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STUDY ON THE PROPAGATION OF HIGH-POWER LASER  
BEAMS IN THE ATMOSPHERE

by

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STUDY ON THE PROPAGATION OF HIGH-POWER LASER  
BEAMS IN THE ATMOSPHERE

Guo Zhenhua, Gu Jianhui, Xu Desheng

**ABSTRACT** This article reports on studies of continuous wave high power CO<sub>2</sub> laser beam atmospheric propagation near the surface. Laser powers are 3kW-5kW. Propagation distances are 77m-107m. Patterns of changes associated with laser reception spots, given rise to by beam distortion and atmospheric influences, were obtained.

## I. INTRODUCTION

Studies of laser beam propagation characteristics began to be brought to the fore based on the development of sounding survey and information technology. Certain technologies among these have, at the present, already become quite mature--for example, laser range finding and laser guidance. Developing lasers to act as military weapons, such nations as the U.S. and the Soviet Union began from the 1960's and 1970's. Following the March 1983 presentation of the U.S. strategic defense initiative, lasers then formally became one of the candidate weapons. High power laser beam propagation characteristics studies also then became one of the important topics which received even more extensive and in depth research. In particular, in 1985, the success of the MIRACLE experiments [1] at the U.S. White Sands target range made people believe even more that laser strategic weapons were already not in the distant future.

In land based laser weapons systems, when laser beams pass through the atmosphere, mutual interactions are given rise to between molecules in the atmosphere, gas sol particles, and so on, thereby producing linear and nonlinear reactions. Among these, linear reactions are primarily absorption associated with gas molecules in the atmosphere and the absorption associated with atmospheric gas sol particles. Scattering leads to radiated energy being lost. Atmospheric turbulence leads to laser beam expansion and drift as well as coherence changes. Nonlinear effects are primarily atmospheric nonlinear thermal distortion effects (heat halo) and excited Raman scattering. Nonlinear effects only show up when propagated laser power densities are comparatively high.

At the present time, domestically, research reports have still not been seen with regard to continuous wave strong laser atmospheric propagation. As far as high power laser beam propagation characteristics studies which we carry out are concerned, the objective lies in observing the influences of near ground atmosphere on high power laser beam propagation characteristics. This has important significance with regard to actual applications of lasers in military and civilian areas--in particular, to their ability to develop into tactical weapons.  
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## II. EXPERIMENTAL RESEARCH

### 1. Experimental Systems and Environmental Conditions

Experimental system and environmental schematic are as shown in Fig.1. Use is made of 10kW level CW CO2 laser devices and unstable resonator lateral direction outputs. Proximate field maculae are nonuniform ring shaped light spots. During experiments, laser power is 1kW-5kW adjustable (illegible).

The environment outside the laboratory during experiments is a section of open country. The surface is undulating and not flat. It is overgrown with weeds. In the vicinity, there are groves of trees, ponds, trash disposal yards, main highways, and so on. Laser light paths are at unequal heights above the ground at 0.5m - 1.8m. As a result, the atmosphere under these types of environmental conditions is comparatively close to environmental conditions on a number of ground battlefields. Before experiments, we opened up a light channel in this type of comparatively complicated ground. In the vicinity safety indicators were set up, stipulating reliable operating regulations. During experiments, use was made of effective communications contact means. All around monitoring was implemented on the periphery of the site--guaranteeing personnel and environmental safety. On light paths, receiving targets were set up respectively 77m and 107m from the laser transmitting window. Among these, the light path reaching the receiving target at the 107m location must cross a gravel road that automotive vehicles go down. Propagation distances in air for light beams in the laboratory is 12.4m.

