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Analysis and Calculations of Laser Damage Threshold for Optical Components Soft Damage

by

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Abstract

Laser Weapons destruction capabilities are classified into hard and soft destruction. In this paper laser soft damage of an IR seeker was studied and CW laser power required for damaging (disturbing) a commercial CCD camera at different distance was calculated. An existing Cw Nd-YAG 130 W solid state laser source was enhanced and used to damage a CCD camera at 2 km, enhancement was performed in terms of power threshold, radiation transfer efficiency, beam overlap efficiency, and partial mirror reflectivity. A study of generation of 135 W output power from a Cw end pumping master oscillator power amplifier (MOPA) Nd doped double clad fiber laser was done to achieve the goal of disturbing a CCD camera. Finally Optimization of laser output power was performed to fulfill the required laser power level that is needed to disturb or damage a CCD camera.

Keywords: Laser soft damage**,** power threshold, radiation transfer efficiency, Beam overlap efficiency, MOPA.

1. INTRODUCTION

Laser weapons are divided into two kinds according to their destruction effect. First type is the soft destruction in which laser destroys some devices of IR seeker, such as optical system, the electronic primary device, or the photo detector. This damaging effect causes system's function to be lost. The second type is the hard destruction in which laser destroys missile's cowling, the power unit, or the warhead. The hard destruction is ruinous where the system loses the bearing capacity to present the detonation. Usually, laser destruction threshold level of soft destruction is lower than that of hard destruction [1]. Many researches [2−6] have been performed to understand damage initiation and damage growth. Mechanism of laser disturbance to photoelectric detector has been studied by many scholars [7,8]. Incidenceof high power laser on a camera causes distortion for the light distribution that is derived from the lens, and laser can induce large electrons generation causing also a charge distribution distortion for the light that is derived from the sensor [13]. Saturation threshold and damage threshold are obtained experimentally in [9]. But it is quite rare that necessary laser energy can be inferred based on these published known data. Laser countermeasures techniques that are used against infrared focal plane array cameras aim to saturate the full camera image. A 1.06μm Nd-YAG 130 W solid state laser system disturbing a CCD imaging system was accomplished in [10]. MOPA is another technique that can be used to generate 135 W from Nd doped double clad fiber laser using end pumping master oscillator power amplifier (MOPA).

2. laser soft damage for ir seeker using solid state laser system:

In this section we will discuss the relations between the main parameters that can affect the laser soft damage of and IR seeker using a solid state laser system.

2.1 Relation between laser damage threshold and laser output power

Assuming a continuous emission from the laser source and suppose that p_{ldt} is the laser power threshold of IR seeker detector, p_{out} is the laser output power at the source, τ_1 is transmission coefficient, τ_2 is fairing through coefficient, τ_3 is filter through coefficient, τ_4 modulation coefficient, D_1 is lens diameter of seeker, D_2 is detector photosensitive diameter, and a is spot radius. Then the relation between laser damage threshold and laser output power can be written as [11]:

$$p_{ldt} = \frac{0.838 p_{out} \tau_1 \tau_2 \tau_3 \tau_4}{\pi a^2} \frac{D_1^2}{D_2^2} \quad W/cm^2 \tag{1}$$

and

$$a = R\,\Theta \quad . \tag{2}$$

and

$$\Theta = 2.33 \lambda B / d_0 \tag{3}$$

Where R is the propagation distance, ϴ is aperture angle of laser source (mrad), B is beam quality factor, λ is laser beam wavelength, and d_0 is laser launch telescope aperture. CCD detector melting damage threshold power density equals to 80 W/cm^2 [12], then the required laser power for disturbing a CCD detector at different distances can be obtained as shown in Fig.1.

