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AND ITS EFFECTS ON PROPAGATION

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Laser Self-focusing in the Atmosphere and Its Effects on Propagation

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Abstract: Self-focusing of a high power laser beam in the atmosphere and its relations with air-breakdown, Stimulated Raman Scattering (SRS) and thermal blooming are reviewed. The effects on the propagation through the atmosphere and the requests on designing future large practical laser systems are analyzed and discussed preliminarily.

1. Introduction

An amount of research [1] has been done on laser beam propagation through the atmosphere including linear effects [2], with absorption, scattering, etc. In recent years, however, a growing interest has been shown in non-linear effects of intense laser beam propagation through the atmosphere [3] such as thermal blooming, air-breakdown [4-5] and Stimulated Raman Scattering (SRS) [6-7]. Owing to the complexity of the atmosphere proper, many problems concerning these non-linear processes remain to be studied and at the same time, the impact of those effects on intense laser beam propagation through the atmosphere also requires comprehensive consideration.

The beam self-focusing effect was first observed in a solid body in 1964 [8], based on which the self-focusing and self-trapping effect model was built [9]. It was also discovered that self-focusing was the cause of many abnormal phenomena observed in SRS [10, 11]. Because of self-focusing, SRS rapidly began before reaching the theoretical threshold. Experiment [12] also showed that with self-focusing, the beam first reduced and then split to form numerous fine threads. This multi-thread structure arose from the weak multimode structure in the beam. If self-focusing

remained stronger than diffraction, it could continue until another non-linear optical effect (including SRS, Stimulated Brillouin Scattering (SBS), dual-proton absorption or light breakdown, etc.) started to terminate self-focusing. As far as self-focusing in the atmosphere is concerned, it attracted attention only recently.

2. Self-focusing Theory

Self-focusing is described using non-linear fluctuation equation as follows [10]:

$$\nabla^2 E - (\partial^2 / c^2 \partial t^2) [(n_1 + n_2)^2 E] = 0 \quad (1)$$

where n_1 and n_2 respectively are the linear part and non-linear part of the medium refraction ratio coefficient.

Considering a collimated laser beam, self-focusing critical power can be derived from non-attenuated medium as follows [18]:

$$P_c = \epsilon_0 n_1 c \lambda / 4 \pi n_2 \quad (2)$$

where λ is wavelength. Then

$$n = n_1 + \frac{1}{2} n_2 \left| \vec{E} \right|^2 \quad (3)$$

where $\vec{E}$ is the electrical field component of the electromagnetic wave.

By solving fluctuation equation (1), the following can be derived:

$$Z_f = \frac{Z_R}{\sqrt{P/P_c - 1}}$$

(4)

where Z_f is self-focusing length, Z_R is rayleigh distance, P is power. Variation of beam radius with distance is given in equation as follows:

$$a(z) = a_0 \sqrt{1 - (P/P_c - 1) Z^2 / Z_R^2}$$

(5)

where $a_0 = w_0 / \sqrt{2}$, w_0 is optical mid point where the beam enters the medium.

The same can be done with a non-collimated beam. In a real attenuated medium, the self-focusing length of the beam which can converge and diverge while entering the medium is smaller than the value given here due to the limitation of instability.

In an absorbing medium, the minimum power P_m which generates self-focusing is given in an equation as follows [14]:

$$P_m / P_c = 1 + \left(\frac{\pi n_1 a_1}{2\lambda} \right) a_0^4$$

(6)

where a_1 is the coefficient of the absorption item in the fluctuation equation. Critical self-focusing power increases with height index due to variation of atmospheric density.

$$Z_f = -1/a_1 \ln(1 - a_1 P/P_c)$$

(7)

where

$$P_c = \frac{\pi n_1 a_1^2}{2\lambda \sqrt{P/P_c - 1}} = \frac{n_1 Z_R}{4\sqrt{P/P_c - 1}}$$

(8)

Figure 1 shows the relationship between Z_f , a_0 , P for a 1.06 μm laser pulse ($a_1=0.035$, $P_c \approx 52 \text{ MW}$) with self-focusing in the atmosphere with one barometric pressure.

