Output beam analysis of high power COIL

Deli Yu (于德利)[1,2], Fengting Sang (桑凤亭)[1], Yuqi Jin (金玉奇)[1], and Yizhu Sun (孙以珠)[1]

[1] *Dalian Institute of Chemical Physics, Chinese Academy of Sciences, Dalian 116023*
[2] *Nanyang Technological University, EEE, Block S1, Nanyang Avenue, Singapore 639798*

Received September 10, 2002

As the output power of a chemical oxygen iodine laser (COIL) increases, the output laser beam instability appears as the far-field beam spot drift and deformation for the large Fresnel number unstable resonator. In order to interpret this phenomenon, an output beam mode simulation code was developed with the fast Fourier transform method. The calculation results show that the presence of the nonuniform gain in COIL produces a skewed output intensity distribution, which causes the mirror tilt and bulge due to the thermal expansion. With the output power of COIL increases, the mirror surfaces, especially the back surface of the scraper mirror, absorb more and more heat, which causes the drift and deformation of far field beam spot seriously. The initial misalignment direction is an important factor for the far field beam spot drifting and deformation.

OCIS codes: 140.1550, 140.3300, 140.4780.

With the output power of a chemical oxygen iodine laser increases, the instability of output laser beam appears, which includes the far-field beam spot drift and deformation for the large Fresnel number unstable resonator.

Figure 1 shows the rooftop resonator and drift of the laser beam. The drift distance and the profile of the far-field beam spot are random for the different laser resonators. If we do not re-fix the resonator box and continue more experiments on this COIL setup, the drift and deformation in the far field beam spot become more serious. In order to explain this phenomenon, a calculation code has been developed and can be used to study the characteristics of this kind of large Fresnel number unstable resonator with nonuniform gain distribution of COIL. A similar computed results on the gas-dynamic laser by fast Fourier transform method[1−3], and the effects on laser performance caused by the flow disturbance and mirror misalignment have been investigated. Now the COIL is a high-energy continuous wave laser, so the optical elements in resonator absorb the heat, especially the surface of the resonator mirror, and some times the optical elements could be damaged[4]. So the thermal distortion of the mirror should be taken into account, even though now most of COIL adopted the single crystal silicon as the mirror substrate material and the reflectivity of the mirror becomes higher and higher[5,6]. The thermal response of heated optical elements can be analyzed[7]. The presence of the nonuniform gain in COIL produces a skewed output intensity distribution, which causes the mirror distortion, such as the tilt and bulge, as the results of the thermal expansion during the laser operation, and thus the far-field beam spot drifts and deforms.

The method of fast Fourier transform (FFT) was adopted to calculate the three-dimensional mode pattern and output beam characteristics. In the positive branch unstable resonator, the optical wave travels from the concave to the convex mirror is plane-wave propagation. It is convenient to adopt FFT method[2]. When the optical wave is reflected by the convex, it is diverging wave propagation. In our code we also expand the coordinate system for one complete unfolded round trip around this confocal unstable resonator. The 45° mirrors are neglected in our code. We transformed the primed coordinates x', y', z' to the collimated coordinate x, y, z according to

$$\begin{aligned} x'(x,z) &= (R_0+L)x/z, \\ y'(x,z) &= (R_0+L)y/z, \\ z' &= (R_0+L)^2(z-z_0)/(z_0 z), \end{aligned} \qquad (1)$$

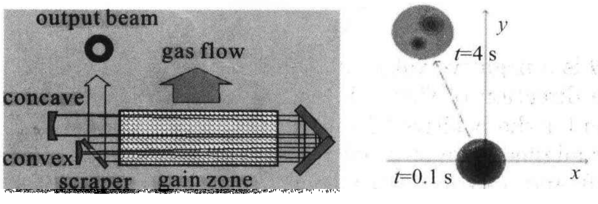
where L is the distance of the diverging optical wave propagation, and R_0 is the radius of diverging spherical wave. Both origins of the coordinates are at the center of the diverging sphere. So the equivalent length L' corresponding to the expanding-beam section in the primed coordinate system is $L' = ML$, M is the magnification of the resonator[2]. Before we apply the FFT process, we should expand the width of the beam M times in front of the convex.

