Flat-top laser beam generated by coherent beam combining of Gaussian lasers

Kun Gao (高 昆), Lixin Xu (许立新)*, Rui Zheng (郑 睿), Guoliang Chen (陈国梁), Huan Zheng (郑 欢), and Hai Ming (明 海)

Institute of Photonics, Department of Physics, University of Science and Technology of China, Hefei 230026, China

**E-mail: xulixin@ustc.edu.cn*

Received March 4, 2009

We present a flat-top laser beam generation scheme using coherent beam combining of hexagonally arranged Gaussian lasers. To produce a beam with a flat-top profile, we optimize the amplitude and phase of each unit laser using the least-square method. Simulation results show that with 13 unit lasers, a beam with the flatness of less than 1% in the optimizing region can be achieved. The main lobe contains over 95% of the total power. The scheme requires no external beam shaping element and has the potential to be designed for high-power applications.

OCIS codes: 140.3298, 140.3300, 050.1970.

doi: 10.3788/COL20100801.0045.

Laser beams with a flat-top profile have special significance in laser optics by their uniform illumination. These lasers find applications in holography, material processing, free-space optical communication, inertial confinement fusion, and laser plasma interaction experiments, etc.[1,2] In order to obtain the desired flat-top beam, we employ external beam shaping elements in most cases. Although conventional beam shaping elements work well in low-power applications, the performance of the elements degrades when they operate at a high power density[3]. The thermal stability of optical elements becomes a main issue in high-power laser devices.

Coherent beam combining (CBC) scheme is one of the solutions to obtain high-power laser output without much performance degradation[4]. The scheme combines several mutually coherent lasers to deliver the required high-power output with a high coherence. In practice, the generation of mutually coherent lasers can be realized by actively locking the relative phase of each unit laser like master oscillator power amplifier (MOPA) structures with phase feedback, or by passively locking the phase like some co-cavity structures, etc.[4−9] The combination of the unit lasers can be realized in two ways: one of the combining schemes is to arrange the unit lasers in a spatial array with proper collimation, which is employed in most CBC devices; the other combining scheme is to build an output beam via a coupling element, which is used in some co-cavity CBC devices[4−9]. The former requires no coupling element so that it has a high damage threshold, whereas the latter usually performs a better beam quality[4,9,10].

In this letter, we discuss the possibility of producing a flat-top beam by arranging several mutually coherent Gaussian lasers in a hexagonal array[11−13]. We assume ideal coherent laser sources and focus on the far field of the combined beam. Instead of using unit lasers with identical parameters as in conventional CBC schemes, we use different unit lasers to produce the flat-top beam. An optimizing method is employed to calculate the optimal parameters of the unit lasers for the given arrangement.

To produce a beam with a flat-top profile in the far field, we can take a review of the Fraunhofer diffraction pattern of a uniformly illuminated circular aperture. The nature of the Fraunhofer diffraction implies that if we have a planar light source of the amplitude and phase exactly as an Airy function, the intensity profile in the far-field plane should be a flat-top one. In practice, a single light source is fixed and limited, so an ideal flat-top profile cannot be achieved. But in a coherently combined light source, we have extra freedom to control the amplitude and phase distributions. An idea is to simulate the near-field distribution of an Airy function by using the combination of unit lasers.

In our simulation, the unit lasers are arranged in a hexagonal configuration[5,14], as shown in Fig. 1. This brings the maximum filling factor for a two-dimensional (2D) configuration. It should be noted that each unit laser in Fig. 1 is actually of a Gaussian profile.

For an N-unit combined system in which all the unit lasers are aligned in the x_0-y_0 plane, the near-field complex amplitude U is the sum of N Gaussian functions:

$$U(x_0,y_0)=\sum_{j}^{N}A_j\exp(\mathrm{i}\varphi_j)\exp\left[-\frac{(x_0-x_j)^2+(y_0-y_j)^2}{w_j^2}\right], \quad (1)$$

where A_j, φ_j, and w_j are the amplitude, the relative phase, and the waist radius of the jth laser, respectively, x_j and y_j are the center coordinates of the jth laser. Since an Airy function is always real, the relative phase φ_j in Eq. (1) is essentially limited to 0 or π, where a phase of π simulates negative value of the Airy function. By integrating the phase term into the amplitude A_j, we will omit the phase term in later discussions, but one should remember that the negative amplitudes actually mean phase inversion.

