Two-Dimensional simulation of thermal blooming effects in ring pattern laser beam propagating into absorbing CO2 gas

M. H. Mahdieh¹, and B. Lotfi
Department of Physics, Iran University of Science and Technology,
Narmak, Tehran, Iran
1 mahdm@iust.ac.ir

Keyword: Thermal blooming, Thermal lens effect, High power lasers, Propagation in atmosphere

Abstract
Thermal blooming has been evaluated numerically in two-dimensional for CO2 laser beam transmitting through high pressure CO2 gas. Thermal blooming occurs when a portion of the laser beam is absorbed when transmitted through an absorbing medium such as atmosphere. High pressure gas medium is very useful for experimental simulations. In our calculation the beam was assumed to have an initially ring pattern. The ring pattern beam can be generated by unstable resonators. Using ray optics theory as well as wave optics, the transmission of such beam was assessed through the CO2 gas and the results were compared. Both the blooming effect and the wind effect were considered in the calculations. The results show a major deformation occurs on the beam due to blooming effect. According to these results, unlike the Gaussian beam in which a ring pattern formed through the propagation into an absorbing media, for the ring pattern beam, in the absence of the gas flow, a symmetrical twofold pattern is formed due to blooming effect. The results also show that such symmetry can be deformed in the presence of the gas flow. The calculations also show that the wave optics gives much precise results especially for the small Fresnel numbers \( N_f = k d^2 / z \approx 1 \), while those of the ray optics theory is valid only for high Fresnel numbers.

1. Introduction
Thermal blooming has been studied extensively for many years [1-6]. It is one of the main subjects in high power laser beam transmission into the atmosphere. Basically, when a high power laser beam propagates through the atmosphere, some molecules and particles in the propagating path can absorb a small portion of the laser beam energy. In fact, the absorbed energy heats up the air, results to a finite expansion. Such expansion forms a distributed thermal lens along the transmission channel that in turn spreads, and distorts the laser beam. Such self-induced effect is so called thermal blooming (or thermal lens effect) and the maximum transmitted will be limited by this effect. Therefore, thermal blooming is one of the most crucial nonlinear problems encountered in the propagation of high power laser beam into the atmosphere.

Historically, there have been some interests in small–scale thermal blooming instabilities [7] and from them the studies of thermal blooming amplification of small-scale intensity perturbations or, stimulated thermal Rayleigh scattering (STRS) was the initial efforts. On the other hand, there have been some interests in the large-scale thermal blooming effects in which the entire beam is spread, bent and distorted. This is so called as “whole-beam” thermal blooming.

Observation of thermal lens effects was reported first by Gordon et al. [8,9]. They studied this effect by placing transparent absorbing liquids (and some solids) in a laser cavity. Considering thermal conduction as the dominant heat transfer mechanism, the refractive index gradient produced by the spreading effect was studied as the main effect on the laser beam.

The thermal lens effect as a practical application for low absorption measurement was studied first by Solimini [10]. Some experimental and theoretical efforts were also applied to develop a basic understanding of atmospheric thermal blooming effects and their limits for CW, pulsed and repetitively pulsed (RP) high-energy laser beam propagation [1-5]. Simple and, more idealized conditions were used to represent the characteristics of the laser beam and atmosphere. Many attempts have been made to reduce the thermal lens effect. The use of focusing and defocusing different beam profiles, and aperture shapes were all considered as possible ways to reduce thermal blooming effects [4].

However, most efforts have been focused on propagation of Gaussian laser beam in the atmosphere. This is more appropriate for the medium power laser with stable resonator. The fundamental mode of the stable resonators is Gaussian, which is excellent for many kinds of applications. However high power beam cannot be obtained from the large bore resonator geometry,
because the spot size of the lowest order transverse mode is small. Unstable resonators have the advantage of producing high quality laser beams of large mode volumes even in a short cavity [11]. Such resonators are widely used in high power gas lasers [12], as well as solid-state lasers [13]. However, the near field output beam of an unstable resonator usually has an annular pattern and the far field output beam has several rings, which causes lower focusing ability, due to the diffraction effect.