As the small signal gain in the COIL is nonuniform[8], we assumed that the gain media could be compressed to a gain sheet along the resonator axis. So the optical wave $\varphi(x,y)$ can be expressed as follows after the propagation through the gain media

$$\varphi(x,y) = \varphi_0(x,y)\exp[\frac{1}{2}(G(x)-\alpha)], \qquad (2)$$

where $G(x)$ is the small signal gain coefficient and α is the absorptive coefficient of the gas[9].

According to the experimental results, we can decompose the energy distribution of laser beam to two parts.



(a) (b)

Fig. 1. (a) Schematic of COIL resonator. (b) Typical position and profile change of the far field beam spot.

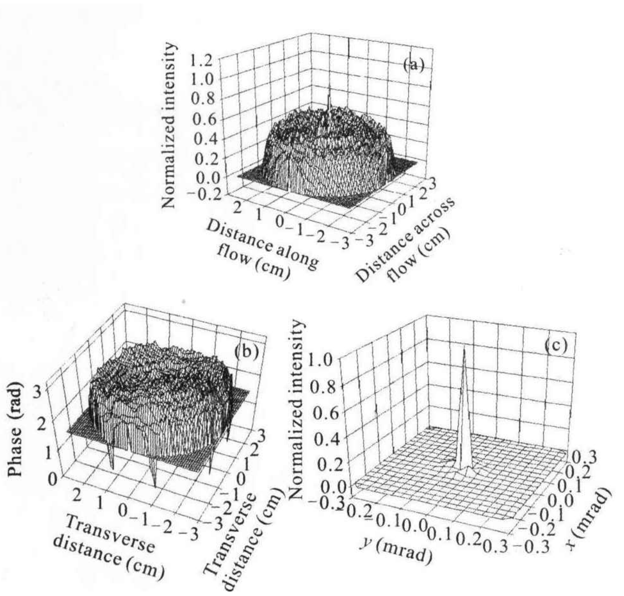


Fig. 2. Bare resonator, (a) near field intensity, (b) near field phase and (c) far field intensity.

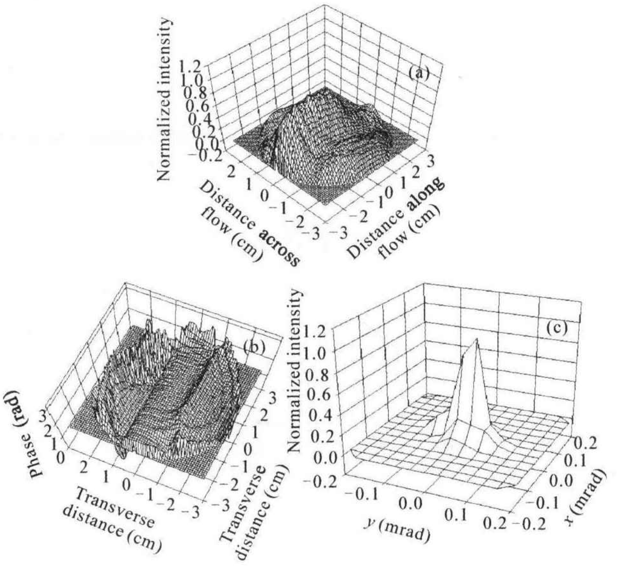


Fig. 3. Loaded resonator with a tilt $\theta = 20$ μrad, (a) near field intensity, (b) near field phase and (c) far field intensity.