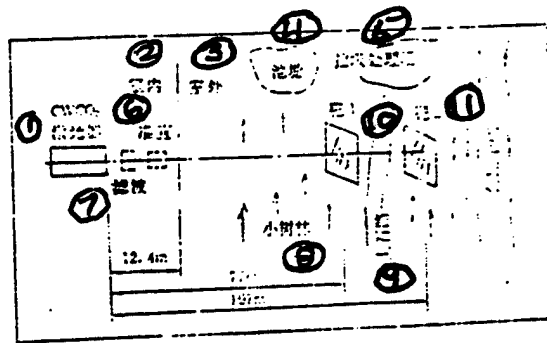


Fig.1 Laboratory System Lay Out Schematic

Key: (1) Laser (2) Indoors (3) Outdoors (4) Pond (5) Waste Disposal Yard (6) Collimation (7) Filter (8) Small Grove (9) (Illegible) (10) Target 1 (11) Target 2 (Illegible)



Fig.2 Proximate Field Light Spot

## 2. High Power Laser Beam Propagation Characteristics

Output beams associated with ten thousand watt CO<sub>2</sub> laser devices are taken and shot out to distant areas after which 4mm thick, 1m<sup>2</sup> area suppression box plates receive them. Analyses are gone through of faculae burn patterns on receiving plates in order to distinguish the status of changes in such characteristics as laser beam energy spacial distributions after going through atmospheric propagation, directionality, and so on.

Laser beam proximate field faculae are as shown in Fig.2. The diameters of inner and outer rings are, respectively, around 25mm and 40mm. The intensity distributions are not uniform. Moreover, they vary with changes in output powers. The bottom parts of round rings are very strong. The upper right corners are next. The rest of the sections are then relatively somewhat weaker.

We carried out observation measurements at 12m, 20m, 77m, and beyond 100m, respectively. At the present time, we are taking distant field faculae burn patterns received at 77m and 107m locations and displaying them respectively in Fig.3 and Fig.4. Basic phenomena which were observed on site were that, 2s to 3s after laser function, cardboard began to turn black. After 4s-5s, thick smoke began to be emitted. In conjunction with this, there was a clear localized catching fire (illegible) (Fig.5). Flames got larger and larger. Combustion losses (illegible) got deeper and deeper. At this time, portions where the surrounding optical intensity was comparatively weak also began to show up on suppression box boards. They presented a distribution of scattered small points. However, they did not reach the level of clearly catching fire. Among these, metrological conditions for one iteration were clear. Tests began at 3:30 in the afternoon. Air temperature was 25°C. There was a slight wind. Multiple iterations were also done under light rain and other metrological conditions.

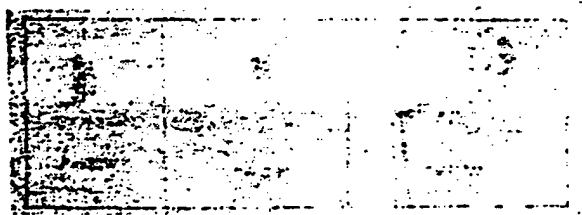


Fig.3 Ablation Patterns Associated with Different Laser Powers When the Receiving Distance is 77m

Seen in terms of results obtained from experiments, after laser beams which have not gone through collimation go through a section of atmospheric propagation, faculae form changes are

relatively great. One already does not see that type of form distribution associated with proximate fields. In the situation shown in Fig.3, when laser power is 3kW, center portion power densities associated with faculae are very large. Most of the laser energy is primarily concentrated in a 30mmx70mm region. When laser power rises to 4kW, the overall dimensional changes



Fig.4 Ablation Patterns Associated with Different Laser Powers  
When Receiving Distance Is 107 m /333

associated with faculae are not large. However, spacial distributions associated with the optical intensities still show the appearance of clear changes. Faculae are composed of a set of 4 comparatively strong light spots connected together to form a section. This type of distribution is capable of being clearly distinguished from the formation processes associated with faculae burn patterns. To begin with, 4 separate spots turn black at the same time and emit smoke. Following that, with the accumulation of time, the black spot area continuously expands. Finally, fire breaks out in a continuous section. When the laser power is 5kW, faculae distribution changes are even larger--creating irregular forms associated with scattered distributions. Seen from the point of view of laser function times and burn loss

levels, local laser power densities at this time will also be lower than for 4kW. This is due to laser output lens thermal distortions producing focusing effects close in, causing distant field beam divergences to be very large and irregular. Propagation and attenuation of laser power in the atmosphere are also made more complicated.