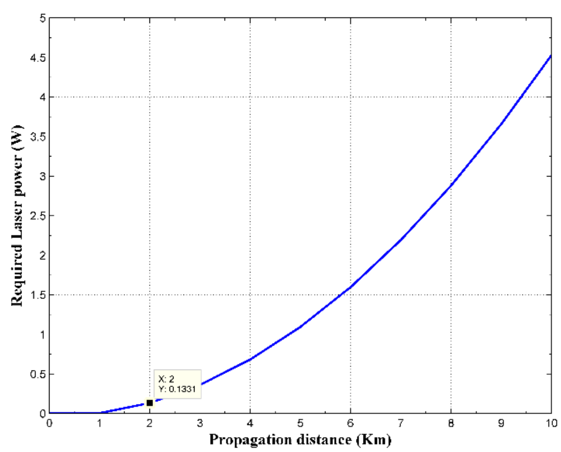

Fig.1: Laser output power required for damage CCD camera IR detector at different distances

As expected we notice that the laser power required for disturbing a camera increases with distance increase. The required laser power for disturbing camera at 2 km was found to be around 133 W as shown in Fig. 1.

2.2 Enhancement of output power of a 1064 µm 130 W laser for damaging IR detector of a CCD camera

A solid state Nd-YAG laser source of 130 W output power is used as a laser source to calculate the distance at which the detector of CCD camera will be disturbed. By substituting in equation (1) with the values of output power and laser damage threshold of detector we found that the distance at which the detector will be damaged can greater than 2 km. To enhance the output power of this laser source we studied the relation between the output laser power and power threshold as follows:

$$p_{out}=\eta_s(p_{od}-p_{th}) \quad (4)$$

And the power threshold can be expressed as follows [14, 15]

$$p_{th}=\frac{(L-\mathrm{Ln}\,R)AI_s}{2\eta_a\eta_p\eta_B\eta_u\eta_T} \quad (5)$$

Where η_a is absorption efficiency, η_B is beam overlap efficiency, η_p is pump source efficiency, η_T radiation transfer efficiency, η_u is upper level efficiency, I_s is saturation intensity of active medium, A is cross section area of active media, L is the internal losses, and $\mathrm{Ln}\,R$ is partial mirror reflectivity. The improvement (decreasing) of power threshold will reflect postiveley on the laser output power.

2.3 Relation between P_{th} with η_B at Different values for η_T

Beam overlap efficiency depends on losses of resonator components and output coupler optimization while radiation transfer efficiency depends on reflector/optics design [16]. Based on equation (4,5); different laser sources from different suppliers implies difference in power threshold values thus different values for laser output power as shown in figure 2. The improvement in beam overlap efficiency and radiation transfer efficiency will lead to a change in the value of required power threshold.

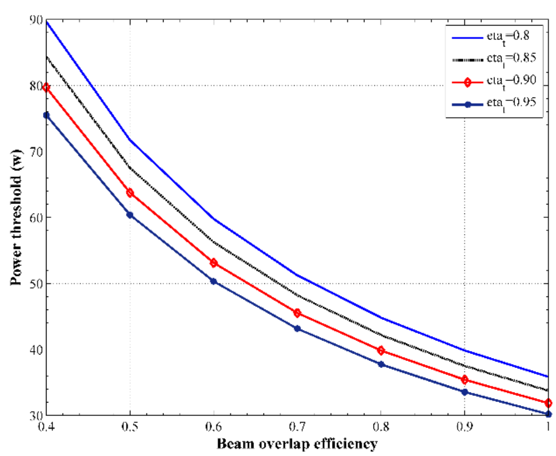

Fig.2: Power threshold with beam overlap efficiency at different radiation transfer efficiency.