1671-7694/2010/010045-03

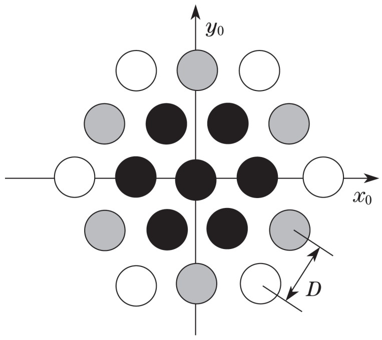

Fig. 1. A hexagonal array of unit lasers in CBC.

Since the arrangement of the unit lasers is hexagonally symmetric, we assume that the unit lasers of the same distance from the origin have the same parameters. Therefore, the unit lasers can be grouped by the distance from the origin, and the unit lasers of the same distance from the origin fall into the same group. The grouping greatly reduces the number of variables in the simulation. For a configuration with L groups, the near-field complex amplitude U becomes

$$U(x_0, y_0) = \sum_{l}^{L} \left\{ A_l \sum_{j}^{N_l} \exp\left[-\frac{(x_0 - x_j)^2 + (y_0 - y_j)^2}{w_l^2} \right] \right\} = \sum_{l}^{L} \left[A_l \cdot U_l(x_0, y_0) \right], \quad (2)$$

where N_l is the number of lasers in the lth group, A_l and U_l are the group amplitude and the combined complex amplitude of the lth group, respectively. In our simulation, A_l is the parameter to be optimized, for that U_l is fixed in a given configuration.

With the knowledge of the complex amplitude in the near-field plane $x_0 - y_0$, we can calculate the far field using the Fraunhofer diffraction formula. Our main concern is the flatness, i.e., the shape of the beam profile in the far field, so the diffraction formula can be essentially simplified to a 2D Fourier transform. To obtain a combined beam with the least flatness, we have to employ an optimizing algorithm to calculate the optimal parameters for all the unit lasers. The least-square method can be used to minimize the error of the combined beam from an ideal beam. The expression of the objective function ΔU for the optimization is

$$\Delta U = \iint_S \{F[U(x_0, y_0)] - U_{\mathrm{C}}\}^2 \mathrm{d}S = \iint_S \Big[\sum_{l}^{L} A_l \cdot U_{\mathrm{F}l}(x, y) - U_{\mathrm{C}} \Big]^2 \mathrm{d}S, \quad (3)$$

where $U_{\mathrm{F}l}$ is the Fourier transform of U_l, U_{C} is a constant representing the object amplitude of the ideal beam, and region S is a round region of which the radius is the same as the ideal beam. Choosing ΔU as the optimizing object implies that the expression in the integral of Eq. (3) should be real. This can be justified by the fact that the near-field complex amplitude U is two-fold symmetric, so the Fourier transform of U is real.

The optimization is carried out by setting the partial derivatives of ΔU with respect to A_l to zeros. For the lth group, the optimizing condition is

$$\sum_{k}^{L} \left(A_k \iint_S U_{\mathrm{F}l} \cdot U_{\mathrm{F}k} \mathrm{d}S \right) = U_{\mathrm{C}} \iint_S U_{\mathrm{F}l} \mathrm{d}S, \quad (4)$$

where A_k is self variable. Equation (4) is essentially a group of L linear equations. The integrals in Eq. (4) are determined by the given configuration of the light source, so we can calculate the integrals in advance to obtain the coefficients of A_k. By solving Eq. (4), we obtain all the group amplitudes with which the least flatness is achieved over region S. This optimization can also be considered as the process of non-orthogonal decomposition in the least-squares sense over region S, in which the basis is limited to the given functions.

