# Theoretical and Experimental Foundations of Laser Weapons

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*Abstract:* - In the contemporary scientific field, in the Middle Eastern war, the laser weapon became a subject of strategic importance used in the field of defense. Our study came to complete the theory and experience of using these weapons in the interaction with metals. Based on the experiences carried out strategically in Romania with lasers of different types, we proceeded to the theoretical evaluation of the laser light field based on the system of Maxwell's equations. The electric field was mathematically obtained with a value of $1{,}05 \times 10^4$ V/m which has the role of producing the light effects and estimating the intensity of the incident laser light that attacks the target and irradiates it. A value was obtained on a 10 mm thick Hardox 400 target that protects electronic equipment equal to $4{,}5 \times 10^6$ W/cm$^2$. Another important quantity in laser attack is the energy supplied to the target to create the piercing bore, where a value of 3 MJ was obtained for a laser spot with a focal diameter of 0.38 mm. Laser radiation intensity and energy are the two important quantities that have destructive effects on metal targets (drones, missiles).

*Key-Words:* - Hardox 400, laser cutting, Maxwell's equations, Fourier analysis, fiber laser.

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## 1 Introduction

The targets are alloys of Fe, C, Si, Mn, B, Ni, Cr, Ti, etc. that are exposed to attack and irradiation with a laser spot. The phenomena in which laser radiation participates when it encounters the metal are reflectivity and absorption. Based on the analytical description of the process of receiving energy from the laser and releasing energy to the material, we can anticipate laser irradiation. The laser attack has the effect of sudden local heating, melting and piercing of a small metallic portion based on the expulsion of incandescent particles. In the case of continuous wave irradiation - monopulse, the initial temperature on the sample coincides with the final temperature at the end of the irradiation. In the case of the Gaussian or rectangular pulse used for pulsed irradiation of the laser wave, the maximum temperature is reached at the end of the pulse. These issues are important in the attack with unconventional laser weapons that lead to an extensive theoretical and experimental basis that we have proposed in this study. Through the interaction of laser radiation with metals, holes/bores are produced by thermal shock. The intensity of the laser increases and implicitly the strong shock received by the material when the spot radius decreases. From these considerations presented above, we thought of giving a more extensive consideration of the electromagnetic field of laser light. Laser light is an electromagnetic wave produced by an intense electric field that generates at the same time a magnetic field varying in time with closed lines.

Similarly, the time-varying magnetic field generates a variable electric field at another point, the two fields being transported by the speed of light in the direction of propagation of the electromagnetic wave. The greater the amplitude and speed of variation of the electric field, the higher the intensity of the wave becomes. Academician Prokhorov presents the transfer of energy by radiation in [1] where he highlights the thermal action on the target. I.M. Popescu, author of many books and collections of physics [2], highlighted the applications of lasers in the military field, through Hughes Aircraft Company, General Dynamics Company, Philco Ford Company, Westinghouse and Texas Instruments, North American Rockell Corp, the Apollo Program. Recently, Iron Beam is a defense laser tested and used on the battlefield. Professor Ion Agârbiceanu invented the first gas laser at the Bucharest Polytechnic Institute in 1965, carbon dioxide. The professor also has other inventions of the He-Ne laser and the ruby laser. Academician Henri Coandă made important contributions to the development of laser weapons in Romania, together with Agârbiceanu and other researchers Velculescu, Blănaru, Agafiței, etc. Ion Agârbiceanu [3] and Professor Honoris Causa, Mihail Megan from Timișoara [6], members of the Romanian Academy made important contributions to laser theory through field analysis, Fourier analysis, Bessel analysis [4]. Mircea Craioveanu, a famous geometry professor from Romania, laid the foundations of geometry that has an important role in laser theory and research with studies at the "Erwin Schrödinger" International Institute for Mathematical Physics in Vienna [5], the professor was part of the military family of General Craioveanu. Agârbiceanu, Megan, Chiriac came from families of priests who revolutionized and fascinated laser science through theorems, laws, equations, formulas, the possible connection between science and religion. Chiriac, an exceptional chemistry professor, explains the rules for the completion of atomic levels and substrates by electrons, a theory also present in the electron-photon laser [7]. Popescu makes assessments of the laser weapon and the energy density in the material [8]. Sabin Vîlceanu appreciates that the laser has become an instrument in science and technology [9]. Dumitras presents that the transmission of laser beams through optical fibers is based on doping with erbium $Er^{3+}$ in a glass matrix, where the valence electrons excited on the $^4I_{13/2}$ level produce laser light through quantum transitions [10].