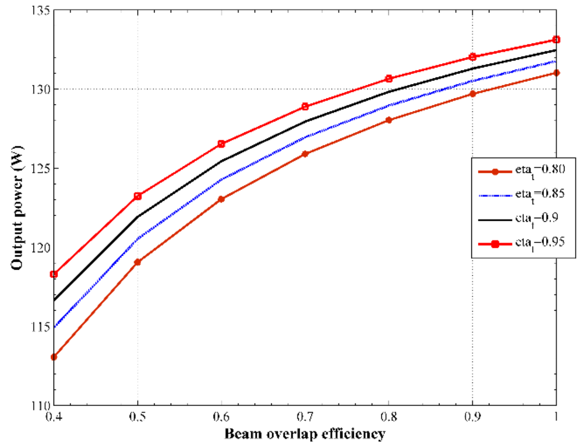

Fig.3: Laser output power with beam overlap efficiency at different radiation transfer efficiency.

By substituting in equation (4) Laser output power can be increased to the desired disturbing power levels by increasing the beam overlap efficiency and radiation transfer efficiency, this can be achieved by the good design of optical resonator as shown in figure 3.

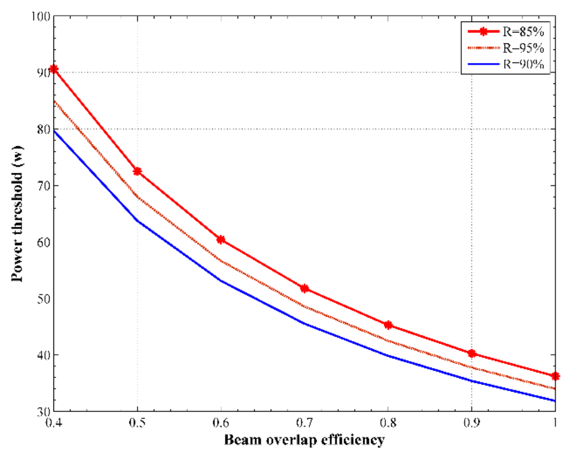

Fig.4: Power threshold with beam overlap efficiency at different output coupler reflectivity

2.4 Relation between Power threshold and η_B at a different value of R (output reflectivity)

Based on Equation (4); Figure (4) shows the relation between η_B and P_{th} for different values of (R), at fixed values of η_T =0.85, and L=0.1. Here we notice the decrease in P_{th} with increasing the values of (R). On the other hand the increase in ηB beside the increase of R leads to an additional decrease in P_{th} values. The reason of this effect can be attributed to the increase in system gain due to the increase in extracting power from the medium by increasing the number of the photon round trips (this is true for specific values of R). The decrease here is larger than that obtained from the last relation (relationship of P_{th} with η_B and η_T), this means that, the effect of R is more effective than η_T.By substituting in equation(4) Then the laser output power will be as shown in figure 5.

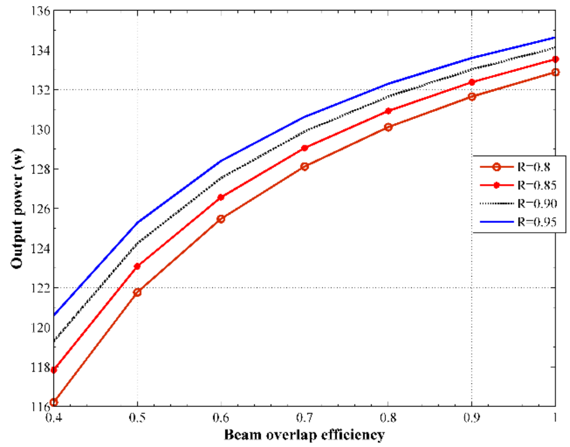

Fig.5: laser output power against beam overlap efficiency at different output coupler reflectivity.

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3. laser soft damage for ir seeker using Fiber laser system:

In this section we will discuss the usage of fiber laser systems in soft damaging of an IR seeker based on MOPA.

3.1Generating OF HIGH output power from fiber laser

Fiber lasers offer several advantages over conventional solid-state and chemical lasers; including compactness, near diffraction-limited beam quality, superior thermo-optical properties, broad gain bandwidth, high output power efficiency, and large saturation power. The most dominant techniques that are utilized for power scaling of the fiber lasers include distributed side-pumping based on multifiber series [16] and end-pumped MOPA configuration [17].