An appropriate optimizing region S is also important to obtain a good beam profile in a fixed configuration. To find the region S which can bring the least flatness and the highest efficiency, a feasible approach is to check ΔU with a varying radius of region S. Since we optimize the beam profile by simulating an Airy function, the corresponding far-field parameters of the Airy function can be a reference. We usually choose the radius of S around $f\lambda/(\pi w_0)$, where f is the far-field distance, λ is the wavelength, and w_0 is the waist radius of the center unit laser.

For convenience, we assume a combining setup using a positive lens in the simulation. The lens is placed closely in front of the $x_0 - y_0$ plane, thus the focal plane of the lens is the far-field plane $x - y$. The focal length f of the lens is 1 m and the wavelength λ is 1060 nm. The waist radii of the unit lasers are 1 mm, which is typical for fiber lasers with collimated outputs. The far-field intensity distribution is calculated by using the Fraunhofer diffraction formula.

To start with, we consider a simplest case: a system consisting of 7 unit lasers which is shown as black in Fig. 1. We assume that the lasers are closely packed together with a distance $D = 2$ mm. The optimized far-field intensity distribution is shown in Fig. 2. The optimized group amplitudes for Fig. 2 are A_0:A_1 = 1 : (−0.040) and the radius of the optimizing region S is 0.14 mm. The corresponding flatness is about 2% in the optimizing region. The result in Fig. 2 is not very satisfying where only the center part of the beam is flattened. This is because the diameter of the main peak of an Airy function is nearly twice as wide as the width of a side ring, identical unit lasers cannot reproduce the Airy function with high accuracy.

To produce a beam with a better profile, a simple approach is to adjust the radius of the center laser according to that of an Airy function. In our simulation, we consider doubling the radius of the center laser. The packing distance varies to $D = 3$ mm to accommodate the size change of the center laser. We also add six more unit lasers to form a third group, which is shown as gray in Fig. 1. The optimizing result of the improved configuration is shown in Fig. 3. The optimized group amplitudes for Fig. 3 are A_0:A_1:A_2 = 1 : (−0.306) :

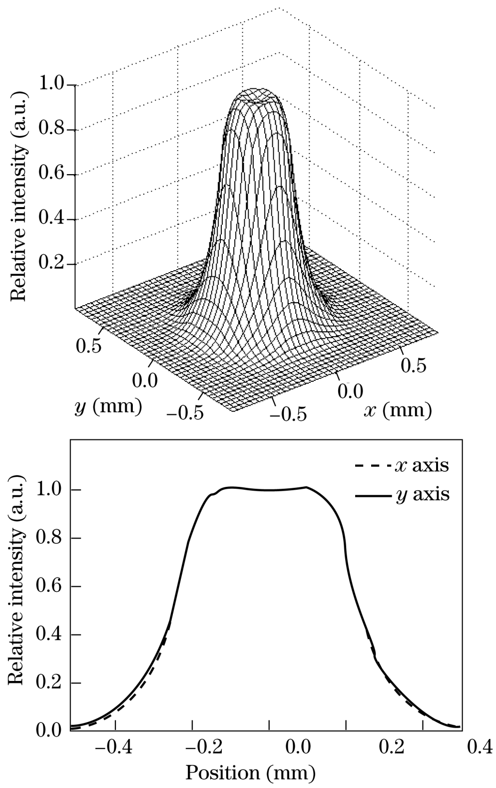

Fig. 2. (a) Optimized far-field intensity distribution of a system consisting of 7 unit lasers; (b) corresponding profiles along x and y directions.