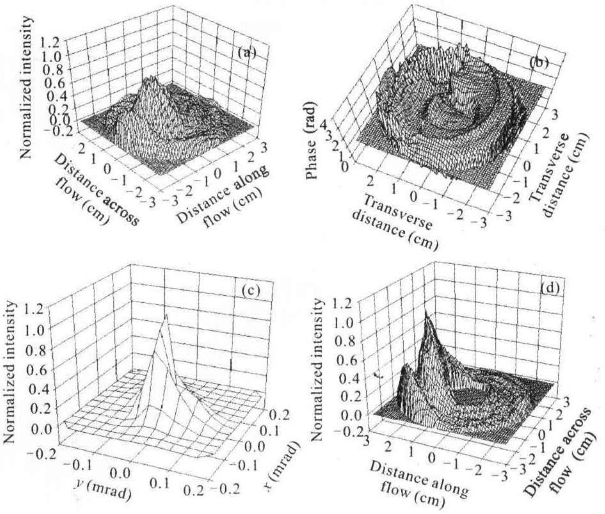


Fig. 4. Loaded resonator with a bulge and a tilt $\theta = -20$ μrad, (a) near field intensity, (b) near field phase, (c) far field intensity and (d) near field intensity with $\theta = 20$ μrad.

One is a uniform distribution on the surface of the resonator, and the other has a linear decreasing gradient energy distribution along the flow direction. It is assumed that the uniform distribution heat energy causes the mirror surface bulge and the linear energy causes a tilt of the mirror surface because of the thermal expansion, and they would deform the wave front of the laser in the resonator. In our code these factors have been considered.

We first calculated the near field intensity and the phase in front of the scraper mirror, and the far field distribution of the out beam from the bare unstable resonator with the equivalent Fresnel number $N_{\mathrm{eq}} = 4.51$, $M = 3.05$ with the collimated beam of radius $a = 2.9$ cm, as shown in Fig. 2.

As presented in Fig. 2, the near field intensity and phase have central symmetrical profile; the far field beam spot is also symmetrical to the position of (0, 0). Then we calculate the near field intensity and the phase, the far field intensity of the loaded resonator with a 20 μrad tilt. The results are shown in Fig. 3. The near field beam intensity distribution of the loaded resonator shows a more noticeable lean toward the upstream high-gain direction. Here the tilt $\theta = 20$ μrad of the optical axis of the resonator, defined by the line connecting the curvature centers of convex and concave mirrors, is related to the mirror tilt angles θ_1 (normal direction of convex mirror to the line) and θ_2 (normal direction of concave mirror to the line) by the formula[2]

$$\theta = \frac{2M\theta_2 - 2\theta_1}{M-1}. \tag{3}$$

If θ is a negative value, it means the mirror was tilted in the direction of flow. The near field intensity distribution for the positive tilt angle is more homogeneous than the aligned resonator, even though there is 34 μrad angle drift and a little deformation of the far field beam spot intensity. We also calculated the near field intensity and phase, and the far field intensity of the loaded resonator with a $\theta = -20$ μrad tilt, and based on the results we visualized that the tilted direction of the mirror caused different skewed near field intensity distribution, but the far field spot profiles are similar.

At last we calculated the near field intensity, the phase and the far field intensity of the loaded resonator with a mirror surface bulge ($\lambda/2$ in the center and 0 at the brim of the mirror with a sine function profile) and $\theta = 20$ μrad tilt, as shown in Fig. 4.

The thermal distribution of the mirrors is main cause of deformation of far field distribution, and it is similar to the calculated near field density distribution in Fig. 4. Figure 5 shows the experimental laser intensity distribution of the far field of COIL. Figure 6 presents the temperature distribution of the scraper surface taken by the thermal image system (Model TH5104 NEC), and the distortion of the mirror surface under the ring output laser beam during the laser operation

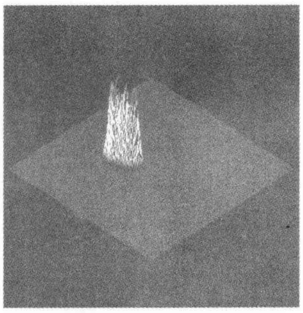
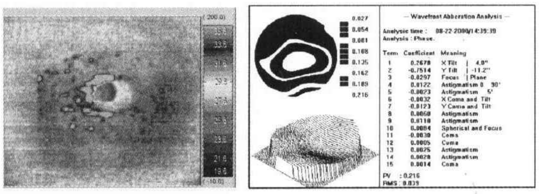


Fig. 5. Experimental far field intensity.