3.2 Nd doped double clad fiber Cw end pumping master oscillator power amplifier (MOPA)

End-pumping is the conventional method that is usually used to couple pump power into the double-clad fiber. A very convenient solution for of power scaling when the injection pump power is limited is MOPA that is shown in figure.6 [19]. It consists of a master oscillator and several cascaded booster amplifier series as indicated in figure. They were built up by fusion splice, which made the all-fiber laser system require less maintenance and no misalignments. The laser seed is transmitted into the fiber amplifier core and the pump light is injected into the inner clad.

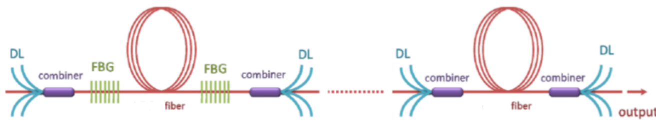

Fig.6: MOPA schemes for amplifying of fiber laser seed in forward pumping

For CW lasers the time-independent steady-state rate-equations can be expressed as [19-21];

$$\frac{N_2(z,\lambda)}{N} = \frac{\Gamma_p(\lambda)\lambda_p\sigma_{ap}(\lambda)[P_p^+(z,\lambda)+P_p^-(z,\lambda)]+\Gamma_s(\lambda)\lambda_s\sigma_{as}(\lambda)[P_s^+(z,\lambda)+P_s^-(z,\lambda)]}{\Gamma_p(\lambda)\lambda_p[\sigma_{ap}(\lambda)+\sigma_{ep}(\lambda)][P_p^+(z,\lambda)+P_p^-(z,\lambda)]+\frac{hcA}{\tau}+\Gamma_s(\lambda)\lambda_s[\sigma_{as}(\lambda)+\sigma_{es}(\lambda)][P_s^+(z,\lambda)+P_s^-(z,\lambda)]} \tag{6}$$

$$\pm\frac{dP_p^{\pm}(z,\lambda)}{dz} = \Gamma_p(\lambda)\left[(\sigma_{ap}(\lambda)+\sigma_{ep}(\lambda))N_2 - \sigma_{ap}(\lambda)N\right] P_p^{\pm}(z,\lambda) - \alpha_p P_p^{\pm}(z,\lambda) \tag{7}$$

$$\pm\frac{dP_s^{\pm}(z,\lambda)}{dz} = \Gamma_s(\lambda)[(\sigma_{as}(\lambda)+\sigma_{es}(\lambda))N_2 - \sigma_{as}(\lambda)N]\, P_s^{\pm}(z,\lambda) - \alpha_s P_s^{\pm}(z,\lambda) \tag{8}$$

Where, $P_p^{\pm}(z,\lambda)$ and $P_s^{\pm}(z,\lambda)$ are the pump and signal powers propagating in the fiber and the plus/minus superscripts refers to propagation along the positive/negative z-direction. Equation (6) describes the variation of the upper lasing level population density, N_2 (z), along the fiber length. The dopant concentration per unit volume (N) is kept invariant to be independent of position z along the fiber core and A is the cross-section area of the core. λ_s (λ_p) is the oscillation (pump) wavelength, Γ_s (Γ_p) ascertains signal (pump) power filling factor, σ_{as} ((σ_{ap}) and σ_{es} (σ_{ep}) denote signal (pump) absorption and emission cross sections, respectively. α_p and α_s represent scattering losses at pump and signal frequency, and spontaneous lifetime is represented by τ. For a CW amplifier, the set of coupled steady-state rate equations are the same as shown equations (6)-(8) except $P_s^-(z)$=0. The rate-equations are solved for a CW fiber laser subject to the following boundary conditions:

$$P_p^+(0) = \eta_1 * P_p(t) \tag{9}$$

$$P_s^+(0) = R_1 * P_s^-(0) \tag{10}$$

$$P_s^-(l) = R_2 * P_s^+(l) \tag{11}$$

Where η_1 ascertains coupling efficiency, R_1 and R_2 are the reflectivity coefficients of signal wavelength at z=0 and L respectively and $P_p(t)$ denotes the total pump power. For a single Nd doped double clad fiber and pumping power of 35 W and fiber length of 10 m, the output laser power is shown in figure.7.