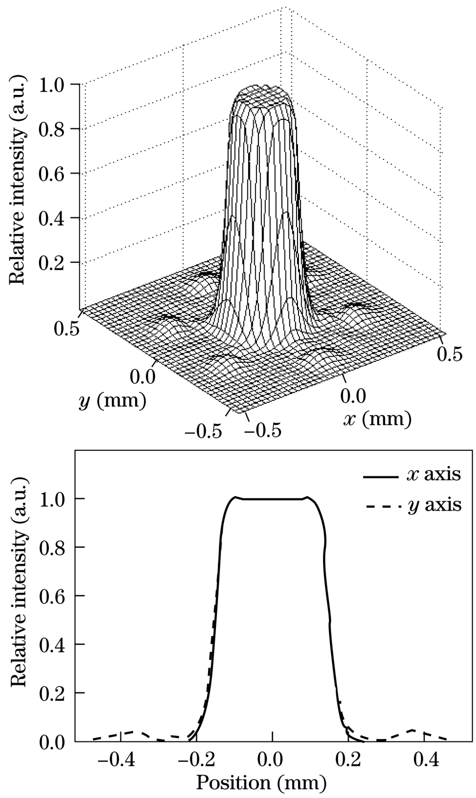

Fig. 3. (a) Optimized far-field intensity distribution of a system consisting of 13 unit lasers; (b) corresponding profiles along x and y directions.

0.012. The main lobe contains over 95% of the total power, and the flatness is less than 1% within an optimizing region of a radius of 0.11 mm. All the side lobes are not obvious compared with the main lobe. This may lead to the idea of further improving the beam profile by adding more unit lasers, while in fact the improvement is not obvious due to the oscillating decrease of the Airy function. As a result, Fig. 3 should be good for a flat-top beam CBC with 13 unit lasers.

In conclusion, we have discussed the possibility of producing a flat-top beam using CBC of Gaussian lasers. A mathematical model and the corresponding optimization algorithm are established for hexagonally arranged unit lasers. Simulation results show that with 13 optimized Gaussian lasers, a beam with the flatness of less than 1% can be achieved. The main lobe contains over 95% of the total power. The same concept can be used to generate the beams of other profiles, such as a hollow beam[15]. MOPA structures with appropriate phase control can be good implementations of the CBC flat-top beam generation scheme[4,16]. The scheme requires no shaping element and is suitable for high-power applications.

This work was supported by Anhui Provincial Natural Science Foundation under Grant No. 07041203.

References

1. Y. Dan, B. Zhang, and P. Pan, J. Opt. Soc. Am. A **25,** 2223 (2008).
2. S. Zhang, G. Neil, and M. Shinn, Opt. Express **11,** 1942 (2003).
3. J. Braat, Appl. Opt. **34,** 2665 (1995).
4. T. Y. Fan and A. Sanchez, Proc. SPIE **5709,** 157 (2005).
5. P. Zhou, Z. Liu, X. Xu, X. Wang, X. Li, and Z. Chen, Chin. Opt. Lett. **6,** 625 (2008).
6. J. Anderegg, S. Brosnan, E. Cheung, P. Epp, D. Hammons, H. Komine, M. Weber, and M. Wickham, Proc. SPIE **6102,** 61020U (2006).
7. V. A. Kozlov, J. Hernandez-Cordero, and T. F. Morse, Opt. Lett. **24,** 1814 (1999).
8. P. Zhou, Z. Chen, X. Wang, X. Li, Z. Liu, X. Xu, J. Hou, and Z. Jiang, Chin. Opt. Lett. **6,** 523 (2008).
9. L. Shimshi, A. A. Ishaaya, V. Ekhouse, N. Davidson, and A. A. Friesem, Appl. Phys. Lett. **88,** 041103 (2006).
10. A. E. Siegman, "How to (maybe) measure laser beam quality" *tutorial presentation in OSA Annual Meeting* (1997).
11. Q. Tang, Y. Yu, and Q. Hu, Chin. Opt. Lett. **5,** S46 (2007).
12. A. A. Tovar, J. Opt. Soc. Am. A **18,** 1897 (2001).
13. G. Wu, Q. Lou, J. Zhou, J. Dong, and Y. Wu, Opt. Laser Technol. **40,** 890 (2008).
14. Y. Li, L. Qian, D. Lu, D. Fan, and S. Wen, Opt. Laser Technol. **39,** 957 (2007).
15. H. Ma, H. Cheng, W. Zhang, L. Liu, and Y. Wang, Chin. Opt. Lett. **5,** 460 (2007).
16. L. Liu, Y. Zhou, F. Kong, and Y. C. Chen, Appl. Phys. Lett. **85,** 4837 (2004).