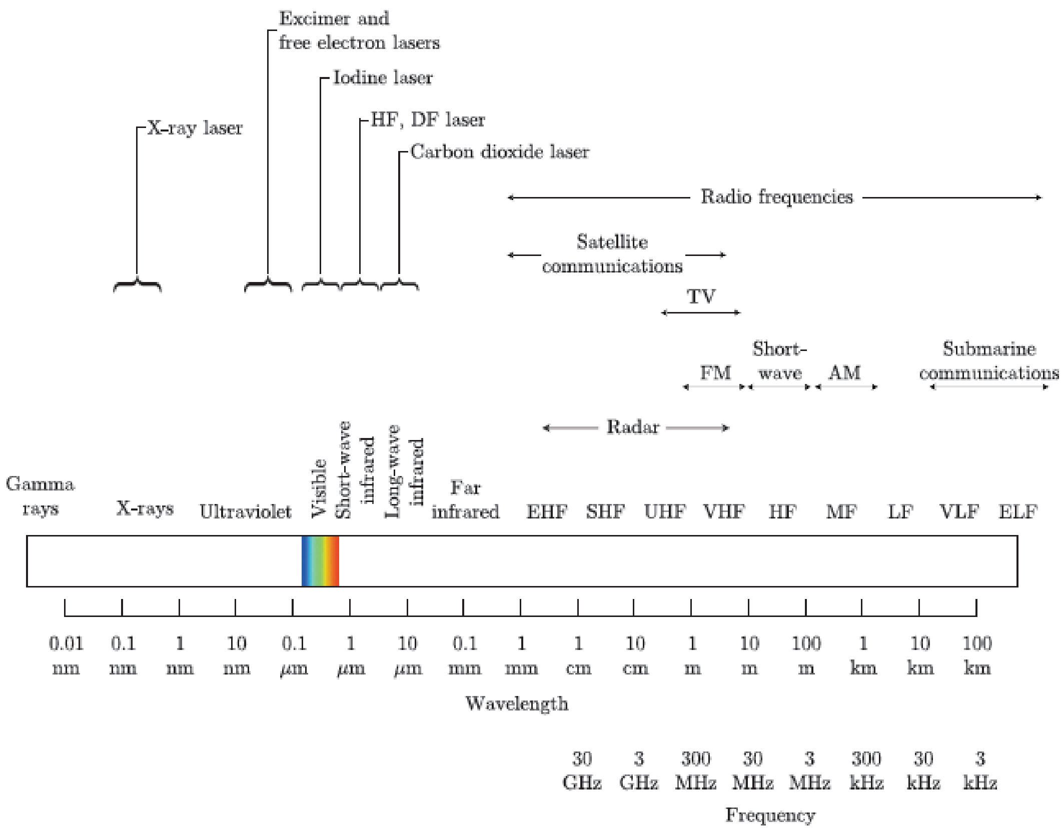

Figure 8. Electromagnetic Spectrum (EM) ([3])

2. CO_2 Laser

2.1 General Aspects of Carbon Dioxide (CO_2) Lasers

The CO_2 laser is the first one that opened the possibility of high energy lasers. At an infrared wavelength around 10.6 μm, the beam is readily absorbed by most materials and readily converted into heat. The power output range is enormous compared with other common types of laser due to the fact that they can achieve power outputs in excess of 50 kW. Nevertheless most metals reflect a radiation of such a long wavelength. In order to overcome this issue much higher output power is needed. By doing this, the extra energy is absorbed by the material and causes vaporization of the hard material.

2.2 Lasing Medium

CO_2 lasers use a mixture of CO_2, N_2 and He in a ratio 1:2:8. N_2 becomes excited with energy from the discharge and the first vibrational energy level of that molecule, provides a pump energy level that is very close to the Upper Laser Lavel of CO_2 molecule. The large quantity of N_2 ensures that CO_2 molecules in the ground state are pumped rapidly in the Upper Laser Level. The whole procedure is schematically shown in Figure 9 below.

Lasing occurs due to the transition between two vibrational energy levels (two modes) in the CO_2 molecule which is a linear chain of one C between two O's. These molecules have two longitudinal modes: a symmetric mode in which the O's move in opposite directions; and an asymmetric mode in which the two O's move in the same direction (opposite the motion of the C). There is also a symmetric bending mode. The transition from the asymmetric stretching mode to the symmetric mode changes the vibrational frequency by 30 THz (which corresponds to a wavelength of 10 μm). The most common and powerful transition results in the production of radiation at $10.6\ \mu m$. From that level, depopulation takes place through the symmetric bending mode to the Lower Laser Level (010) and then to the ground state (a procedure that gives radiation of $9.6\ \mu m$).