(a) (b)

Fig. 6. Experiment results, (a) temperature distribution of the scraper surface and (b) distortion of the mirror under ring laser output beam.

that was tested by Hartmann-Shack wave-front sensor. As the temperature is not uniformly distributed on the front surface of the resonator, the mirror thermal expansion is also inhomogeneous and our assumption on the resonator mirror surface distortion is confident. From Fig. 4(c) and Fig. 5 we can find that the calculated ones are very close to the experimental profile.

During operation, the resonator mirrors absorb the heat of laser and the heat accumulates, so the thermal expansion of the mirror substrate continues. As the laser intensity distribution in the resonator is nonuniform, the thermal expansion of the mirror could cause a tilt of the mirror surface and a center bulge. The tilting and bulging of the resonator mirror surface could be demonstrated by the laser far field beam spot drifting and deformation. The initial misalignment direction of the resonator mirror affects the laser intensity distribution in the resonator, and the absorbed heat distribution of the scraper back. If the initial misalignment direction of the resonator mirror along the gas flow, the laser beam intensity distribution is more skewed than the converse direction, as shown in Figs. 4(a) and (d). Because the initial misalignment in resonator is random, the intensity distribution of the laser beam, and thus the thermal expansion of the mirrors is also random, especially for the scraper mirror back, so the far field beam spot drift and deformation some times is very large and some times is very small. Here we should note that the final misalignment θ involves θ_1 and θ_2. If we neglect the mirror thermal effect, the direction of the mirror initial misalignment is not important. In fact, when the laser operates, the misalignment and the bulge of the mirror become more and more serious. Table 1 presents the far field beam spot drift vs the angle of misalignment for a $\lambda/2$ maximum mirror central bulge. Table 2 presents the far field beam spot drift vs the maximum mirror central bulge for $\theta = 20$ μrad mirror misalignment.

From Tables 1 and 2, we can find that the far field beam spot drift and deformation are serious when the laser operates with the mirror tilting and bulging. The bulge of the mirror surface causes the far field beam spot deforming easily and so does the tilt of the mirror for the far field beam spot drifting. If the bulge of the mirror surface is not more than one wavelength, the far field beam spot deform is small. Sometimes it is agreeable to the experimental results that the far field beam spot trembles when it drift. The negative angle of mirror initial misalignment will reduce the far field drift even though the deformation is serious; because the negative angle of the mirror tilt could get a more uniform laser beam intensity distribution and a small tilt of the mirror even though the bulge of the mirror is serious. When we assemble the resonator box, we do our best to avoid the initial misalignment along the flow, so the drift and deformation of far field beam spot will be reduced obviously. If we reduce the initial misalignment of the resonator mirror, the back of the scraper mirror will absorb less heat and the thermal expansion of the scraper mirror can be reduced. Table 3 presents the far field beam spot drift vs the tilt angle of scraper for $\theta = 20$ μrad mirror misalignment and a $\lambda/2$ maximum mirror central bulge.

A more uniform output was obtained by deliberately initially misaligning one of the mirrors, and the tilt of the mirror caused by the nonuniform intensity was reduced. When the tilt of mirror is fixed at a certain angle, the nonuniform of near-field laser beam intensity is reduced and the far-field beam spot is stabilized.