## 2 The mathematical model of the laser wave

Maxwell's equations govern the laws of the electromagnetic field. A laser light wave is an electromagnetic radiation in which the electric field and the magnetic field simultaneously vary in time. The speed of variation of the electric and magnetic fields determines the lightning of death. A large amplitude of the electric field means a laser intensity that produces miraculous local effects. Maxwell's laws in a vacuum form a system of 4 differential equations:

$$\frac{\partial E}{\partial t} = c^2 \nabla \times B = c^2 rotB \tag{1}$$

$$\frac{\partial B}{\partial t} = -\nabla \times E = -rotE \tag{2}$$

$$\nabla \cdot E = divE = 0 \tag{3}$$

$$\nabla \cdot B = divB = 0 \tag{4}$$

The rate of change of the electric field is directly proportional to the square of the speed of light and to the rotor of the magnetic field. The rotor of the electric field is calculated with the associated determinant applying Sarrus' rule:

$$rotE = \begin{vmatrix} \vec{i} & \vec{j} & \vec{k} \\ E_x & E_y & E_z \\ \frac{\partial}{\partial x} & \frac{\partial}{\partial y} & \frac{\partial}{\partial z} \end{vmatrix} = \vec{i}\left(\frac{\partial E_y}{\partial z} - \frac{\partial E_z}{\partial y}\right) + \vec{j}\left(\frac{\partial E_z}{\partial x} - \frac{\partial E_x}{\partial z}\right) + \vec{k}\left(\frac{\partial E_x}{\partial y} - \frac{\partial E_y}{\partial x}\right) \tag{5}$$

The differential operator ∇ is defined using unitary versors:

$$\nabla = grad = \frac{\partial}{\partial x}\vec{i} + \frac{\partial}{\partial y}\vec{j} + \frac{\partial}{\partial z}\vec{k} \tag{6}$$

The electric field is a vector $\vec{E}$ that has origin, direction, sense, mode that through its variation in time generates destructive light. This light is surrounded by a time-varying magnetic field $\vec{B}$ whose lines are closed. The magnetic field lines are transported by the electric field lines forming together the electromagnetic wave, the monochromatic lightning, or laser light. This lightning of light with a very small diameter propagates in another direction at the speed of light c. The ideal case would be for the two fields, electric and magnetic, to be perpendicular.
The divergence of the electric field is the light flux of a vector electric field that passes through a closed surface of the magnetic field.

$$div\vec{E} = \nabla \cdot \vec{E} = grad\vec{E} \tag{7}$$

Maxwell's 3rd law:

$$\nabla \cdot \vec{E} = (\frac{\partial}{\partial x}\vec{i} + \frac{\partial}{\partial y}\vec{j} + \frac{\partial}{\partial z}\overrightarrow{k)} \cdot \left(E_x \cdot \vec{i} + E_y \cdot \vec{j} + E_z \cdot \vec{k}\right) = \frac{\partial E_x}{\partial x} + \frac{\partial E_y}{\partial y} + \frac{\partial E_z}{\partial z} \tag{8}$$

The wave function establishes the space-time equation of the electric field:

$$\frac{\partial E}{\partial t} = c^2 \nabla \times B \quad (9)$$

The finite increase in the electric field means that we derive the first equation with respect to time:

$$\frac{\partial^2 E}{\partial t^2} = c^2 \nabla \times \frac{\partial B}{\partial t} = c^2 \nabla \times (-\nabla \times E) = -c^2 \nabla \times (\nabla \times E) = -c^2 [\nabla(\nabla \cdot E) - (\nabla \cdot \nabla) E] = c^2 \nabla^2 E = c^2 \Delta E \quad (10)$$

The differential equation is obtained:

$$\frac{\partial^2 E}{\partial t^2} = c^2 \Delta E \quad (11)$$

Variation of the electric field in the x direction:

$$\frac{\partial^2 E(x,y,z,t)}{\partial t^2} = c^2 \Delta E(x,y,z,t) \quad (12)$$

## 3 Theoretical research

We obtain a partial derivative electric field equation that depends on the 4-dimensional Minkowski-Einstein space (Cartesian coordinates and time coordinate). The unidirectionality of the field on 0x gives us:

$$\frac{\partial^2 E_x}{\partial t^2} = c^2 \frac{\partial^2 E_x}{\partial x^2} \quad (13)$$

$c^2$ – is a field invariant.

The wave equation of laser radiation has the general form:

$$\frac{\partial^2 E}{\partial x^2} - \frac{1}{c^2} \frac{\partial^2 E}{\partial t^2} = 0 \quad (14)$$

The solution to the differential equation of the laser light wave is a superposition of two solutions:

$$E(x,t) = E(t - \frac{x}{c}) + E(t + \frac{x}{c}) = E_0 sin\omega(t - \frac{x}{c}) + E_0 sin\omega(t + \frac{x}{c}) = 2E_0 \cdot cos2kx \cdot sin\omega t \quad (15)$$

Putting the boundary condition $cos2kx = 1$ we obtain the maximum amplitude of the field twice the initial amplitude. The laser wave equation is obtained: $E(x,t) = 2E_0 \cdot sin\omega t$. The intensity of the laser light $I_0 = 4{E_0}^2$.