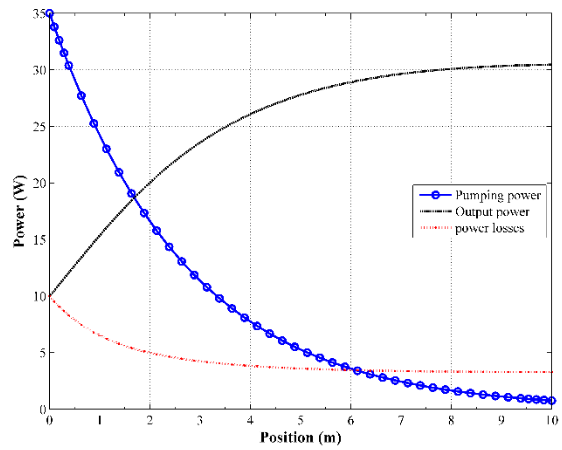

Fig.7: Pump and signal power distribution along the fiber length.

By using 35 W laser diodes pumping source we get an output power around 30 W with an optical efficiency of 85 %. The output power for MOPA array at the total fiber length of 50m and total pumping power 175 W applied on an equalized portions of fiber length as shown in Fig. 8. The output power from master oscillator are amplified through four cascaded Nd doped double clad fiber each one pumped with an equivalent summation of 7 laser diodes power of 5 W for each diode. The net obtained power around 131 W.

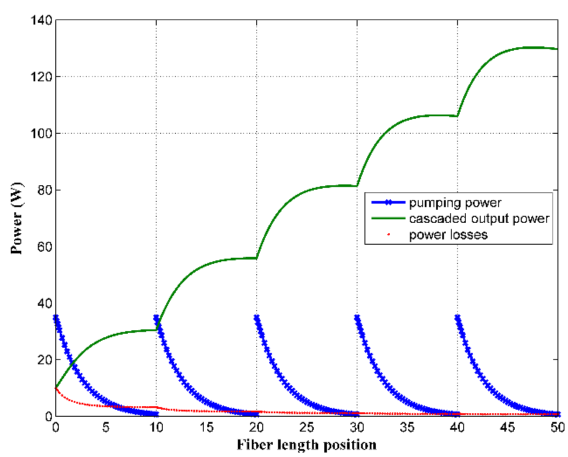

Fig.8: Pump and signal power distribution along the fiber in MOPA scheme for 4 amplifier stages following a master oscillator.

4.Conclusion

Soft destruction of optical components can be achieved by using suitable laser source and suitable output power. The laser output power and the performance of any solid state laser source depend on its internal efficiencies such as Beam overlap efficiency, and Radiation transfer efficiency which mainly vary with the structure of the laser source. The output coupler reflectivity play main role in increasing the gain inside the resonator and magnifying the output laser power. Double clad fiber laser has more advantages than solid state laser from a point of view of required pumping power, and optical power transfer efficiency. In our future work we will increase the output of Nd-YAG solid state laser by design multistage amplifiers to achieve a far damage (disturb) distance for CCD camera. We will study laser damage threshold of different detector types.