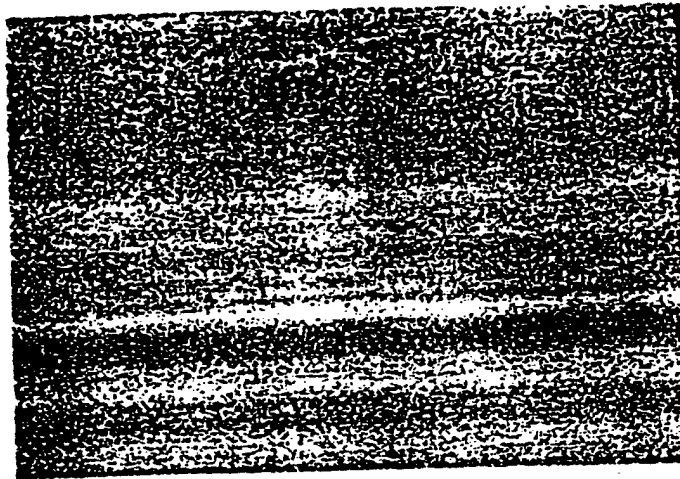


Fig.5 Target Fire in the Field at Long Range Given Rise to by Strong Laser Light

When receiving targets are placed at 107m receiving locations (Fig.4), laser powers are, respectively, 3kW, 4kW, 4.5kW, and 5kW--achieving trends basically similar to results shown in Fig.3. It is only at this time that laser intensities are clearly weakened. Faculae are more obviously scattered. In order to obtain comparatively clear faculae burn patterns--after distances are extended--we take laser function time periods and stretch them to around 10s.

### 3. Experimental Result Analysis

With regard to changes given rise to after laser beams shown in Fig.3 and Fig.4 go through atmospheric propagation--going through analysis--the preliminary belief is that they may possibly have been caused by the several types of factors below.

(1) The laser beams which experiments make use of--in and of themselves--possess a certain nonuniformity and comparatively large laser angles of divergence. After going through atmospheric propagation, sections with relatively weak edges then--because of atmospheric absorption and scattering--do not show up for short periods of time on receiving targets. Only the sections that have comparatively high power densities are then able to burn out patterns on targets relatively rapidly. However, the intensities are much weaker as compared to proximate fields. As a result, even for  $10.6\mu\text{m}$  light in the far infrared,

energy attenuation created by atmospheric absorption and scattering are still important factors.

(2) On the basis of already existing research materials, atmospheric index of refraction  $n$  is capable of being expressed using :

$$n \approx 1 + 77.6 \times (1 + 7.52 \times 10^{-3} \lambda^{-2})(P/T) \times 10^{-6} \quad (1)$$

In the equation,  $\lambda$  is light wave length.  $P$  is atmospheric pressure.  $T$  is atmospheric temperature.

Atmospheric temperature, humidity, and pressure vary randomly within small ranges and short periods of time. In equation (1), the influence of humidity has been omitted because it only accounts for 0.5%-1.0% . Therefore, atmospheric indices of refraction vary, for the most part, randomly along with temperature, causing laser beams propagating through the atmosphere to produce a series of distortion effects. Besides this, on the basis of the experimental environmental conditions introduced above, external perturbing factors giving rise to random variations in atmospheric parameters on laser propagation paths are also comparatively numerous--for example, garbage burning at the garbage disposal yard, vehicles going back and forth on highways, as well as the swaying of surrounding groves of trees, and so on. Due to the fact that what is being done is strong laser, near earth, atmospheric propagation, and the strength of surface turbulence will be much greater than for high altitudes, turbulence effects are capable of giving rise to beam expansion, faculae shake, and deteriorations in coherence characteristics. Under normal circumstances, turbulence expansion is 2-3 orders of magnitude larger than diffraction limitations, causing beam quality to drop severely. Very, very great drops in the intensity of lasers propagating through the atmosphere are also created. At the present time, what is comparatively universal outside China is to use coherence optics autoadaptive technologies to carry out compensations for beam distortions created by faculae shake as well as with regard to beam expansion. In regard to strong laser light, we have still not reached this stage.