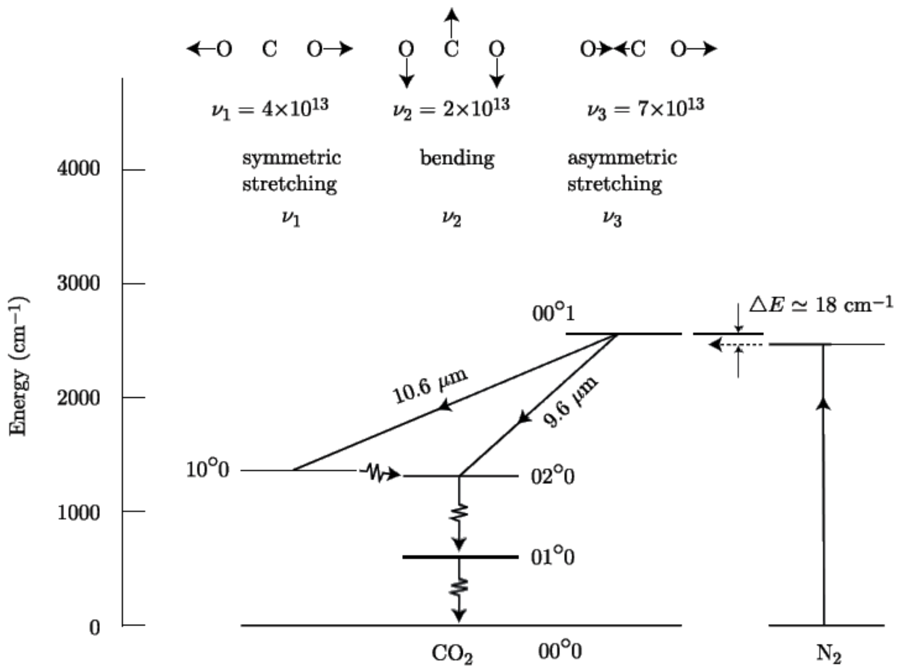

Figure 9. The lowest vibrational levels of the ground state of an N_2 molecule and a CO_2 molecule ([3])

3. Chemical Laser

3.1 General

Chemical reactions between highly reactive atoms/molecules can be very exothermic. The simple act of bringing some species together can lead to a rapid reaction with considerable energy production and which leaves the reaction products in higher excited vibrational states.

3.2 Space-Based Lasers

3.2.1 General

The "Space-Based Chemical Laser Program (SBL)" of the U.S.A. is part of the BMDO (Ballistic Missile Defense Organization). The project's objective task is to engage ballistic missiles during their boost phase and before the re-entering of the independent warheads in the atmosphere (during the last stage of their trajectory). The high power lasers are installed on space platforms and they can radiate a laser beam in ranges beyond 4000 km.

SBL uses chemical lasers HF (Hydrogen Fluorine). In these lasers the beam is created with the mixture of chemical substances inside an optical cavity. Chemical reactions are responsible for the excitation of atoms or molecules in higher energy levels having as a result the radiation of a laser beam. The HF laser operates like a rocket-motor. In the optical cavity, atomic F reacts with the molecular H and they produce excited molecules of HF. The laser's beam wavelength is between 2.7 – 2.9 μm. This wavelength is absorbed from the atmosphere and for this reason is used only in higher altitudes (outer-atmosphere) [8].

Nevertheless with the appropriate manipulations of the optical cavity, the HF laser can radiate in 1.3 μm where this wavelength penetrates the atmosphere in 35000 ft (10.668 km) having as a result the capability of hitting ballistic missiles in their boost phase [9]. In the following figure [Figure 10(a)], a schematic illustration of the space platforms is demonstrated while in Figure 10(b) a space platform of the SBL program can be seen.

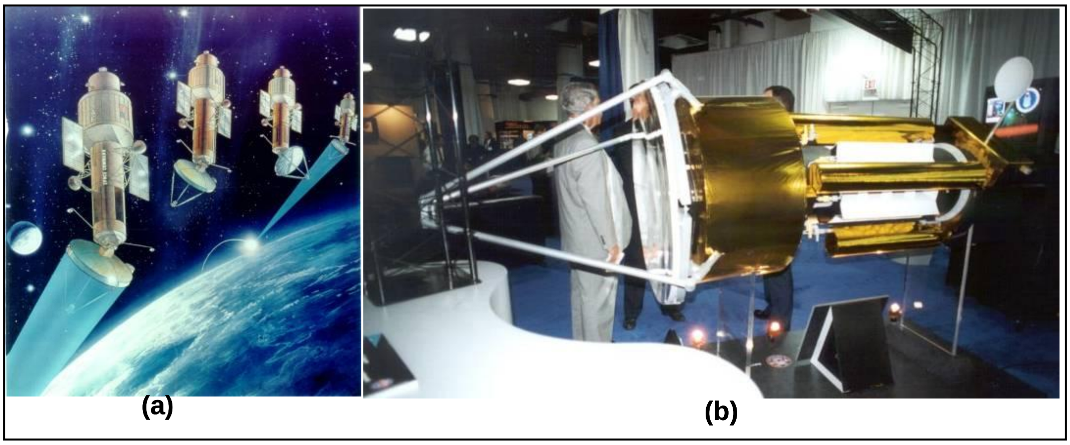

Figure 10. (a) Schematic illustration the SBL's platforms and **(b)** an SBL platform

3.2.2 Operational Capabilities

A satisfactory SBL system is consisted of 20 space platforms that operate in 40^o incline at 1300 km higher than earth's surface. Coverage per satellite is almost 1/10 of the earth's surface. With this trajectory, the system can destroy a missile in 2-5 sec depending on the range of the target. The required power for each laser fluctuates in the area of 5.6 MW. Each laser can aim again in other missile-target in 0.5 sec if the angle target – space platform is relatively small ([8]). The atmospheric penetration is almost 3000m due to IR absorption of the vapour.

3.2.3 SBL Plus

In order to reduce the number of space platforms that SBL carries, another alternative has been implemented (SBL Plus). This project is based on the installation of special mirrors that their orbit enables them to be continuously in the optical field of view of lasers. These mirrors can "retransmit" the laser beam. A possible formation of this system is consisted of 3 satellites that carry SBL lasers moving in orbit around the Equator and in an altitude of 5200 km. This altidute permits the visual contact of each mirror with at least one laser. The power output of each laser is almost 6.8 MW in order to compensate for the losses due to the retransmission of the beam. The main mirror of the SBL has a diameter of 6 m while the mirror of the retransmitter has 7.3 m diameter [9].