The effect of the scraper mirror thermal expansion on the far field beam spot drift and deformation is related to

Table 1. Typical Far-Field Beam Spot Drift and Deformation vs Misalignment

Misalignment (μrad)	Far-Field Beam Spot Position (Max) x (μrad)	y (μrad)	Deformation Peak* Number	86% E (μrad)
0	0	0	1	80
20	0	0	1	100
40	34	68	1	150
60	−34	68	1	180
80	0	0	3	270
100	34	136	2	306

*Peak: > 0.5.

Table 2. Typical Far-Field Beam Spot Deformation vs Mirror Central Bulge

Central Bulge (λ)	Far-Field Beam Spot Position (Max) x (μrad)	y (μrad)	Deformation Peak* Number	86% E (μrad)
0	0	34	1	80
0.5	0	0	1	100
1.0	34	0	1	170
1.5	68	0	1	150
2.0	34	68	3	350

*Peak: > 0.5.

Table 3. Typical Far-Field Beam Spot Drift and Deformation vs Scraper Mirror Misalignment

Misalignment (μrad)	Far-Field Beam Spot Position (Max) x (μrad)	y (μrad)	Deformation Peak* Number	86% E (μrad)
−20	−68	0	1	120
0	0	0	1	100
20	0	0	1	110
40	68	68	1	190
60	34	170	1	200
80	0	102	1	240
100	0	136	1	310
120	0	170	1	360

*Peak: > 0.5.

the laser intensity distribution. Since the converging laser beam will definitely heat the back of scraper mirror after the convex mirror reflects the collimated laser beam to the concave mirror, we can visualize that the initial misalignment direction will not only affect the distribution of the laser intensity, but also determine the heat distribution on the back of the scraper mirror. Thus the laser intensity would decide the resonator and the scraper mirror thermal expansion, so the far field beam spot position and profile. In our experiments, after improving the stability of the resonator box and reducing the initial misalignment of the mirrors, the output far field beam spot drift and deformation decreases obviously, as shown in Table 4.

Table 4. Measured Far-Field Beam Spot Drift (Focal Length= 5 m)

Exp. Number	Initial Position x (mm)	y (mm)	Drift D (mm)	Direction
04141	0	0	1.31	Downward
04142	0	0	1.31	Downward
04143	0	0	1.02	Left
04144	0	0	0.08	Left
04145	0	0	1.40	Left-Upward

The drift and deformation of the far field beam spot of a COIL is the result of the resonator and scraper mirror surface tilting and bulging during the laser operation. The randomness of the drift distance and the profile of the far-field beam spot depend the random direction of the initial misalignment of the resonator mirror. The initial misalignment direction is an important factor to the far field beam spot drift and deformation. During the laser operation, the bulge of the mirrors due to the thermal expansion seriously influences the far field beam spot profile and drift.

D. Yu's e-mail address is edlyu@ntu.edu.sg.

References

1. T. T. Yang, D. A. Copeland, A. H. Bauer, *et al.*, in *AIAA 97-2384, 28th Plasmadynamics and lasers Conference,* (1997).
2. E. A. Sziklas and A. E. Siegman, Appl. Opt. **14,** 1874 (1975).
3. D. B. Rensch and A. N. Chester, Appl. Opt. **12,** 997 (1973).
4. J. R. Palmer, Opt. Eng. **22,** 435 (1983).
5. G. Koop, J. Hartlove, C. Clendening, *et al.*, in *AIAA 2000-2421, 31th Plasmadynamics and lasers Conference,* (2000).
6. H. E. Bennett and A. M. Khounsary, ANL/XFD/CP-811S2, CONQ 930722-53.
7. S. J. Cohen, R. E. English, C. J. Stolz, *et al.*, UCRL-JC-110937 (1992).
8. L. P. Duo, B. L. Yang, F. T. Sang, *et al.*, IEEE J. Q. E. **34,** 1065 (1998).
9. Z. F. Wei, R. W. Wang, and Z. J. Wang, Chin. J. Lasers A (in Chinese) **22,** 881 (1995).