The wave equation of the magnetic field is obtained by a similar reasoning:

$$I_0 = 4{E_0}^2 \quad (16)$$

Elementary increase in the rate of change of the magnetic field:

$$\frac{\partial^2 B}{\partial t^2} = -\nabla \times \frac{\partial E}{\partial t} \quad (17)$$

$$\frac{\partial^2 B}{\partial t^2} = c^2 \nabla^2 B \quad (18)$$

The laser wave equation of the magnetic field has the general form:

$$\frac{\partial^2 B}{\partial x^2} - \frac{1}{c^2} \frac{\partial^2 B}{\partial t^2} = 0 \quad (19)$$

The solution is in phase with that of the electric field:

$$B(x,t) = 2B_0 \cdot cos2kx \cdot sin\omega t \quad (20)$$

The relationship between the amplitudes of the electric and magnetic fields:

$$E_0 = B_0 \cdot c \quad (21)$$

Another method of searching for solutions for the 2nd order differential equation, i.e. the law of variation of the magnetic field, results from the following reasoning:

$$B(x,t) = g(x) \cdot e^{i\omega t} \quad (22)$$

with a real and an imaginary part.

$$\frac{\partial^2 B}{\partial x^2} - \frac{1}{c^2} \frac{\partial^2 B}{\partial t^2} = 0 \quad (23)$$

$$\frac{\partial^2 g}{\partial x^2} - \frac{\omega^2}{c^2} g = 0 \quad (24)$$

This is the time equation of laser waves:

$$\frac{\partial^2 g}{\partial x^2} - k^2 g = 0 \quad (25)$$

Eigenvalue equation:

$$g(x) = Asinkx + Bcoskx \quad (26)$$

The laser beam propagation equation results:

$B(x,t) = g(x) \cdot e^{i\omega t} = (Asinkx + Bcoskx)e^{i\omega t} = (Asinkx + Bcoskx)(cos\omega t + isin\omega t)$ (27)

with A and B constants belonging to real numbers, in which we applied Euler's formula.

## 4 Experimental research with variable fields of the fiber laser beam

Following complex experiments on different steels, we used the following input parameters for Hardox 400:

Table 1. Input parameters for Hardox 400:

| Fiber laser 10 KW | Laser power [W] | Focusing diameter [mm] | Incident intensity [W/cm$^2$] |
|---|---|---|---|
| Values | 5200 | 0,38 | 4,5x10$^6$ |

We propose to approximate the electric field amplitude to develop new analytical calculations about the laser wave.

$$I_0 = 4{E_0}^2 \text{ resuting } \Rightarrow E_0 = \frac{\sqrt{I_0}}{2} \quad (28)$$

Using the data in the table, we get $E_0 = 1{,}05 \times 10^4 V/m$, a sufficiently intense field that destroys the metal almost instantly. The magnetic field has an amplitude of $B_0 = \frac{E_0}{c} = 0{,}35 \times 10^{-4} T = 3{,}5 mT$ (29)

The two time-varying fields generate each other instantaneously and travel in the air at speed c.
The fiber laser has the following characteristics:

Table 2. Characteristics of the fiber laser

| Fiber laser 10 KW | Wavelength [m] | Frequency of light [Hz] | Periods [ps] |
|---|---|---|---|
| Values | $1{,}06\times 10^{-6}$ | $2{,}83\times 10^{14}$ | 35 |

The equation of the electric field produced by the laser source:

$$E = E_0 sin\omega \cdot t = 1{,}05 \times 10^4 sin 2\pi \cdot 2{,}83 \times 10^{14} \cdot t \quad (30)$$

At a point located at a distance x from the source, the field has the plane wave equation:

$$E(x,t) = E_0 sin(\omega \cdot t - k \cdot x) \quad (31)$$

where k is the wavenumber $k = \frac{2\pi}{\lambda}$, and $\omega$ represents the angular velocity.
A laser weapon that destroys metal targets, swarms of drones, missiles has a variable electric field according to the relationship:

$$E(x,t) = E_0 \sin[\omega\left(t - \frac{x}{c}\right) + \varphi_0] \quad (32)$$

At a distance of x = 2 Km , shooting at an angle $\varphi_0 = 45^\circ$, speed of light $c = 3 \times 10^8 m/s$, t is the duration of a laser signal:

$$E(x,t) = 1{,}05 \times 10^4 \sin[2\pi \times 2{,}83 \times 10^{14}\left(t - \frac{2000}{3\times10^8}\right) + \frac{\pi}{4}] \quad (33)$$