3.3 Airborne Laser (ABL)

3.3.1 Operational and Technical Issues

The ABL is consisted of a Chemical Oxygen Ionide Laser (COIL), with power in the order of several MW, installed in a Boeing 747-400F, with an operational altitude over 40000 ft (~12km). In COIL, the required chemical reaction takes place between Chlorine (Cl) and Hydrogen Peroxide (H_2O_2), a reaction that produces molecules of Oxygen in an excited energy state. These Oxygen's molecules transfer their energy, through collisions, to Iodine atoms which their energy excites too. The excited Iodine atoms are responsible for the transmission of a laser beam in the wavelength of 1.315 μm (IR spectrum and so invisible to the human eye) which is smaller from those of HF and DF lasers. The advantage of this laser is that it permits the use of smaller optics than those used in other high energy lasers. Additionally the laser beam is propagated in the atmosphere with fewer losses due to absorption from water vapor molecules with respect to HF laser. The ABL is consisted of 6 IR sensors for the missiles tracking, a solid state laser of some kW power responsible for the guidance of the main laser beam to the desired aimpoint onto the target and a second solid state laser in the kW power range responsible for the measurement of the atmosphere conditions.

Figure 11. The AirBorne Laser (ABL)

The basic technical issues that ought to be resolved are the following:

- The development and basically the installation of a high power laser inside an aircraft. The most crucial problem is to overcome the vibrations due to aircraft flight. So a stabilization system is necessary in order to keep the aiming of the laser beam stable onto the target. The objective for the ABL is to be able to satisfy the single mission requirement of 40 engagements of 3 to 5 seconds each ([10]).

The requirement for the ABL is to be able to produce a high energy laser beam and radiate it from the ABL towards the target which might be hundreds of kilometres away, with sufficient power in order to cause a structural failure to the missile's body. In order for this to be achievable, a system for compensating the various effects of the atmosphere, is necessary. Without it, only a small portion of the produced energy will reach and hit such a distant target. This problem has been resolved by the use of adaptive optics. In order to have a continous feedback of the weather conditions a ground based laser is used to gain information for the entire optical path through the atmosphere. This ground based laser illuminates and excites a sodium layer 90 km above ground. These excited sodium ions then emit photons and a telescope collects the light from the excited sodium layer. The image is compared to an undistorted ideal image. The information from this comparison is then used to adjust the deformable mirror and correct the distortion. The ABL's adaptive optics will have to operate in the kHz range [10]. An example of the final image is given below (Figure 12).

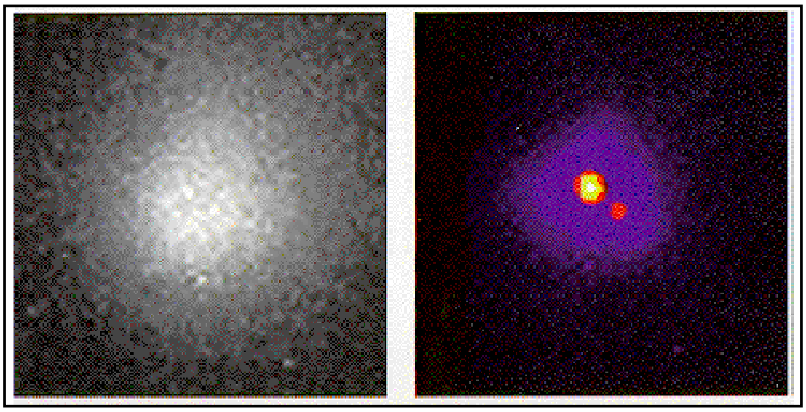

Figure 12. Initial image of the target (on the left) and adjusted from the adaptive optics (on the right)

- The necessity of a precise aiming and engagement of a moving target from a moving platform from a distance of hundreds of kilometres. During the boost phase of the missile, the tracking through the high temperature exhaust gases is possible only with suitable IR sensors. From the moment that the missile's motor burns out and the plume disappears, the tracking of it is initiated with an active procedure by using a laser beam (called active laser tracking) ([10]). This method is based on the emmitance of a laser beam towards the target and the evaluation of the returning beam to perform tracking. Based on the initial calculations of the trajectory given by the IR sensors, the relatively low-power illuminating laser will cover almost half of missile’s surface. The laser’s spot then will be moved forward until it reaches the forward edge of the missile. The illuminating laser beam is held on the forward edge to perform fine tracking of the missile. The forward edge is used as a reference point. Then the high energy laser is pointed back from the forward edge a predermined amount in order to hit the fuel tank of the missile.

3.3.2 Airborne (Advanced) Tactical Laser (ATL)

The Boeing Rocketdyne develops the Airborne (or Advanced) Tactical Laser (ATL) which is a reduction in size of ABL, designed for tactical level anti-missile and anti-aircraft defense. This type of laser can be installed in smaller aircrafts like C-130 Hercules or in CH-47 Chinook helicopter. The ATL will have as main mission the destruction of Cruise missiles and secondly the destruction of incoming rockets and artillery projectiles. Additionally it can be used for the engagements of other types of targets in attack mode. The maximum range of the system is designed to be almost 20 - 25 km while the air or ground platform (if it installed in ground platform) it can execute almost 100 “fire missions” without resupply of the energetic material of the laser. The laser will be a 100 kW Chemical Oxygen Ionide Laser (COIL).

Figure 13. The Advanced Tactical Laser (ATL)

3.4 Ground Based Laser (GBL)

The GBL is consisted of multiple high energy ground lasers, installed in various places. The system includes the laser and two types of space-based optical components: the reflecting mirror responsible for the relay of the laser beam and the reflective mirror responsible for the final relay of the laser beam. In order for the laser beam to penetrate the atmosphere without significant losses due to atmospheric absorption, the laser type is DF or COIL, with a wavelength between 3.5 – 4 μm. The reason for not using HF laser is that the wavelength of this type of laser is absorbed by the atmosphere. The required laser power has to be somewhere around 15.7 MW.

Due to the fact that environmental conditions like clouds, water vapor, air pollution etc may have a negative effect on the laser beam, GBL must be installed in places where the atmospheric and weather conditions can be stable and predictable for the whole year. A typical distance between the two lasers is about 1000 km.

