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W15P8S Commander
U. S. Army Electronics Command
Attn: CS TA Lab.
Electro-Optics Technical Area
AMSEL-CT-L
Fort Monmouth, New Jersey 07703

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Subject: Quarterly Report on Contract (15) DAAB07-74-C-0028 for the Period January 1, 1974, through March 31, 1974.

Project Title: (6) Reduction of Thermal Blooming by Beam Optimization.

Contracting Officer: Dr. Rudolph G. Buser

Principal Investigator: Dr. David C. Smith

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Gentlemen: (10) F. G./Gebhardt

The United Aircraft Research Laboratories are herewith pleased to deliver the second Quarterly Technical Report under Contract DAAB07-74-C-0028 in accordance with the approval and instructions received verbally from the technical monitor Dr. R. G. Buser in the telephone conversation of May 8, 1974.

(14) UARL-N921769-2

Very truly yours,

UNITED AIRCRAFT CORPORATION
Research Laboratories

David C. Smith
Principal Scientist
Gas Laser Physics

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Enclosures: (150)
cc: Dr. Rudolph G. Buser

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United Aircraft Research Laboratories UNITED AIRCRAFT CORPORATION

Report No.: N921769-2
Date: April 11, 1974
Prepared by: F. G. Gebhardt

W15P8S Commander
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Subject: Quarterly Report on Contract DAAB07-74-C-0028 for the Period January 1, 1974, through March 31, 1974.

Gentlemen:

(1) The United Aircraft Research Laboratories are engaged in an experimental and theoretical research program to determine the optimum beam configuration to minimize thermal blooming effects on high power laser beams propagating in the atmosphere. This research is sponsored by the U. S. Army Electronics Command and represents a logical extension of the self-induced thermal distortion studies that have been carried out here at UARL during the past three years under the sponsorship of both the Army and the Office of Naval Research. In this letter, progress on the subject contract is reported for the quarterly period of January 1, 1974, through March 31, 1974. During the past quarter progress has been made in the following areas: 1) calculations of beam shaping effects on thermal blooming; 2) the reciprocity approach to the correction of thermal blooming; 3) the analysis of MO phase correction for blooming reduction in a GDL MOPA system; and 4) the study of thermal blooming effects on multiple pulse or pulse train propagation. The results of this work including future research plans are discussed in the following paragraphs.

(2) The study of the influence on blooming of different beam shapes described in the last report has been extended to include the infinite Gaussian and the linear ramp with reversed orientation, i.e., with the abrupt edge facing into the wind. Several interesting things were observed in the results. First, with the infinite Gaussian beam the shape of the target intensity versus power curve is significantly different than for the truncated uniform, Gaussian and ramp beam shapes. With the infinite Gaussian beam the target intensity initially increases much more rapidly

and reaches its maximum value at a much lower power level than for the other beam shapes. Furthermore, beyond the value of P_{crit} the infinite Gaussian target intensity falls off much more rapidly than for the other beam shapes which tend to almost saturate and have a very large range of power levels for which the intensity change is small. For the conditions examined, which are described in the previous report (UAR-N921769-1, January 11, 1974) the maximum target intensity for the infinite Gaussian is about 90 percent of the maximum for the uniform beam, but it occurs at a power level P_{crit} that is about one-third of the value of P_{crit} for the uniform beam. These results show that blooming estimates based on infinite Gaussian beams may tend to exagerate the amount of blooming loss a more realistic beam shape may encounter and also to underestimate the value of P_{crit} for the truncated beam shapes. The second point to be discussed is with regard to the results for the linear ramp beam oriented in reverse or 180° from that used in the last report. With this orientation there is a noticeable reduction in the blooming effects relative to the other three truncated beam shapes. In particular, the ramp beam with the abrupt edge facing the wind gives a higher target intensity than the uniform beam, which was the best of the three previously examined, for all power levels considered. At the maximum intensity, the reversed ramp beam gives an improvement by about 1.24, 1.66 and 2.70 times over the uniform, truncated Gaussian and original ramp beams, respectively. For the annular version of the reversed linear ramp similar results are obtained with improvement factors of 1.24, 1.44 and 2.38 obtained with respect to the other three annular beam shapes. The results of these calculations are consistent with experimental results we have obtained previously in some corporate sponsored work, where the uniform and two ramp beam shapes were obtained by using a small fixed square aperture placed at the center and then over either half of the Gaussian CO_2 laser beam. There, the best orientation of the ramp was also found to be with the steep edge facing the wind. The maximum intensity for this orientation of the ramp was about a factor of two higher than with the opposite orientation; however, it was essentially the same as obtained with the aperture centered approximating a uniform beam. The explanation for the improved performance of the reversed ramp beam is currently under investigation.