In this paper we have presented the results of numerical simulation for a high power CW laser, propagating into the atmosphere as well as a high pressure CO2 gas medium. The later case is very useful for estimation of the thermal blooming effect on the laser beam pattern in experimental simulations. The beam was assumed to be formed by a positive branch unstable resonator. Such resonator has ring pattern intensity in near field. Here the blooming is characterized by isobaric heating in which the convection dominated heat transfer, due to the combined effects of wind and the beam motion. The case has been considered for both the collimated beam regime i.e. in the ray optics limit as well as wave optics regime. In the ray optics regime the Fresnel number is high \( N_f = k a^2 / z \gg 1 \). The ray optics limit is no longer valid for the conditions in which the Fresnel number is small \( N_f = k a^2 / z = 1 \). In this case the wave optics model must be applied. The calculations show that for the conditions of small Fresnel number, significant difference exists between the results of the ray optics and those of the wave optics regime.

2. Theory and the model

As explained, when a laser beam propagates through an absorbing medium, a small fraction of the laser beam energy is absorbed, and heats the medium. Such effect in turn will cause localized gradients in the density. Consequently, the refractive index of the medium will be changed due to such density variation. The changes in the refractive index can act as a distributed lens like media on the laser beam propagation. The beam is usually defocused and spread, since the laser beam heats up the absorbing medium. Such effects usually results in the expansion and decrease in the refractive index of the medium in the region of the beam where the heating is greatest.

The thermal blooming generally depends on several factors that must be considered in the beam evaluation. These factors are:

1) The laser beam characteristics
2) The kinetics of the absorption process, which determine the time required for the absorbed energy to heat up the gas
3) The heat transfer mechanisms that balance the absorbed energy (e.g. thermal conduction, natural or free convection, forced convection, or the generation of sound waves)
4) The time scale of interest (e.g. transient versus steady-state conditions);
5) The propagation medium and its characteristics (e.g. the path length, optical properties, etc.).

Thermal blooming effects can be evaluated if the Maxwell wave equation is solved for the laser beam complex electric field \( E(r) \). The general form of the Maxwell wave equation for a non-uniform media with slowly time and space varying refractive index \( n \) is given by [14]:

\[
\nabla^2 E - \left(\frac{n^2}{c^2}\right) \frac{\partial^2 E}{\partial t^2} = 0
\]

(1)

In the “ray optics” limit where the Fresnel number has a high value \( N_f = k a^2 / z \gg 1 \), the diffraction effects are negligible and the general solution for the wave equation can be given by [14,15]:

\[
E(\rho, t) = e(\rho) \exp\left[i k_0 S(\rho) - i \omega t\right]
\]

(2)

in which \( S(\rho) \) is the wave front, \( e(\rho) \) is a slowly varying function of space, \( k_0 \) and \( \omega \) are the wave number and the laser frequency respectively.

The wave front \( S(\rho) \) can be found from relation (3) as:

\[
\nabla S(\rho) = n^2(\rho)
\]

(3)

in which \( n(\rho) \) is the refractive index.

The refractive index \( n(\rho) \) in the above equations consists of a constant value \( n_0 \) and blooming contribution \( n_B(\rho) \) that is a function of the absorbed laser beam power.
density $\alpha d \propto [E - E^\prime]$, where $\alpha$ is the absorption coefficient of the propagation media. Accordingly, the wave front $S(r)$ consists of two parts: A constant value $S_0$ and a blooming contribution of $(\Delta \phi)$ associated with the refractive index parameters $n_a$, and $n_B(r)$ respectively. Therefore we have:

$$n(r) = n_0 + n_B(r)$$ (4)

$$S(r) = S_0 + \Delta \phi$$ (5)

However, the ray optics limit is no longer valid for the case of low values of Fresnel numbers. Using the “wave optics” regime for this condition, a relatively more accurate solution can be obtained especially for the cases with low values Fresnel number i.e., $(N_f = k d^2 / z) \approx 1$. In this case the Maxwell wave equation (1) can be solved numerically, using the refractive index $n(r)$ in relation (4).