Figure 14. The ground laser for the GBL

3.5 Mid Infrared Advanced Chemical Laser (MIRACL)

3.5.1 General

The MIRACL is one of the most powerful laser systems designed for military applications. It is a DF chemical laser, Continuous Wave - CW, with a power output of several MW, that operates in the range of 10 different lines of the electromagnetic spectrum (spectral lines) between 3.6 μm and 4.2 μm [11]. In the following figure (Figure 15), the MIRACL which is installed in the High Energy Laser Systems Test Facility (HELSTF) in White Sands Missile Range (N.Mexico, U.S.A.) is demonstrated.

Figure 15. The Mid Infrared Advanced Chemical Laser (MIRACL)

3.5.2 Operational Capabilities - Characteristics

Laser's "fuel" is ethylene (C_2H_4) which is burned with the oxidizer Nitrogen Trifluoride (NF_3). From this reaction, excited atoms of F in free state are produced. Next, atoms of Helium (He) and Deuterium (D) are released, the D reacts with the F and they produce molecules of DF while He stabilizes the reaction and controls the temperature. The excited gas mixture is confined between special reflecting mirrors and optical energy is transmitted. The resonator cavity is cooled continuously up to point where the supplying of C_2H_4 is stopped. The power output of the laser is controlled with respect to the flow and the special characteristics of ethylen.

The MIRACL has the capability of focusing to a target from the minimum 400 m up to the (approx.) infinity. Visual contact with the target is necessary. For this reason, in the upper part of the system, IR and optical sensors are installed for tracking and surveillance of the target. All the systems have been integrated in an electronic control system which is capable of maintaining the focus and stability of the beam in large ranges.

3.6 Tactical High Energy Laser (THEL)

3.6.1 General

The type of laser used is DF and it is designed to protect ground forces against the threat of incoming small range rockets, artillery projectiles and anti-tank projectiles. It is a product between U.S.A. and Israel. The laser is either installed in a stable base (project «THEL» and «Skyguard») or it is self-propelled installed in a special vehicle (MTEL-Mobile THEL). In the figure below (Figure 19) THEL and MTHEL are illustrated.

Figure 16. (a) The Tactical High Energy Laser (THEL)
(b) The Mobile Tactical High Energy Laser (MTHEL)

The laser beam due to the DF laser follows the general operating principles of MIRACL. The laser beam can heat steel up to the melting point, from the minimum distance of 200 m. The engagement system will focus and keep the laser beam onto the target up to the point where the developed heat will lead to the explosion of the projectile. THEL can execute almost 60 “fire missions” before it needs resupply of its’ energetic material.

4. Free Electron Laser (FEL)

4.1 General

The Free Electron Laser (FEL) is one of the most promising directed energy weapons. It is a system that its' development began in 1971. It can operate in a wide range of wavelengths (UV-mm). It is based on the transmission of an electron beam that is propagated initially in a variable magnetic field. This magnetic field forces the electron beam to oscillate and to transmit radiation.

4.2 Description of the FEL

The principles of operation of the FEL are shown schematically in Figure 17 below:

- **Injector**: It contains a cathode which is responsible for the generation of electron beam. A high voltage inside the injector accelerates these generated electrons and they leave injector with $P\ 10MB$.

- **Accelerator**: RF accelerator cavities accelerate the electron beam coming from injector. Power output of accelerator $100MW$. Accelerator receives power from RF power and from circulated electrons.

- **Bending magnets**: They drive the electron beam from electron accelerator to the undulator.

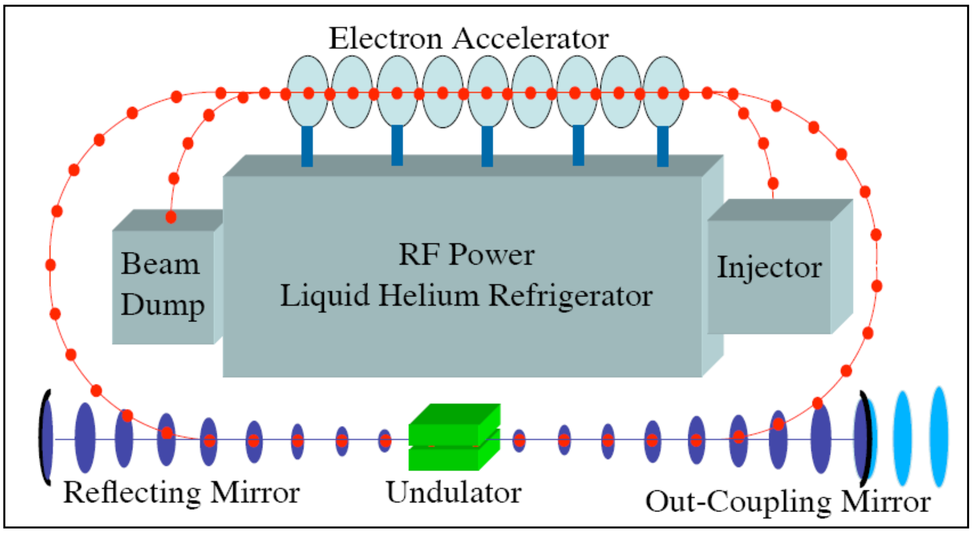

Figure 17. Schematic description of FEL operation ([6])

- **Undulator**: Device that has magnetic field from which the electron beam passes through and electrons accelerate by moving from side to side in the undulator. Accelerated by this wiggling motion, electrons can emit light in the forward direction (towards the target) an area where electrons and light interact. The operation of the undulator can be seen in Figure 18 below.