(3) The numerical procedure for investigating the reciprocity approach to beam optimization has now been developed. The basic idea here is to make use for beam optimization the amplitude and phase distribtuion obtained at the transmitter by propagating through the blooming medium from the target plane with the desired diffraction limited intensity distribution assumed as the source. Thus, the amplitude and phase

shape so obtained represents, in a sense, the optimum beam shape for minimizing blooming effects because of the reciprocal relationship that holds between the transmitting and receiving plane, including the effects of the nonlinear medium. The procedure consists of calculating the source plane optical field distribution with the nonlinear propagation code for a diffraction limited Gaussian intensity profile assumed at the target corresponding to a given aperture diameter. The power assumed at the target plane is the same as would be obtained by propagation from the actual source plane taking attenuation by the medium into account. Further, a negative absorption coefficient is used to increase the power as the beam propagates to the source, which makes the strength of the thermal blooming exactly the same as in the real case where the beam propagates toward the target. Using the resulting phase and amplitude distribution as the source, one finds that the original ideal target intensity distribution is recovered with no reduction in intensity due to thermal blooming. The basic problem with this scheme, however, is that the aperture size required for the optimum beam shape is increased by the blooming. For example, with a particular set of blooming conditions such that N=5.44 and a truncated Gaussian source beam 28 cm in diameter, the average target intensity is only about 16 percent of the value that would be obtained for an infinite diffraction limited Gaussian source. Using the optimum beam shape determined by reciprocity increases the target intensity by a factor of 6.2 to the ideal diffraction limited value; however, a rectangular aperture of approximately 52 x 104 cm^2 or, about 8.8 times the area of the original beam, is required. We have looked at how the improvement with the optimum beam shape depends on the aperture size by truncating it with circular apertures of various diameters. As the optimum beam shape is truncated by circular apertures of 80, 60, 40 and 28 cm in diameter, the amount of improvement in the average target intensity is reduced from 6.2 to 5.8, 4.2, 2.3 and 1.3, respectively. Actually, a more realistic way of viewing the improvement obtained with the optimum beam shape would be by making the comparison with the results obtained for an unshaped beam, e.g., a uniform profile, with the same aperture diameter. Future plans for these studies include modifying the numerical procedure to account for beam slewing, which is generally encountered in situations of practical interest. Also, the optimum phase shape obtained by reciprocity will be compared with the conventional perturbation approaches to determine if it can provide a greater reduction in blooming effects for a fixed aperture diameter.

(4) Regarding the MOPA phase correction work the basic approach is to examine its feasibility by using a numerical model for the GDL amplifier

medium. The first step will be to look at the effect of the GDL medium on the output phase of the amplifier to see if and how it may be controlled by adjusting the initial low power MO beam phase. If initial results suggest that this is feasible then the GDL model will be combined with our cw blooming code to evaluate directly the use of MO phase correction to compensate for thermal blooming.