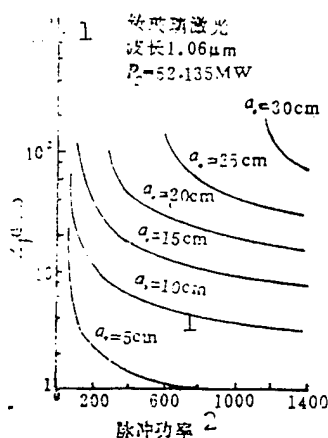


Fig. 1 Relationship between self-focusing length, laser power and initial beam radius in an absorbing atmosphere

Key: 1. Neodymium glass laser wavelength; 2. Pulse power

3. Beam Splitting and Fine Thread Formation

Since non-uniformity of the laser beam in transverse space can give rise to non-linear increase of small perturbations, the self-focusing beam will split into very intense and fine threads [12,15], whose intensity may rise to 10 GW/cm² and therefore damage the beam. In fact, it was observed that those fine beam threads sometimes would further split into even finer threads before the beam is damaged [14]. Because of beam splitting, actual focusing length is much smaller than Z_f .

Based on the theory of small perturbations developed by Akhmanov et al. [15], wave amplitude and phase distortion derived from the fluctuation equation increase with the propagation distance index whose gain coefficient is:

$$g = \frac{k_{\perp}^2}{2k} \left(\frac{8}{n_1 a_0^2 k_{\perp}^2} \cdot P/P_c - 1 \right)^{1/2} \quad (9)$$

where $\vec{k}_{\perp} = \sqrt{k_x^2 + k_y^2}$, k_x and k_y are transverse space frequency of distortion.

The duration of instability which causes formation of fine threads can be approximated as:

$$Z_c = 1/g \approx \frac{1}{\frac{1}{2} g_{max}} = \frac{kn_1 a_0^2}{P/P_c} = \frac{2\pi n_1 a_0^2}{\lambda P/P_c} \quad (10)$$

As for a laser beam with limited cross section, there can be a struggle between separation and integral self-focusing. If the total power of beam P does not exceed critical power P_c very much, then the beam will be subject to integral self-focusing instead of splitting.

Calculations of 1.06 μ m laser beam propagation in the atmosphere with one barometric pressure are shown in Figs. 2 and 3

[17]. The figures suggest that when a_0 is great, beam splitting requires a very long propagation distance and very high power; for a laser beam with an initial radius of 50 cm, a power of about 10^8 Pc is enough to cause beam splitting within the range of less than 1 km.

Recently, P. L. Kelly [18] discussed, in view of SLLS effect caused by Miker effect, the process of beam amplification through non-linear effect due to transverse non-uniformity, as well as its impact on SRS and beam splitting.

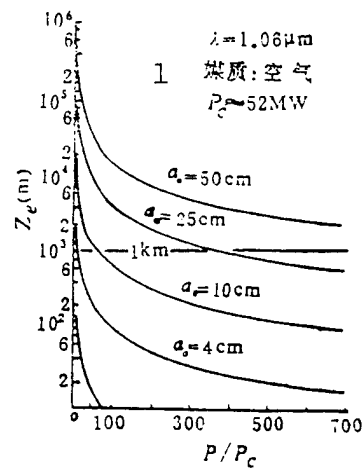


Fig. 2. Duration of instability causing formation of fine threads

Key: 1. Medium: air

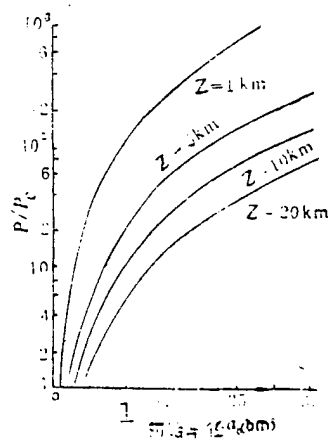


Fig. 3. Relationship between power ratio needed for beam splitting (P/P_c), beam radius and propagation distance

Key: 1. Initial radius

4. Air-breakdown

In an ideal non-linear medium, self-focusing will continue until the beam radius reaches zero at the self-focusing point (as indicated in equations (4) and (5)). In the actual atmosphere, with the increase in power density, the self-focusing beam may finally reach the breakdown point of the medium [19] and generate plasma to block itself.