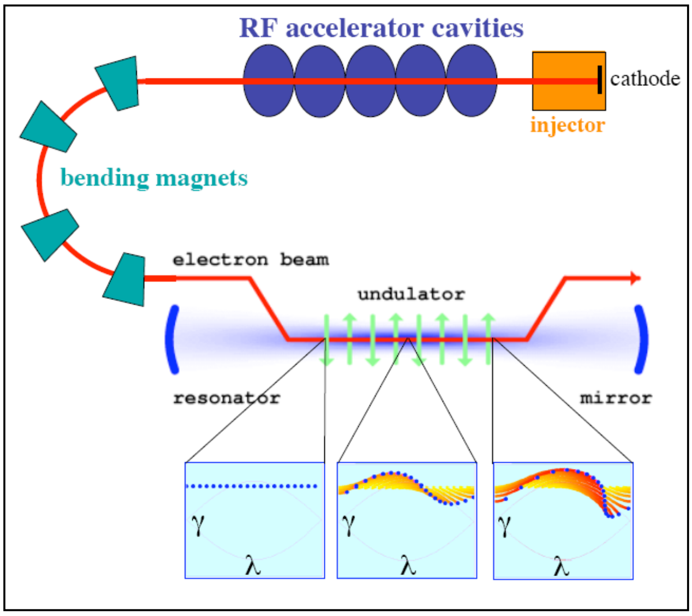

Figure 18. Schematic description of Undulator's operation ([6])

- **Optical Resonators**: There are 2 mirrors. The front mirror (shortest to the target) can transmit fraction of light (50%). The other mirror is only reflecting (it reflects all the light). So the system of 2 mirrors allows the light emitted from electrons to bounce back and forth, remain in the system and a fraction of almost 50% is partially transmitted to the target. This back and forth movement of light between the 2 mirrors allows the interaction of electrons with light in the undulator which creates the coherent radiation.

- **Liquid Helium Refrigerator**: Because of the heat emission due to the whole procedure, Liquid Helium refrigerator cools the system (1MW FEL with 10% efficiency gives 10 MW of heat removal).

- **Beam Dump**: When electrons re-enter to the accelerator (coming from injector and from undulator), we have 2 pulses. One gain energy and the other loses energy (goes to RF fields). Electrons that have not the suitable energy in order to continue the circulation path, go to the beam dump (they have almost 5 - 10 MeV energy).

4.3 FEL Capabilities

The FEL is designed to hit missiles towards sea targets. It has a range from 5-10 km. The 10 km limit has been set due to the fact that if the laser beam propagates more than 10 km there is the possibility of interaction of the beam with the atmospheric conditions. This has as a result the modification of some atmospheric characteristics like air density, creation of plasma and light reflection, factors that are not desirable for the laser operation. Additionally, the limit of 2 km has been set because if the laser beam destroys the incoming missile, the velocity and the angle of fall are such that some missile's debris will hit the sea target.

The typical output power of a FEL that is mounted on a ship is ~1MW. The duration of a continuous laser beam is ~5 sec (with respect to 1MW FEL with 10% efficiency). In this case 50 MJ of energy is required. The necessary power for the operation of a FEL with efficiency 10% is 10-20 MW.

4.4 Propagation of FEL's Radiation

The coherent optical mode radius expands like

$$W(z) = W_0 \left[1 + \frac{z^2}{Z_0^2} \right]^{\frac{1}{2}} \quad (19)$$

where

$$Z_0 = \frac{\pi w_0^2}{\lambda}$$

is the Rayleigh length for the mode, w_0 is the optical mode waist, λ is the optical wavelength. The beam director will focus power on target with optical mode radius focuses like

$$W(z) = W_0 \left[1 + \frac{(z-R)^2}{Z_0^2} \right]^{\frac{1}{2}} \quad (20).$$

In the following figure (Figure 19), the propagation and the focus of the laser beam is demonstrated [6].

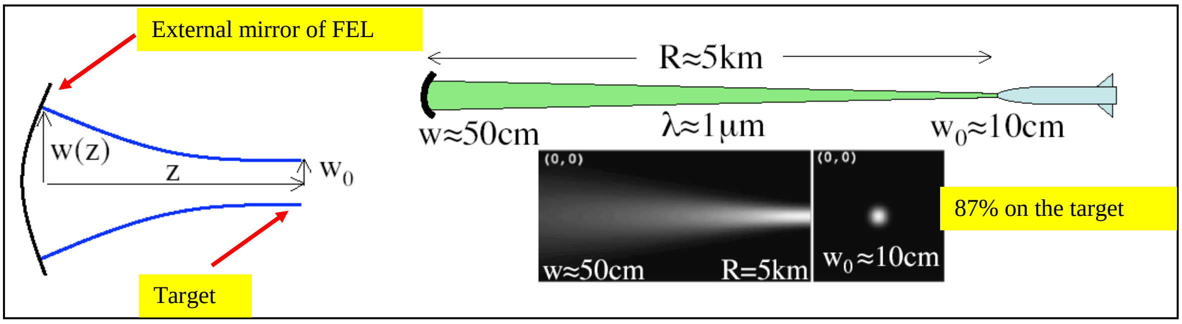

Figure 19. Schematic description of FEL's propagation and focus on the target ([6])

4.5 Problems of FEL Radiation

Two of the most crucial problems with respect to the propagation of the FEL's beam through the atmosphere are atmospheric turbulence and thermal blooming.

Because of the temperature differences in the medium (air), differences in density etc, we have different indexes of refraction. For this reason, a plane wave propagating in turbulent air will move slower over some areas than others and it becomes distorted as it propagates (moves in random directions). This procedure works like having several random lenses (focusing and defocusing) in propagation path. Laser beam becomes distorted, moves in random directions and changes intensity.

Atmospheric turbulence has negative influence for the laser beam because finally we do not have the desired focus (generally the shape of beam) and intensity of beam onto the target as it is distorted. These effects are demonstrated in the following figure (Figure 23).