(5) The initial task of obtaining a suitable numerical model for the GDL medium is being approached in two different ways. The first involves the modification of an existing FFT propagation and kinetics code currently being used for chemical laser studies here at UARL. This work is expected to provide a code for modeling the GDL amplifier with regard to the gain and saturation effects for the specific geometry and number of passes involved. Preliminary runs involving a single pass through the amplifier have been made and are currently being evaluated. The second option that is available is to make use of Ed Sziklas' GDL code at FRDC. Current plans are for several single pass runs to be made with this code early in the next report period. While these code results will not model the four pass geometry of the TSL device, this approach has the advantage of including the refractive effects of the nozzle shock waves. Comparision and evaluation of the results obtained from the two approaches will be made to determine which should be used for the subsequent work of establishing the feasibility and effectiveness of the MOPA phase correction concept.

(6) Recent communications with the program technical monitor, Dr. R. G. Buser, and Dr. T. G. Miller at MICOM, have involved the discussion of plans for an experiment to examine the thermal blooming of a train of CO_2 laser pulses. The purpose of the experiment is to determine under what conditions it is advantageous to propagate a train of laser pulses as compared to a cw laser beam of the same average power. Also, from the experiments, quantitative data and benchmarks for the theoretical analysis carried out at MICOM on this problem would be obtained. This will be a cooperative effort with Dr. R. G. Buser of ECOM who is providing the beam diagnostics for the experiment. The major problem associated with the experiment is obtaining a high enough repetition rate from the TEA CO_2 electrically pulsed laser. We have operated TEA lasers for a number of years and have several in continuous operation on other experimental programs. We have also examined the problems associated with high repetition rates and are confident that this problem can be handled in a relatively short period of time. In the following paragraphs some of the specifics associated with the planned program are described.

(7) The problem we are addressing is the thermal blooming of a train of pulses and comparison of this with cw laser beams. It is assumed that the laser pulse is sufficiently short in duration that a thermal lens does not form during the pulse itself. This requires that the laser pulse duration be less than the acoustic transit time across the beam. Subsequent pulses in the train will be distorted and the amount will depend on the repetition rate and other parameters. The problem is determining how much is gained by pulsing the laser and this depends very critically upon the pulsed repetition rate compared to the gas transit time across the beam. For a slewed beam or a focused beam this time is a variable depending on the distance from the laser source. For the sake of defining the problem we have analyzed the non-dimensional parameters which must be simulated in a laboratory experiment. These parameters are listed below

$$N = \frac{\alpha P \mu_T Z^2 F}{\pi c_p a^3 V}$$ - distortion parameter defined by the cw or average power and uniform wind

αZ = absorption length, generally less than one

F - Fresnel number = ka^2/z,

$R = t_b/tw$ - ratio of time between pulses to the wind transit time

v_o/v_t - ratio of initial and final wind velocity

where α is the linear attenuation coefficient, P the laser power (average for pulsed and the cw power for continuous laser sources) μ_T the index of refraction change with temperature, Z the range, ρ the gas density, c_p the specific heat, a the e^{-1} beam radius for a gaussian beam shape, V the transverse wind velocity, k the wave number of the laser radiation $(2\pi/\lambda)$. In addition to these non-dimensional parameters there are also inequalities which must be satisfied in the experiments in order to simulate the atmospheric propagation problem. These are