For CW laser beams propagating into the atmosphere, it is usual to assume that the heating occurs instantaneously and that the heating rate is sufficiently small so that the pressure disturbances can be neglected.

At constant pressure, the heating assumed to be isobaric, and the blooming contribution to the refractive index is given by [5]:

$$n_B = n_T T_B$$ (6)

in which, $n_T$ is the refractive index change with respect to temperature of the gas at constant pressure and given by:

$$n_T = \frac{dn}{dT} = \frac{(n_0 - 1)}{T_0}$$ (7)

where $n_0$ and $T_0$ are the constant background values for the density and the temperature respectively.

In relation (6) the parameter $T_B$, is the temperature rise due to laser heating, and is given by the energy balance equation:

$$\rho C_p \left[ \frac{\partial}{\partial t} + \nabla \cdot \mathbf{v} \right] - \mathbf{\nabla} \cdot \left[ \frac{k \mathbf{\nabla} T}{\rho C_p} \right] = \alpha l$$ (8)

in which $C_p$ is the specific heat capacitance in constant pressure, $\rho$ is the gas density, $\alpha$ is the absorption coefficient of the propagating media and $l$ is the intensity of the beam.

For the case of “ray optics” limit, simultaneous solution of the equations (2–8) can describe the transient development and steady-state solutions for the thermal blooming of CW or RP laser beam when both thermal conduction and convection heat transfer are present. On the other hand, for the “wave optics” regime, direct solution of the Maxwell equation (1) together with the refractive index of relations (4) and (6-8) will give more accurate results for any values of Fresnel number $N_f$.

### 3. Results and discussion

For the ray optics limit, the equations (2-8) solved simultaneously to describe the phase and the intensity of a CO2 laser beam ($\lambda = 10.6 \mu m$) propagating through CO2 gas with a pressure of 10 atm. ($10^5 Pa$). In the “wave optics” regime more accurate results can be obtained for the cases with smaller Fresnel number. In these cases the results from the ray optics theory cannot be correct at all. In the “wave optics” regime, the Maxwell equation (1) together with the relation (4, 68) was solved simultaneously. Computer code has been developed for these two-dimensional simulations.

In order to validate the calculations, the condition of an experimental simulation for a CO2 laser beam propagating through high pressure CO2 gas as well as atmosphere [3] applied to the software. We have applied the wave optics theory in this calculation. The condition is summarized in Table (1) and the results of the calculations and those of reference [3] are shown in figure (1). In this figure the contours of the intensity for two cases are shown. Perfect agreement can be seen between the experimental results of the reference [3] and those of our numerical calculations. From the two results it can be seen that the laser beam with a Gaussian intensity is deformed due to thermal blooming and the wind effects. The thermal blooming separately changes the beam intensity from Gaussian into a ring pattern. Due to the wind effects, the peak intensity is also moved to the opposite wind direction. In fact in such condition, the convection dominated blooming effects that in turn alters initially symmetrical circular beam to form an asymmetrical crescent shaped pattern. The prominent features of
this type of blooming are to spread or bloomed symmetrical transverse to the wind direction of the laser beam.

Table 1: The conditions for an experimental simulation [3] that are used for our numerical simulation

<table>
<thead>
<tr>
<th>Medium</th>
<th>atmosphere</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absorption Coefficient, $(m^{-1})$</td>
<td>$1.45 \times 10^{-4}$</td>
</tr>
<tr>
<td>Wind velocity $(m/sec)$</td>
<td>4</td>
</tr>
<tr>
<td>Wavelength $(\mu m)$</td>
<td>10.6</td>
</tr>
<tr>
<td>Laser Power $(KW)$</td>
<td>100</td>
</tr>
<tr>
<td>Beam diameter $(2a)$ $(m)$</td>
<td>0.3</td>
</tr>
<tr>
<td>Fresnal Number $(N_f)$</td>
<td>6.6</td>
</tr>
<tr>
<td>Range $(m)$</td>
<td>2000</td>
</tr>
</tbody>
</table>

Figure (1): Two-dimensional intensity contour for a CO2 laser beam propagating through a windy atmosphere. (a): Our numerical simulation, (b): Experimental simulation from reference [3].