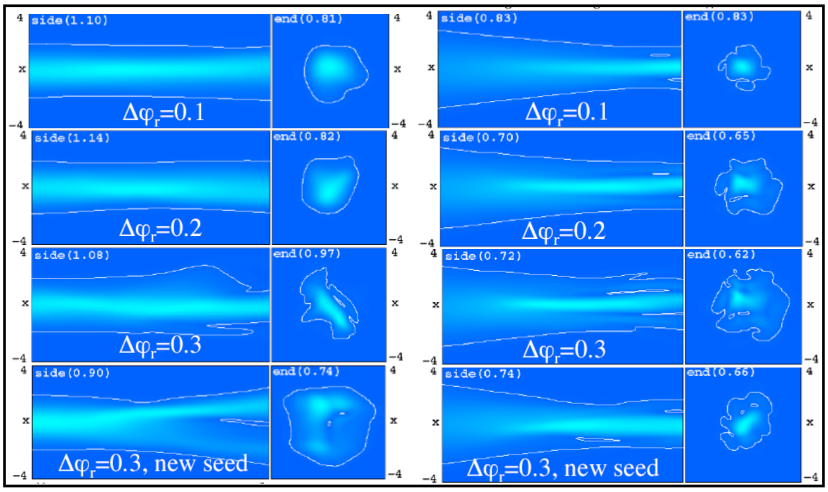

Figure 20. Results of the atmospheric turbulence in the laser beam ([6])

A laser beam propagating through the air will lose power through atmospheric absorption. This is given by

$$P = P_0 \, e^{-az} \quad (22)$$

where

$$a \, \frac{10^{-6}}{km}$$

and z is the length of propagation. The absorbed energy heats the air, so density is decreased and index of refraction will be decreased too. Through atmospheric absorption energy from the laser beam is transferred to atoms (in medium) that they change, because of this, energy states. Scattering is not a real problem since always we anticipate half of light is going to the target. This procedure works like having several defocusing lenses in propagation path. Because of these defocusing lenses, we have a divergence of light.

Propagation to the target depends on the power

$$a_{after} = \left(e^{-ia^2 \Delta\Phi_s}\right) a_{before}.$$

If we increase the power leaving the weapon, from a specific point and after, intensity within the target is decreased. This happens because of thermal blooming. Thermal blooming is a negative effect because it limits power propagating and because of this spreading (divergence of light), centering intensity of the beam decreases (we can see from graphs of Figure 21, a hole in the middle of the beam's pattern) where it should have been more intensity in order to destroy the target.

In order to get rid of thermal blooming, we should find the right wavelength that gives little absorption. We should make laser spectrum narrow enough in order to decrease absorption and increase transmission. Key points are the amount of absorption in atmosphere and the length of stagnation zones.

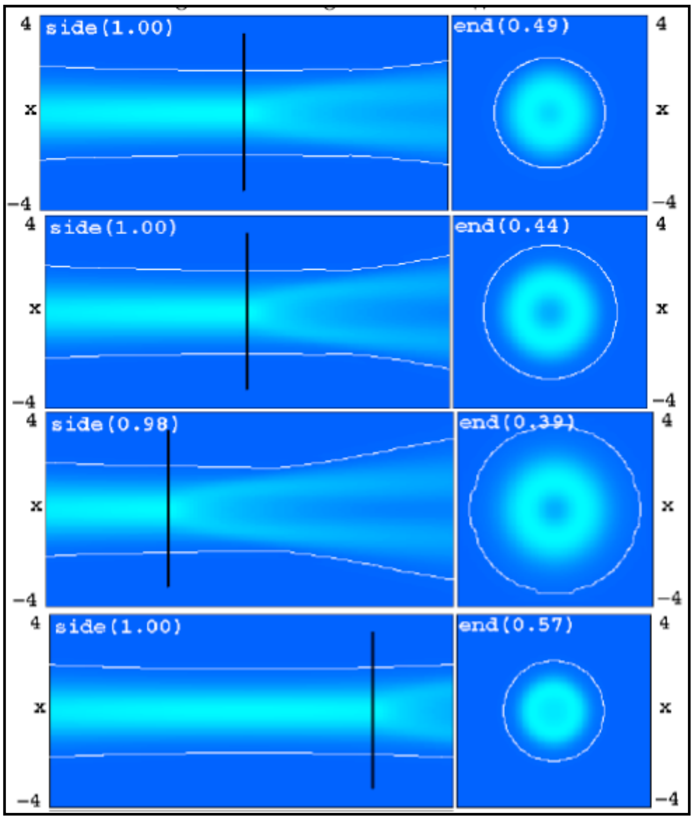

Figure 21. Results of the thermal blooming in the laser beam ([6])

In Figure 22 below, various atmospheric transmittance values for 0-15 μm wavelengths, over a 1820 m horizontal path at sea level are demonstrated. In vacuum the transmittance is almost 100%. From Figure 22 it is noticeable that the atmospheric transmittance has a range from 0-90% depending on the wavelength. The difference is due to atmospheric attenuation. Atmospheric attenuation is related with the propagation of a laser beam through scattering and absorption. Scattering is the deviation of energy (laser light for our purpose) from a straight trajectory due to collisions with aerosols and other particles contained in the air. Absorption, from the other hand, is the loss (transfer) of energy from the laser beam to the molecules conatained in the atmosphere. Figure 22 is very crucial due to the fact that it illustrates the importance of wavelength selection for laser weapon use.