(3) Turbulence effects appear due to the influences of factors inherent in the atmosphere. Besides this, one type of effect is nothing else than--when strong laser light passes through the atmosphere--molecules in the atmosphere as well as gas sol particles absorbing laser radiation energy and causing them to heat up themselves, thereby altering the atmospheric indices of refraction on light paths. The beam expansion and distortion created by this type of nonlinear interaction between the atmosphere and laser light is thermal halo. On the basis of the research of J.L. Walsh and others [3], when continuous light waves propagate in ideal gases, the threshold value laser power  $P$  (illegible) which is associated with the production of heat halo is capable of being expressed in the form below:

$$P_{th} = 0.1v/\alpha a \quad (2)$$

In the equation,  $v$  is fluid speed perpendicular to the direction of laser propagation.  $\alpha$  is atmospheric absorption coefficient with regard to light waves.  $a$  is characteristic lateral direction length associated with light beams. Here,  $P_{th}$  is the total power associated with propagating laser beams. Selecting appropriate values to substitute in, it is generally possible to obtain threshold value laser powers producing thermal halo in  $10.6\mu\text{m}$  lasers as being on the order of 103 W.

Laser powers which we have used in experiments have already reached threshold value laser powers associated with thermal halo. Carrying out comparisons between Fig.3, Fig.4, and Fig.2, although laser beams--after passing through the atmosphere--all give rise to distortions, following along with rises in power, however, distortions become more and more severe. The forms of distortions are also different. However, the forms of distortions for the same laser power at the same distance are basically similar. It is possible to see that atmospheric thermal halo effects cause laser beams to give rise to obvious distortions.

During experimental measurements, after laser beams stop radiating, users are capable of clearly feeling the air in the light path as very hot. Air temperature rise is approximately  $2^{\circ}\text{C}$ - $3^{\circ}\text{C}$ . It can be seen that, along the entire over 100 meter length of light paths, air has been heated because of the absorption of laser energy. As a result, atmospheric absorption is also one very important area associated with laser power losses. Moreover, heat halo effects, which are produced by this, directly give rise to laser beam expansion and distortion--severely influencing propagation results. Compared to lasers with other wave lengths, despite the fact that  $10.6\mu\text{m}$  CO2 lasers are the ideal window for atmospheric propagation, with regard, however, to high power laser beam propagation and atmospheric absorption, they are still factors which it is not permissible to ignore.

On the basis of reports relating to lasers heating the atmosphere [3], in 1989, the Soviet Union's Kuerqiatuofu (phonetic) research institute made use of CO2 laser beams associated with electron beam pumps and was able to burn a path out in the atmosphere. The laser power was 1MW. Beam diameter was 13cm-20cm. This type of laser output power causes it to enter into the category of high energy laser weapons. At the same time, this type of path burned out beforehand in the atmosphere using laser beams is capable of being used in order to propagate other laser beams. It supplies another new type of technology and path for laser propagation through the atmosphere.

### III. CONCLUSIONS AND DISCUSSION

Seen from the point of view of experimental observations and analysis of results, as far as near ground atmospheric propagation of strong lasers is concerned--because of absorption associated with atmospheric molecules making laser power losses comparatively great and atmospheric turbulence effects and nonlinear thermal halo effects giving rise to beam expansion and distortions--these are important factors severely influencing high power laser beam atmospheric propagation. Despite the fact that we used the atmospheric effects above to carry out preliminary explanations with regard to experimental results, detailed mechanisms and effects associated with strong laser atmospheric propagation, however, await further study.

With regard to this first instance of the realization in China of ten thousand watt level continuous wave high power laser beam atmospheric propagation, precious first hand materials were obtained, laying an experimental foundation for research associated with mechanisms in strong laser distant field target hits as well as destruction. In order to obtain more ideal propagation results, it is necessary to improve beam quality a step further, advancing laser transmission systems and perfecting the means associated with faculae reception and corresponding test measurements.

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