5. References

[1] Y. J. He, J. C. Ren, Y. W. Liu, "Military Laser Technique," Beijing , Hai Cao Press, 2004
[2] S. Papernov, A. W. Schmid, "Laser-induced surface damage of optical materials: absorption sources, initiation, growth, and mitigation", Proc. SPIE 7132, Laser-Induced Damage in Optical Materials: 2008
[3] H. Bercegol, P. Bouchut, L. Lamaignere, B. Le Garrec, G. Raze, "The impact of laser damage on the lifetime of optical components in fusion lasers," in Proceedings of Laser-induced Damage in Optical Materials : 2003, G. J. Exarhos, A. H. Guenther, N. Kaiser, K. L. Lewis, M. J. Soileau, C. J. Stolz, Eds, Proc. SPIE 5273, pp 312-324 (2004).
[4] Han W, Huang W, Wang F, Li k, Feng B, Li F, Jing F and Zheng W " The effect of laser beam size on laser-induced damage performance" 2010 Chin.phys.B19 106105.
[5]Xiang X, Chen M, Zu X, Zhu S, and Wang L "Numerical simulation of the modulation to incident laser by the repaired damage site in a fused silica subsurface" 2010 chin. Phys. B 19 018107.
[6] Liu F, Zhang L AND LI. G "Laser-induced damage on large aperture fused silica gratings" 2005 Chin. Phys. 14 2145
[7] Z. J. Liu, Q. S. Lu and Z. P. Jiang, "The underwater laser target detection and its development," Laser Technology, vol. 18, pp. 344-347, Dec. 1994.
[8] T. H. Liu, H. R. Zhong and Q. S. Lu, "Study on mechanism of laser damage in photoelectric," Laser Journal, vol. 22, pp. 5-8, Dec. 2001.
[9] G. G. Ren, "Current situation and development trend of high energy laser weapon" Laser and Optoelectronics Progress, vol. 45, pp. 61-69, Sep. 2008.
[10] Tamer Kashef, Samy Ghoniemy, and Ayman Mokhtar, "Robust modeling and performance analysis of high-power diode side-pumped solid-state laser systems," Appl. Opt. 54, 10666-10677 (2015).
[11] C. J. Yang and J. Z. Zhou, "Study on calculation of minimum laser energy of sheet metal deformation by laser shock forming," Optics and Precision, vol. 15, pp. 396-400, Mar. 2007.
[12] C. J. Ke and C. Y. Wan, "Analysis of Laser Damage on Infrared Detectors,". Optical Technique. vol. 28, pp. 118122, Mar. 2002.
[13] Z.Zhang, J.Zhang, B.Shao, D.Cheng, X.Ye,G.Feng, "Typical Effects of Laser Dazzling CCD Camera " in Proc. of SPIE Vol. 9543, 2015, pp.95430A1-95430A7.
[14] R. L. Burnham, G. Witt, D. DiBiase, K. Le, and W. Koechner, Diodepumped solid state lasers with kilowatt average power," Proc. SPIE 2206, pp. 489- 498, 1994.
[15] Zendzian W. Optimization of energetic parameters of passively Q-switched lasers. Opt Appl; 30:383–99, 2000.
[16] Yan, P., Gong, M., Li, C., Ou, P. and Xu, A., "Distributed pumping multifiber series fiber laser," Optics Express, 13(7), 2699–2706 (2005).

[18] Yin, S., Yan, P. and Gong, M., “End-pumped 300 W continuous-wave ytterbium-doped all-fiber laser with master oscillator multi-stage power amplifiers configuration,” Optics express, 16(22), 17864–17869 (2008).
[19] Yuan Y, Gong M, Li C, Yan P. Theoretical and experimental study on transverse mode competition in a partial-coiled multimode fiber laser. Laser Physics 2008; 18:52–7.
[20] Parvin, P., Ilchi-Ghazaani, M., Bananej, A. and Lali-Dastjerdi, Z., “Small signal gain and saturation intensity of a Yb: Silica fiber MOPA system,” Optics & Laser Technology, [21] 41(7), 885–891 (2009). [5] Parvin, P., Ilchi-Ghazaani, M., Bananej, A. and Lali-Dastjerdi, Z., “Modeling a CW Single-Frequency Yb: silica Fiber MOPA System and Determination the Gain and Saturation in the Optimum Length,” in Photonics Global conference @ Singapore. Proc. IEEE, 1–4 (2008)