Simulations of far-field optical transmission properties influence by mirror thermal deformation for high-power pulsed transversely excited atmospheric CO\textsubscript{2} with unstable resonator

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High-power pulsed transversely excited atmospheric (TEA) CO\textsubscript{2} laser has gained much attention for its widely used applications of high-power laser system\cite{1,2,3}. TEA CO\textsubscript{2} laser has its applications in the lidar, the infrared laser directed countermeasure, and the laser propulsion for its advanced properties of the high-peak power, short pulse tail, and high-repetition rate. However, the high power density of TEA CO\textsubscript{2} laser will definitely cause the thermal deformation of the mirror and ultimately will have influence on the far-field optical beam quality.

At present, many research groups have paid great attention for the heat distortion of mirror irradiated by high-power laser\cite{4,5,6}. However, there are rarely any reports about the heat distortion of mirror influenced by the different time interval, that is, with different repetition rates. The researchers mostly focus on how to improve the laser power with the high-repetition rate, not including the issue that the thermal accumulate variation with different thermal relaxation processes. At the same time, the optical intensity distribution of high-energy laser beam is usually generated by the unstable resonator which is hollow in center and asymmetric\cite{5}. Therefore, it is necessary to investigate the heat distortion of the mirror for high-power pulsed TEA CO\textsubscript{2} laser system, especially the influence of far-field optical beam quality.

When the high-power beam irradiates the optical elements, mostly it refers to mirrors. There must be a small fraction of laser power to be absorbed by the mirror, which makes the mirror temperature increasing. The temperature field of mirror can be expressed as\cite{6}

$$\frac{\partial}{\partial x} \left( k(T) \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( k(T) \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left( k(T) \frac{\partial T}{\partial z} \right) = \rho \frac{\partial T}{\partial t}. \quad (1)$$

The temperature field of mirror is influenced by three factors: 1) heat injection, 2) heat exchange, and 3) heat convection with the ambient atmosphere. Therefore, the boundary condition is as

$$k \frac{\partial T}{\partial n} \bigg|_{z=z_i} = \left[ (1-\varepsilon) I(r,\phi) / S - h_i (T_s - T_i) \right],$$

$$k \frac{\partial T}{\partial n} \bigg|_{z=0} = h_i (T_s - T_i), \quad (2)$$

where $T$ is the temperature of time $t$ at the points $(r, \phi, z)$ of mirror, $k$ is the coefficient of heat exchange for the material of mirror, $\rho$ is the density of mirror, $c$ is specific heat, $T_c$ is the ambient temperature, $T_s$ is the surface temperature of mirror, $h_i$ is the coefficient of convection heat exchange, $\varepsilon$ is the reflectivity of mirror, $I(r, \phi)$ is the optical intensity of laser, $S$ is the area of irradiation, $\Sigma$ is the load region of laser beam distribution, and $\Sigma$ is the load region of heat convection. Substituting Eq. (2) into Eq. (1), the temperature distribution of mirror can be obtained under the...
can be solved through the angular spectrum propagation theory of diffraction

\[
I_p = \left[ \text{IFFT}\{\text{FFT}\{U_n \exp(-2jk \cos \theta u_n(x,y))\}\} \times \right]^2,
\]

where \(U_n\) is the field distribution before \(n\) mirror, \(z\) is the distance of beam transmission, \(f_x\) and \(f_y\) are the coordinates of frequency region, and \(\lambda\) is the laser wavelength.

The structure of unstable resonator is as shown in Fig. 1(a). The output beam distribution of TEA CO\(_2\) is shown in Fig. 1(b). The energy of single pulse is 20 J and the pulse duration is about 80 ns. The radius of inner ring is about 32 mm and the radius of exterior ring is about 40 mm. Here one polygon copper mirror is chosen with a thickness 15 mm and 96% reflectivity with three point clamp. The other material parameters are listed in Table 1.

Based on Eq. (5) and the above parameters, we use the finite element analysis of thermodynamics instantaneous method to obtain the thermal deformation of single mirror with 45° incident angle with the repetition rate of 500 Hz for 2 s. The result is shown in Fig. 2. With different time intervals of laser pulse, the thermal deformation is summed up as in Fig. 3.