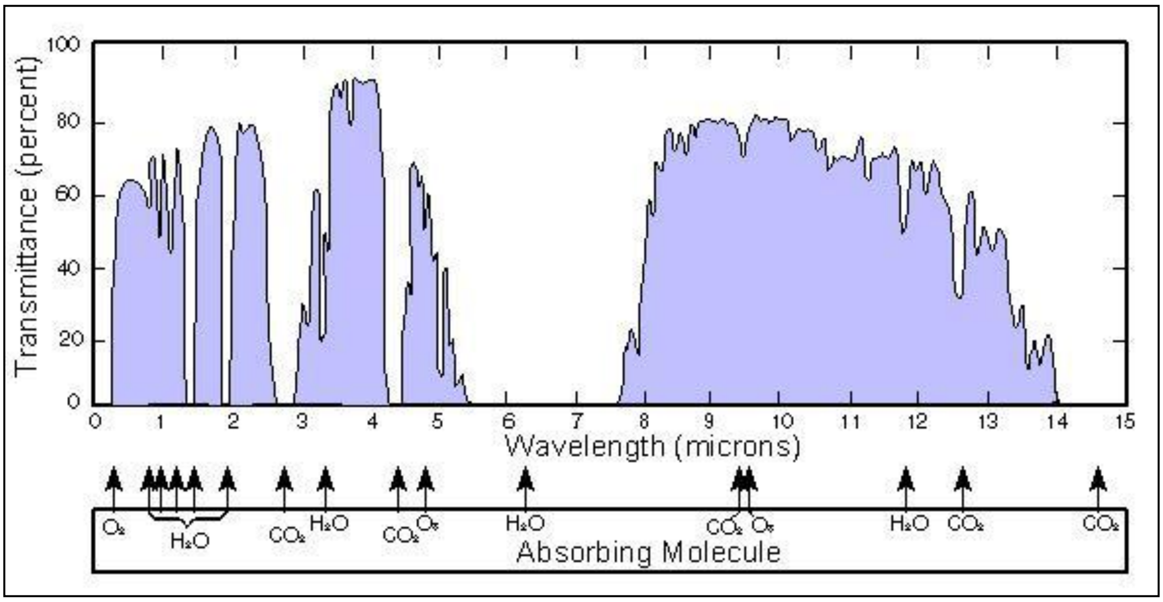

Figure 22. Atmospheric transmittance for 0-15 μm

If we separate the effects of scattering and absorption so as to define a common extinction coefficient, the result is demonstrated in Figures 23-25 below. In Figure 23 the aerosol attenuation is evaluated in maritime environment, in Figure 24 in urban conditions while in Figure 25 it is evaluated in rural conditions, all of them in the same wavelength range and with the same relative humidity. The three different atmospheric conditions have different attenuation coefficients especially due to the increase in air moisture in the maritime environment. The graphs have been made with matlab based on data from [7].

From the figures below (Figures 23-25) it can be noticed that for wavelengths up to 10 μm, the scattering coefficient dominates with respect to absorption coefficient while for wavelengths greater than 10 μm the absorption coefficient dominates with respect to the scattering coefficient. The absorption leads to thermal blooming due to the local heating of air which in turn lowers the index of refraction.

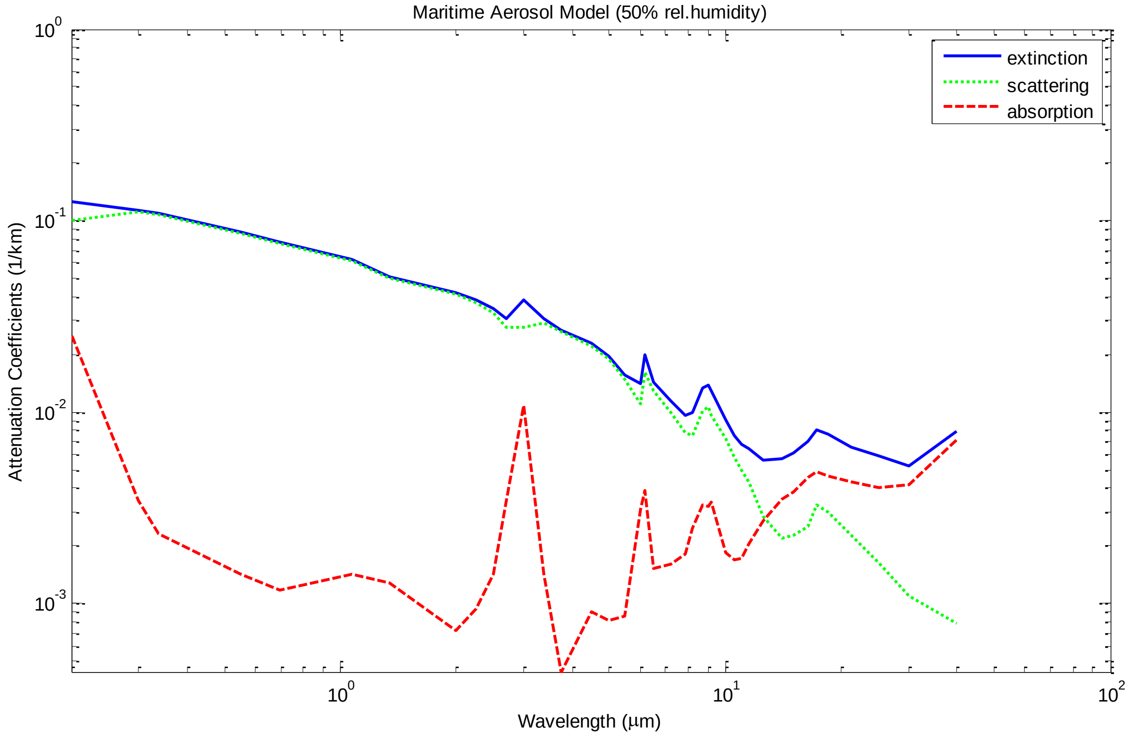

Figure 23. Atmospheric attenuation coefficients in maritime environment (data from [7])