X is the distance where the target is located, $\varphi_0$= initial phase at the time t=0s. The magnetic field evolves according to:

$$B(x,t) = B_0 \sin\left[\omega\left(t - \frac{x}{c}\right) + \varphi_0\right] = \frac{E_0}{c}\sin[\omega\left(t - \frac{x}{c}\right) + \varphi_0] \quad (34)$$

Energy density is an important quantity when interacting with the target:

$$w = \varepsilon_0 E_0^2 sin^2[\omega\left(t - \frac{x}{c}\right) + \varphi_0] \quad (35)$$

Maximum energy density:

$$w = \varepsilon_0 E_0^2 = 8{,}856 \times 10^{-12} \times 1{,}1 \times 10^8 \frac{J}{m^3} = 9{,}76 \times 10^{-4} \frac{J}{m^3} = 9{,}76 \times 10^2 \frac{J}{cm^3} = 976 \frac{J}{cm^3} \quad (36)$$

The laser weapon has the following features:

Table 3. features of the leaser weapon

| Laser weapon | Energy density $[\frac{J}{cm^3}]$ | Magnetic field [T] | Electric field $[V/m]$ |
|---|---|---|---|
| Valori | 976 | $3{,}5 \times 10^{-3}$ | $1{,}05 \times 10^4$ |

## 5 Results and discussions

We propose to determine what energy density is focused on the target to produce the penetration of a 10 mm thick Hardox 400 steel plate that protects the drone's electronics. The idea is based on the thermal flux entering the upper face in a focusing diameter equal to 0.40 mm and the mathematical relationship that describes the physical interaction:

$$q = q_0 \times e^{-2 \cdot \frac{r^2}{a^2}} \tag{37}$$

Here, $q_0$ is the heat flux entering the center of the circular region, $q$ is the heat flux located on the Gaussian curve, *a* is the radius of the circular area on the target, r is the radial coordinate.

Our energetic reasoning respects the physical relationship of heat flow, in which we will similarly describe the mathematical relationship for energy density:

$$w = w_0 \times e^{-2 \cdot \frac{r^2}{a^2}} \tag{38}$$

Our model is based on gas laser and fiber laser processing experiments. The target is hit almost instantly by the laser light that pierces it through stationary piercing. In less than 1 second the target is destroyed in the air by the laser weapon. We will capitalize on the data obtained on the ground based on the working parameters and calculations, balancing and testing of the weapon.

Table 3. Data obtained from the Gaussian distribution

| Working para-meters | Radius of the circular area on the target [mm] | Radial coord. [mm] | Volumetric energy density $[\frac{J}{cm^3}]$ | Central vol. energy density $[\frac{J}{cm^3}]$ centrală |
|---|---|---|---|---|
| Values | 0,20 | 0,15 | 976 | 2928 |

Mathematically we obtain a novel relation for the central volume energy density that estimates the process of melting and destroying the drone:

$$w_0 = w \times e^{2 \cdot \frac{r^2}{a^2}} \tag{39}$$

An important analytical process relationship is obtained:

$$w_0 = w \times 3 \cong \frac{1000J}{cm^3} \times 3 = \cong 3000 \frac{J}{cm^3} \tag{40}$$

The melted volume is calculated according to the relationship:

$$V = 2\pi a^2 \times g = 2 \cdot 3{,}14 \cdot 0{,}2^2 \cdot 10mm^3 = 0{,}92mm^3 \tag{41}$$

The heat received was dispersed in a 1 $cm^3$ at a 3000 J value. It turns out that in 0.92 $mm^3$ a much greater energy entered which instantly shattered the material. The hole produced by the laser radiation has a volume approximately 1 $mm^3$. It turns out that the energy transferred to the target is 3 MJ. These calculations represent the physical and engineering foundations of the laser weapon. Not many states possess this terrible weapon which is effective against a cloud of drones or missiles. It is important that they are destroyed in space which has become extreme in order to reduce the destructive effects of the deadly blast.

## 6 Conclusions

The following ideas can be drawn from the research carried out:

-The laser weapon destroys any material existing on Earth in fractions of a second

-Maxwell's relations establish the values of the electric and magnetic fields that generate laser light

-Experiments with gas or fiber lasers lead to the identification of important physical quantities for the description of the attack based on melting and the expulsion of the material.

-For the Hardox 400 material, examined with the 10 KW fiber laser, we obtained a melting volume with a value of in 0.92 $mm^3$in which the thermal energy of 3 MJ was concentrated in the center of the spot by the

stationary piercing method and which dissipated through thermal conductivity in the metal.
-An impact result is that the mathematical relation for the electric field of the laser radiation when it encounters the target was obtained.

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