$$v >> \left(\frac{\alpha P g}{\rho c_p T}\right)^{1/3}$$

$$v >> \frac{k}{\rho c_p a}$$

$$\Delta T/T << 1$$

$$tp << ta = a/Va$$

where g is the acceleration of gravity, ΔT is the gas temperature rise caused by the absorbed laser power and V_a is the acoustic velocity (for STP air $V_a = 3 \times 10^4$ cm/sec). The first two inequalities insure that the convection heat transfer dominates over natural convection and thermal conduction. In our experiments we have found that one way the first inequality can be satisfied is by operating the cell in the vertical direction thus reducing the influence of natural convection; the second inequality is met by operating the absorption cell at 10 atmospheres. The maximum temperature rise is also kept within reasonable limits in our experiments. For our apparatus the beam radius is typically never smaller than one mm so $t_a = 3 \times 10^{-6}$ sec and so the last inequality is met by using pulses shorter than a μ sec. It has also been found that if the Fresnel number is of the same order there is little difference in the thermal distortion and the same is true of αZ. Strictly speaking these two parameters have some latitude in accurate simulation. In order to compare the pulsed and cw blooming it is necessary to have sufficient average power in the pulsed case to observe the same thermal blooming as occurs in the cw case. Severe distortion occurs when N is greater than unity. In fact the peak intensity vs power decreases for further increases in laser power for an N of ~ 4. We will use this value of N to calculate the power requirements for the laboratory simulation.

(8) Typical parameters for the laboratory simulation are:

$\alpha = 10^{-3} \text{cm}^{-1}$ $F = 5$ $\mu_t = 10^{-5}$

$Z = 10^2$ cm $\rho = 10^{-2} \text{gm cm}^{-3}$

$a = 0.3$ cm $c_p = 1.0$ J/gm°K

Using these values, we can calculate the power required to simulate an N of 3.

$$P = \frac{\pi c_p a^3 V N}{a \mu_T Z^2 F} = 1.6 \text{ watts}$$

Thus a very low power is required. In order to allow flexibility and to allow parametric studies we will try for 10 watts of average power with 10 pps. We can then vary the wind by an order of magnitude and therefore vary the ratio of t_b/tw from 0.3 to 3. This ratio is calculated for the initial beam size and for the focused case there is another factor of 5 reduction in this ratio calculated at the end of the cell. For small values of R the blooming is effectively cw and for values greater than one the thermal blooming should be effectively eliminated. The range of most interest and the least understood is R in the range of 0.1 to 2 and this is the range that the experiments will be concentrated on, keeping the value of N approximately the same, by varying the average power, absorption coefficient and wind velocity.

(9) The laser source to be used in this study is a TEA electric discharge CO_2 laser that is presently being tested at the Research Laboratories. Typical outputs are $\sim$ 10 joules per pulse with a pulse consisting of a 100 nsec spike followed by a one μ sec low intensity tail. The laser box has been designed to allow transverse gas flow and we anticipate that we will be able to operate this laser at 10 pulses per second. A significant reduction in pulse energy is expected in order to operate the laser in the fundamental mode. From past experience a factor of 4 or 5 reduction in power is anticipated and so we have a factor of two margin for errors and should have no problem generating the 10 watts of average power at 10 pps.

(10) The absorption cell to be used in the experiments is presently being used in other thermal blooming tests. It is a 5 cm diameter one meter long cell with AR coated germanium windows. The cell is translated relative to a fixed CO_2 laser beam thus simulating a uniform wind. Provisions are also made for pivoting the cell about a fixed point to simulate a slewing condition. Because of the time involved we do not plan to use slewing but rather concentrate on the uniform wind case which should be a case that is easiest to analyze and compare with theory.

(11) There are several detector schemes that can be used in the experiment. We have available gold doped germanium detectors which can follow the fast rise time of the TEA laser and measure the intensity at a fixed point as a function of time. Thermopile detectors are also available for scanning the profile of the average intensity of the thermally distorted beam. "Power in a bucket" type measurement are the simplest to perform where the average power in a fixed (but variable) radius aperture is measured.

(12) Recently, one day of cooperative experiments were carried out with Drs. R. G. Buser and R. S. Rohde. The tests involved monitoring the distortion of a low power cw CO_2 laser probe beam subsequent to the transmission of a single TEA laser pulse coaxially through the moving absorption cell. This data, which is currently being analyzed, should give some results for the dependance of the pulse train blooming on the ratio of the interpulse spacing relative to the wind transit time across the beam. Efforts are also in progress to increase the TEA laser repetition rate to about 10 pps with an average power of 5-10 W.

Very truly yours,

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