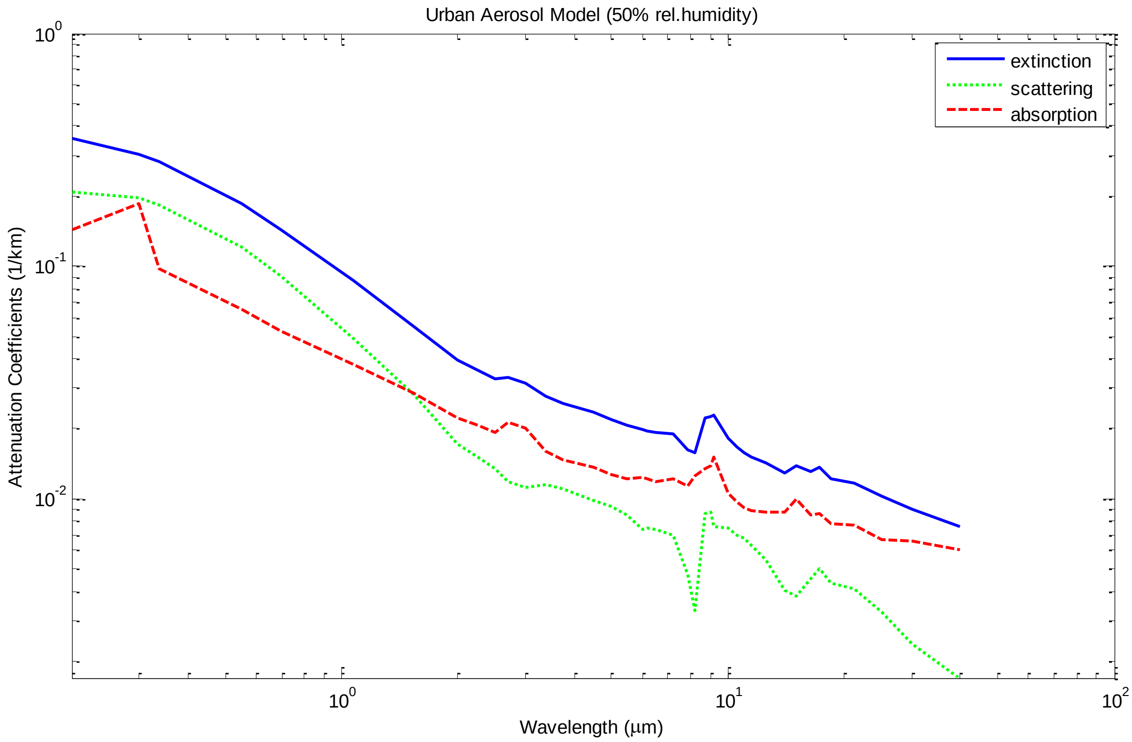

Figure 24. Atmospheric attenuation coefficients in urban environment (data from [7])

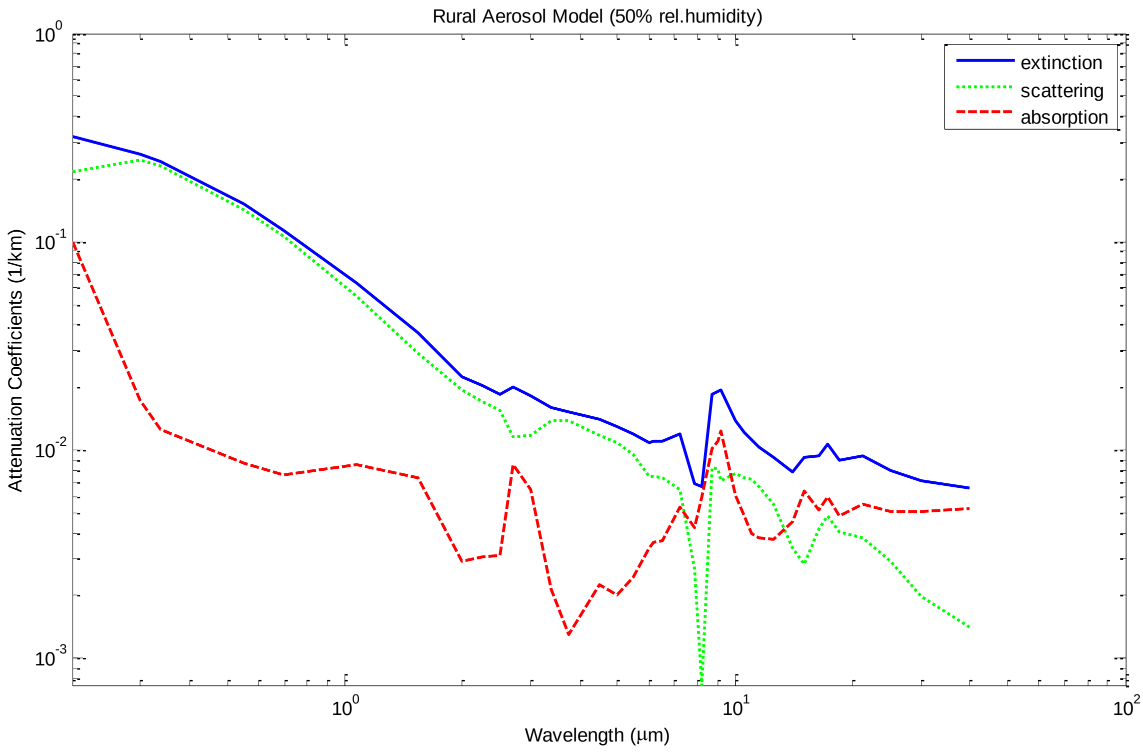

Figure 25. Atmospheric attenuation coefficients in rural environment (data from [7])

5 Epilogue

From all of these we can see clearly that laser technology covers the tactical, operational and strategic area of operations with the advantages and disadvantages that have been analyzed. Laser is the future in the scientific area of directed energy weapons.

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