It can be seen from Fig. 2 that the thermal deformation is like the elliptical ring distribution because of oblique incidence. In Fig. 3, with increasing

### Table 1. Parameters of Material Copper

<table>
<thead>
<tr>
<th>Density</th>
<th>Specific Heat</th>
<th>Heat Conductivity</th>
<th>Heat Exchange Coefficient</th>
<th>Line Expand Coefficient</th>
<th>Poisson’s Ratio</th>
<th>Elastic Module</th>
</tr>
</thead>
<tbody>
<tr>
<td>8933 (kg/m(^3))</td>
<td>386.4(J/kg·℃)</td>
<td>384.8(W/mK)</td>
<td>60 W</td>
<td>14.6 × 10(^{-6})(/℃)</td>
<td>0.32</td>
<td>1.298 × 10(^{11})(N/m(^2))</td>
</tr>
</tbody>
</table>

Fig. 1. TEA CO\(_2\) laser with unstable resonator: (a) the structure of resonator and (b) the picture of beam distribution.
repetition rate, the thermal deformation increases as the period of the cumulative heat diffusion is shorter. When the repetition rate is 500 Hz, the maximum thermal deformation is about 0.787 μm, which is almost three times that of 10 Hz. Furthermore, when repetition rate is lesser than 100 Hz, heat diffusion will take the main effect, and the temperature distribution is uniform so that the surface of mirror is quite smooth.

From Eqs. (4) and (5) with the Zernike fitting, the far-field optical beam quality is obtained with the influence of thermal deformation. For the real application, the laser beam transmission properties are not only influenced by the thermal deformation of mirror, but also by the turbulence of atmosphere, which can be simulated by the Kolmogorov spectrum statistical law\cite{12}. The distance of transmission is taken as 5 km, the external dimension $L_0$ is 10 m, the inside dimension $l_0$ is 1 mm, the turbulence intensity $C_n^2$ is $1 \times 10^{-14}$, the width of phase screen $G$ is 6 m, and the sampling point is $512 \times 512$. The far-field optical beam transmission properties with 500 Hz repetition rate is shown in Fig. 4.

It can be seen from Fig. 5(a) that when the ring beam of uniform distribution propagates to the far field, the energy concentrates in the center of optical spot. After the influence of the thermal deformation of mirror, there exist multiple diffraction rings, which broaden the radius of spot, as shown in Fig. 5(b). Adding the turbulence effect, the spot is divided into many small parts and the peak power decreases greatly.

For quantitative evaluation of the far-field optical beam quality, the $\beta$ factor, Strehl’s ratio, and the far-field energy density $E_d$ are listed in Table 2 for the different time intervals of TEA CO$_2$ laser pulse with the influence of the turbulence effect.

<table>
<thead>
<tr>
<th>Repetition Rate</th>
<th>10 Hz</th>
<th>50 Hz</th>
<th>100 Hz</th>
<th>300 Hz</th>
<th>500 Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_t$</td>
<td>0.946</td>
<td>0.872</td>
<td>0.813</td>
<td>0.570</td>
<td>0.539</td>
</tr>
<tr>
<td>$\beta$</td>
<td>1.111</td>
<td>1.311</td>
<td>1.372</td>
<td>1.672</td>
<td>1.772</td>
</tr>
<tr>
<td>$E_d$ (mJ/cm$^2$)</td>
<td>0.326</td>
<td>0.233</td>
<td>0.213</td>
<td>0.143</td>
<td>0.128</td>
</tr>
</tbody>
</table>
quality of high-power TEA CO₂ laser with unstable resonator.

In conclusion, the inner channel thermal deformation of the copper polygon mirror is theoretically analyzed by using the finite element method. The simulation results show that the repetition rate and the turbulence effect are the key factors to influence the far-field optical beam quality when the material and the boundary are determined. When the time interval between each pulse becomes shorter, the heat diffusion is not remarkable and the heat cumulative effect takes the key role. The results provide the reference for the optical beam control of entire path of the high-power laser system.

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References