Suppose I_{bd} is the power density during air-breakdown, then the distance for the self-focusing beam to reach the breakdown point can be derived from equation (5) as follows:

$$Z_{fbd} = \frac{Z_R}{\sqrt{P/P_c - 1}} \cdot \sqrt{1 - \frac{P}{2a_0^2 I_{bd}}} \quad (11)$$

Calculations (with equations (7) and (8)) on a 1.06 μm laser beam with a wide-range power (0-1400 MW) and initial radius (10-25 cm) of Z_{fbd} and Z_f suggest [17] that owing to attenuation, when the beam reaches the self-focusing point before arriving at the breakdown point, its radius may no longer reduce and may not lead to a breakdown. It is not yet clear what will happen to the beam when Z_f reaches the minimum radius; probably it will begin to diverge outward. One possibility [20] is that the beam radius will possibly oscillate between a_0 and $a(Z_f)$ when the propagation distance is much greater than Z_f . Here, beam separation from self-focusing is beyond consideration.

5. Self-focusing Window

The laser pulse configuration provides significant restrictions over self-focusing in the atmosphere. Figure 4 approximately shows the window where self-focusing is possible, which is limited by pulse width and energy.

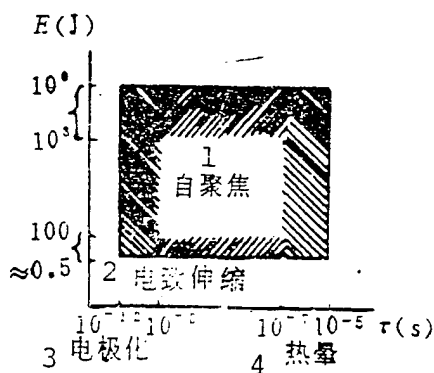


Fig. 4 Self-focusing window of neodymium glass laser pulse in the atmosphere

Key: 1. Self-focusing;
2. Electricity-caused extension; 3. Electric polarization; 4. Thermal blooming

The lower boundary of the pulse width, which is determined by the response time of the physical mechanism that makes the medium's refraction ratio change with light intensity, is located at about 1 ps for electric polarization and about 10 ns for electricity-caused extension. Its upper boundary, caused by thermal blooming, will produce the thermal blooming effect when the pulse width exceeds 100 ns-10 s. The limitation of pulse energy is rather hard to determine. Its lower boundary is acquired through multiplication of critical self-focusing power by the shortest pulse width, whereas its upper boundary is determined by beam splitting and breakdown.

6. Calculations for Upward and Downward Atmospheric Propagation

By using an actual atmospheric model, W. E. Martin and R. J. Winfield [21] made calculations for laser beam upward and downward propagation considering the self-focusing effect as well as

analyzing the possibility of beam splitting and the effect of integral self-focusing on SRS.

Figure 5 shows the decrease of beam radius with propagation distance during upward propagation due to integral self-focusing. Figure 6 suggests the relationship between atmospheric transmissivity, rotational Raman gain coefficient of nitrogen (Γ), beam splitting parameter (B) and wavelength in the case of upward propagation (3-400 km) of Gaussian beam with intensity 100 MW/cm² and radius 2 m. B describes the impact of the non-linear refraction ratio coefficient on laser beam propagation; normally in a large solid-state laser system $B > 5$, self-focusing can possibly lead to beam splitting [22,23].

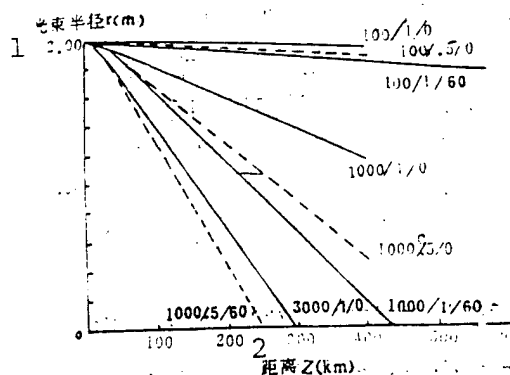


Fig. 5. Decrease of beam radius with propagation distance due to integral self-focusing during upward propagation. Notations: light intensity (MW/cm²)/wavelength (μm)/zenith angle(deg)

Key: 1.Beam radius; 2. Distance

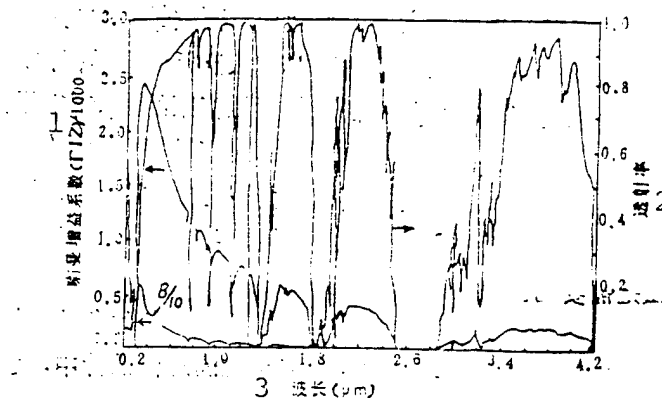


Fig. 6. Relationship between atmospheric transmissivity, rotational Raman gain coefficient of nitrogen, beam splitting parameter and wavelength. Upward propagation, 3-400 km