As explained, the experimental simulation reported by Gebhardt et al. [3] was for just Gaussian beam laser. We were employed in our model similar conditions for a typical experimental simulation using a CW CO2 laser beam but the laser with an initially ring profile intensity propagating into a $10^6$ Pa CO2 gas and presented the results in this paper. Technically, it is possible to provide a condition for the CO2 gas to be moved intentionally across the beam with a finite horizontal fluid velocity. The fluid under such conditions behaves similar to the atmosphere in the present of the wind. It is also assumed that the laser to be switched on for typically 0.2 second. The conditions are tabulated
in Table 2. The CO2 gas was chosen in this simulation because of its high absorption coefficient that in turn deforms the beam effectively. Figure (2) shows the intensity for a ring profile laser beam, propagating into 1.5 m path high pressure CO2 gas with the effect of the wind. The intensity peak is reduced due to blooming effect and an asymmetric beam is formed at the present of the wind.

**Table 2:** the conditions for numerical simulation of thermal blooming that can be used for typical experimental simulation

<table>
<thead>
<tr>
<th>Medium</th>
<th>CO2 at $10^6$ Pa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Pattern</td>
<td>Ring</td>
</tr>
<tr>
<td>Absorption Coefficient, $(m^{-1})$</td>
<td>0.4</td>
</tr>
<tr>
<td>Fluid (Wind) velocity $(m/sec)$</td>
<td>0.02</td>
</tr>
<tr>
<td>Wavelength $(\mu m)$</td>
<td>10.6</td>
</tr>
<tr>
<td>Laser Power $(W)$</td>
<td>30</td>
</tr>
<tr>
<td>Beam diameter $(2a)$ $(m)$</td>
<td>0.02</td>
</tr>
<tr>
<td>Range $(m)$</td>
<td>1.5 – 5</td>
</tr>
</tbody>
</table>

**Figure (2):** Laser beam pattern with initially ring profile propagating into 1.5 m path (of a high pressure CO2 gas predicted by ray optics (a, and c) and wave optics (b, and d) theories. (a) and (b): Blooming without the effect of gas flow (c) and (d): Blooming with the effect of gas flow (similar to wind effect)
Two theories were used for the simulation: a) ray optics, and b) wave optics. Since the Fresnel number in this condition is high ($N_f = ka^2 / z \approx 20$), therefore both theories predict more and less the same results. Such agreement does not exist for the conditions of low values Fresnel number. In order to provide condition with low Fresnel number, for a longer propagation path i.e. 5 m was considered. The Fresnel number in this case is ($N_f = ka^2 / z \approx 6$). Figure (3) shows the results for this calculation. From this figure, significant discrepancy can be seen between the predictions of the two theories. The wave optics predicts a double folded ring with much lower peak intensity, while the intensity profile does not change very much from the original beam in ray optics limit. Such difference in the results is due to the invalidity of the ray optics technique for low Fresnel number. Basically, in the wave optics theory, the diffraction effect is taken into account, thus the peripheral region of the beam would spread out. Therefore, the energy distribution evaluated by the wave optics theory is localized in an area about 10 times larger than that of the ray optics. This effect results to significant reduction at the peak intensity calculated by the wave optics theory. The wind effect in this condition is very similar to that of the small Fresnel number, but the blooming influences the beam more effectively in larger transmitting path.