Key: 1. Nitrogen/Raman gain coefficient;
2. Transmissivity; 3. Wavelength

Calculations for downward propagation indicate that from space to the height of 25 km, variation of natural divergent Gaussian beam appears very small but implies a remarkable increase of non-linear effect in the case of a convergent beam. Figure 7 shows how laser beam, vertically propagating downward from 400 km in height, converges at different heights.

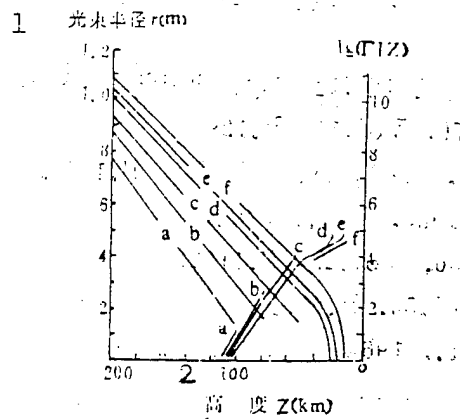


Fig. 7. Radius variation and rotational Raman gain of laser beam, focusing from space to ground. Initial height 400 km, focusing height: a. 100; b. 75; c. 50; d. 25; e. 15; f. 0 km

Key: 1. Beam radius; 2. Height

7. Result and Discussion

The self-focusing effect and thermal blooming effect are both light wave behaviors caused by the non-linear refraction ratio of an electric field-induced medium but display different physical mechanisms of generating electric field-induced refraction ratio. A laser beam with a pulse width 10 ns to 10 μ s and power ranging from $10^2 P_c$ to $10^3 P_c$ is likely to self-focus in the atmosphere, i.e. there exists a window in which self-focusing can take place (Fig. 4). Thermal blooming is a process of slow response, which is possible for longer pulse width (10 s) and for a continuous wave laser (CW); as for shorter pulse width, it is necessary to consider SLLS caused by the Miker effect.

Self-focusing may result in further beam splitting, air-breakdown and accelerating SRS, which can lead to energy loss and beam quality disruption. However, there has not been in-depth discussion on their relationships and cooperative effects. In the

actual atmosphere, according to current calculations, self-focusing does not lead to air-breakdown at least for a $1.06\mu\text{m}$ neodymium glass laser device. During upward propagation, there is the possibility of beam splitting at a particular height when its power is reduced to less than critical power due to diffraction attenuation or because of transverse non-uniformity. Contributions that self-focusing makes to gain cannot be ignored; a very large propagation distance implies emergence of very high gain. In the case of downward propagation of a convergent beam, when it converges to lower than 50 km in height, the drastic decrease of its radius caused by self-focusing may give rise to SRS, beam splitting or breakdown effects, which are disastrous. Self-focusing can exercise an even greater effect during slanting propagation, as the beam propagates over longer distances.

The most suitable method to reduce non-linear effects discussed here in this paper is to decrease beam power density. To achieve the given total energy, a longer pulse width or larger beam cross section are required. If pulse width is longer, other slower non-linear processes must be considered, whereas a larger beam cross section requires optical parts with a very large diameter or accurate fixed phases of many small beams. Due to their difference in response time, thermal blooming and self-focusing require different laser beam pulse widths. Thus, to design a practical intensive laser system, pulse width and corresponding compensation measures should be given serious consideration in view of thermal blooming and self-focusing. Considering the possibility of beam splitting, a specific requirement should be set for the quality of the laser beam transverse module. To prevent a high-powered laser beam from self-focusing, beam transverse distortion should be minimized as much as possible by using a space filter. In addition, careful study of the SRS effect is also required, as well as taking the self-focusing effect and SLLS effect into consideration.

To design a large applied laser system, various parameters should be examined so as to pick out the optimum value to meet special needs. In any case, non-linear processes including self-focusing need to be considered in the overall design of a high-powered pulse laser system adaptable to atmospheric use.

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