Figure (2) Laser beam pattern with initially ring profile propagating into 5 m path of a high pressure CO2 gas predicted by ray optics (a, and c) and wave optics (b, and d) theories. (a) and (b): Blooming without the effect of gas flow (c) and (d): Blooming with the effect of gas flow (similar to wind effect)
The calculations show also phase change occurs for the beam through the propagation. The results show change for phase (in shape not magnitude) associated to the blooming and the wind effect similar to that of the intensity. The results can be better described if one-dimensional phase across the $x$ and $y$-axis is demonstrated. Figure (3) shows typical phase change ($\Delta \phi$) of the beam propagating through the CO2 gas for two cases: (a) and (b) phase change associated with the blooming for transmission into 1.5 and 5 m of CO2 gas respectively, and (c) and (d) the phase change associated with the blooming and the wind for the 5 m transmission into CO2 gas. If the wind effect is not taken into account, the phase across the $x$ and $y$-axis is symmetrical for both 1.5 and 5 m transmission path, but higher phase change occurs for the longer path (figure 3b). In the absence of the wind, the propagating media acts like a negative lens and the intensity would be reduced due to this effect. However, the symmetrical phase change cannot be obtained if the wind effect is considered.

![Figure (3): Typical phase change of the beam propagating through the CO2 gas for two cases: (a) and (b) phase change associated with the blooming for transmission into 1.5 and 5 m of CO2 gas respectively, and (c) and (d) the phase change associated with the blooming and the wind for the 5 m transmission into CO2 gas.](image)

From the figure (3-c) and (3-d) it can be seen that the phase ($\Delta \phi$) is asymmetrical across the $x$-axis while it is symmetrical across the $y$-axis. This is due to the direction of the gas flow (wind) that causes such asymmetrical deformation on the beam across the $x$-axis. The phase across the $x$-axis is the outcome of the propagating media that acts similar to a prism and a negative lens together. In principle, an optical prism refracts a laser beam towards the base part of the prism. Based on this effect, if a ring pattern beam with a finite diameter hits to the side of such prism, different part of the beam would be bent non-uniformly towards the base and consequently a deformed beam would walk out. Similar circumstance takes place in a propagating media that is influenced by the wind.
In fact, the spatial profile of the phase and consequently the intensity are different at the presence of the gas flow. The forced gas flow can change the symmetry due to convection effects. Basically, the contributions of the gas flow and the thermal conduction on the beam deformation can be evaluated by comparison of the second and the third terms of relation (8). Thermal conduction dominated blooming, described by the third term in (8) occurs when the beam is stationary (i.e. \( V = 0 \)) and for early enough times or small enough heating that natural convection is still negligible. The basic requirement for this condition is that the natural convection velocity \( V << \chi / a \), where \( \chi = K / \rho \cdot C_p \) is the thermal diffusivity of the medium, with \( K \), \( \rho \) and \( C_p \), the thermal conductivity, density and specific heat at constant pressure respectively, and \( a \) is either the beam radius (for the case of whole-beam blooming) or the smallest scale size of interest in the case where small-scale blooming effects on very large uniform intensity beams are of concern. The heat transfer and associated thermal blooming is convection dominated according to (8) when the velocity \( V >> \chi / a \).

4. Conclusion

An initially ring pattern high power laser beam was simulated when propagating through a high pressure CO2 gas. The simulation was performed using “ray optics” theory as well as “wave optics”. The conditions of high and low values Fresnel number applied to the simulation. According to the calculations for the condition of high Fresnel number, both “wave optics” and “ray optics” theories give similar predictions for the ring laser beam propagating into the absorbing gas. Such results are due to the fact that for the high values Fresnel number the diffraction effects are negligible. Significant discrepancy exists for the results of the two theories when the Fresnel number is low. It was concluded that the ray optics cannot predict the simulation precisely for the conditions of lower Fresnel numbers. The results show that while the initially Gaussian beam can be spread out through the propagation, initially ring pattern from high power unstable resonators behaves differently and the beam spread into the central region and a twofold beam is created. The gas flow with enough high velocity where \( V >> \chi / a \) has substantial effects on the beam pattern. Such numerical simulations give enough information on the beam through the propagation and the results are very useful for prediction of experimental simulation.

References: