

An adaptive laser beam shaping technique based on a genetic algorithm

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A new adaptive beam intensity shaping technique based on the combination of a 19-element piezo-electricity deformable mirror (DM) and a global genetic algorithm is presented. This technique can adaptively adjust the voltages of the 19 actuators on the DM to reduce the difference between the target beam shape and the actual beam shape. Numerical simulations and experimental results show that within the stroke range of the DM, this technique can be well used to create the given beam intensity profiles on the focal plane.

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In some domain, such as inertial confinement fusion (ICF) and laser machining, focusing the beam profile to shape a specified intensity on the target plane is the ultimate goal^[1]. However, conventional shaping devices are generally designed for the given beam parameters thus cannot be used broadly. As one of the active correction elements of adaptive optics (AO) systems, piezo-electricity deformable mirror (DM) is widely used in adaptive optics for wavefront aberration correction^[2,3]. Because of the fast response and large deflection range of DMs, it is possible to apply them to change laser beam profile into a specified intensity. Generally, there are two ways to apply voltages on DMs. One is to measure the incident wavefront exactly by using a Hartmann wavefront sensor^[4-6], and the other is to employ some iterative strategies to control the DM surface shape based on a single experimentally measurable variable^[7]. Compared with the first approach, the later one is low-cost and convenient to implement because of omitting the direct wavefront measurement course.

In practice, the environment where the laser is placed in is not always free from interference, moreover, before laser beam is incident on the target plane, it usually passes through a series of imperfect optical elements. Therefore some phase aberrations will inevitably be brought into the beam, as a result, the needed beam profile, for example, a Gaussian beam profile or a super-Gaussian beam profile could not be obtained in the given plane.

To control the DM surface for beam intensity shaping, a simulated annealing method has been reported in Ref. [1]. However, as a stochastic parallel algorithm based on natural selection and biological genetics, genetic algorithm (GA) can operate on a population of potential solutions through applying the principle of survival of the fittest to produce the more and more closer solution to the optimal solution. It is often used to search the global optimum value of multi-target problems^[8]. In this paper, a global GA is employed to control a 19-element piezo-electricity DM to change the incident laser beam to produce a given profile on a chosen plane. Simulated and experimental results show that within the deformation

range of the DM, GA can be well used to control the DM for changing certain incident beam to form the needed beam intensity profile.

Figure 1 shows the experimental setup of beam shaping system with a 19-element piezo-electricity DM controlled by GA. A 650-nm laser beam is expanded and collimated by a telescope, and then this beam is incident on the DM. After DM, this beam is focused on a charge coupled device (CCD) camera by a focusing lens. Information of the light spot which is formed on the CCD is acquired by an image acquisition card within an industrial computer. Using this spot information, the computer calculates the digital voltages that control the DM to change its surface shape to produce the target beam profile. And then, these digital voltages are converted by a digital-to-analog (D/A) converter and amplified by a high voltage amplifier (HVA) before they are applied on the actuators of the DM. The whole course is controlled by a global GA.

The 19-element piezo-electricity DM which was fabricated in our laboratory is controlled by the global GA. The stroke range of this DM is 4 μm , the voltages that can be applied to the 19 actuators on the DM are in the range of $[-200 \text{ V}, 200 \text{ V}]$. Using this GA, the initial population consists of a group of random mirror surface shapes which are represented by a series of voltages. The voltages on the actuators of the DM are

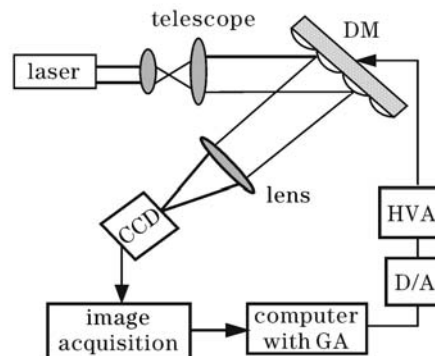


Fig. 1. Schematic of adaptive beam shaping system based on GA.

presented by a 19-element array $\mathbf{U} = [v_1, v_2, \dots, v_{19}]$. A variable $V_i(x, y)$ is used to represent the influence function of the i th ($i = 1, 2, \dots, 19$) actuator on the DM, which could be described as

$$V_i(x, y) = \exp[\ln(w)(\sqrt{(x-x_i)^2+(y-y_i)^2}/d))^p], \quad (1)$$

where w is the coupling value of DM and is set to 0.082; (x_i, y_i) is the space position of the i th actuator, p is set to 2, and d is the distance between every two neighbor actuators, and x and y are two directions in the orthogonal coordinate plane.

After $V_i(x, y)$ is known, the surface deformation $\psi(x, y)$ of the DM is

$$\psi(x, y) = \sum_{i=1}^{19} v_i V_i(x, y). \quad (2)$$

In comparison with a standard Gaussian beam, a super-Gaussian beam has less side lobe distribution which makes the super-Gaussian shape attractive in some industrial applications^[9]. We need to evaluate whether the beam shaping system has the ability to make a laser beam with phase aberrations form a specified Gaussian or super-Gaussian intensity profile.

The target laser beam profiles (both Gaussian and super-Gaussian intensity distributions) which are the goals of our system are saved in computer and can be defined as

$$F_{\text{object}} = \exp[-(a(x-x_0))^{2M} - (b(y-y_0))^{2N}], \quad (3)$$

where a and b determine the beam widths in the x and y directions in the orthogonal coordinate plane, M and N are integers, x_0 and y_0 are the centered positions of target beam spot,

$$x_0 = \frac{\sum X_i I_i}{\sum I_i}, \quad y_0 = \frac{\sum Y_i I_i}{\sum I_i}, \quad (4)$$

where X_i and Y_i are the coordinate values of the i th pixel, I_i is the intensity of the i th pixel.

GA begins with generating an initial population (a group of DM shapes) and the next step is to calculate the fitness value. The absolute difference between the target beam intensity profiles F_{object} and F_{DM} is regarded as the objective function of the GA to optimize and can be calculated by

$$\text{Error} = \sqrt{\sum_x \sum_y (F_{\text{object}}(x, y) - F_{\text{DM}}(x, y))^2}. \quad (5)$$

For convenient calculation, F_{object} and F_{DM} are set to have the same position center, the maximum pixel intensities of F_{object} and F_{DM} are both normalized to be the same unit value. What we can know from Eq. (5) is that the smaller the Error is, the more similar the F_{object} and F_{DM} are, and when Error equals zero, F_{object} and F_{DM} have the same beam intensity profile. The fitness function of the GA can be defined as

$$F_k = C - \text{Error}, \quad (6)$$

where C is a positive number and is greater than Error. From Eq. (6) we can see that the smaller the Error is, the larger the F_k is. After fitness calculation, GA will execute selection operation, in this paper, we adopt the roulette selection operation^[7].

As a main step of GA, crossover operation is a constructive process of which crossover probability P_c determines the number of individuals that enter into the mating pool. We adopt the non-uniform arithmetical crossover operator. Suppose that Y_A^t and Y_B^t are two individuals which are selected from a parent population by probability P_c , then two offspring individuals Y_A^{t+1} and Y_B^{t+1} can be generated as

$$Y_A^{t+1} = mY_B^t + (1-m)Y_A^t, \quad (7)$$

$$Y_B^{t+1} = mY_A^t + (1-m)Y_B^t. \quad (8)$$

The variable m which is determined by the evolution generation can be described as

$$m = r^{g(1-t/T)}, \quad (9)$$

where r is the random distribution number in the range of $[0, 1]$, T is the total iterative generation and is set in the range of $[300, 1000]$ in this paper, t stands for the current generation in the range of $[1, T]$, g is the weight factor and set to 2.

Mutation operation creates new individual by making changes in single individual. The mutation operator adopted here is a uniform one: choose the gene of an individual randomly, then alter this gene with a mutation probability P_m . Assume that the k th gene of an individual $\mathbf{X} = [x_1, x_2, \dots, x_k, \dots, x_n]$ is selected for a mutation, the new individual after mutation is $\mathbf{X}' = [x_1, x_2, \dots, x'_k, \dots, x_n]$, then the new k th gene x'_k can be obtained according to

$$x'_k = L_{\min} + R(L_{\max} - L_{\min}), \quad (10)$$

where x_k ($k = 1, 2, \dots, n$) is in the range of $[L_{\min}, L_{\max}]$, $[L_{\min}, L_{\max}]$ is the optimization space, R is the random number from a $(0, 1)$ uniform distribution.

To use the GA successfully, a series of simulant work have been done firstly, and then three optimum parameters of GA, i.e., population size, P_c and P_m are set to 20, 0.8, and 0.2, respectively. GA executes fitness value calculation, selection operation, crossover operation, and mutation operation in sequence until a global convergence is achieved. The global convergence is assumed if no improvement in the fitness value takes place after a fixed number of iterations.

Figure 2 shows the far-field intensity profile of a computer-generated beam with phase aberrations. This profile is used as the starting profile for simulant shaping and it will be shaped by DM for both standard Gaussian target and super-Gaussian target profiles.

Figures 3 – 6 are beam shaping results corresponding to four groups of parameters. Figure 3(a) is the standard Gaussian far-field target profile, Fig. 3(b) is the far-field profile of the beam shaped by GA, Fig. 3(c) represents the point spread function (PSF) curves of standard Gaussian target beam (solid line) and the shaped beam profile (dashed line), Fig. 3(d) shows the convergence of GA according to the iterative generations. Figures 4 – 6 are the beam shaping results based on three groups of

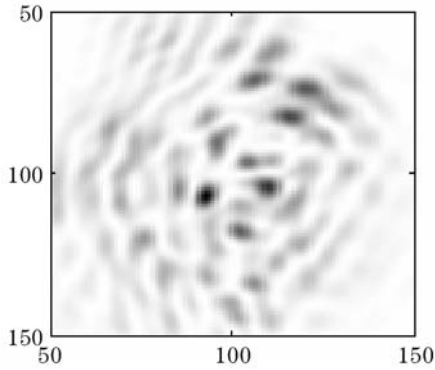


Fig. 2. Far-field intensity profile of a laser beam with phase aberrations for simulant beam shaping.

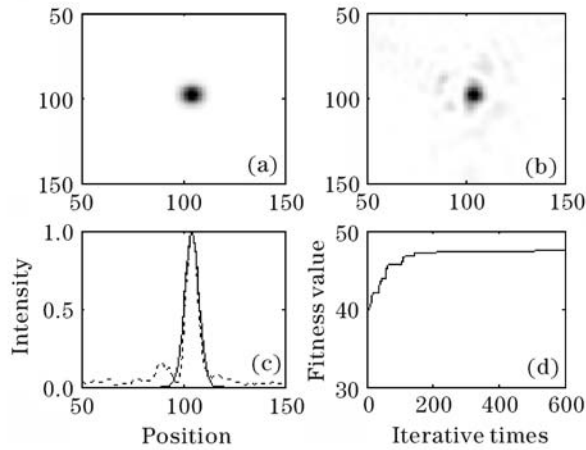


Fig. 3. Beam shaping simulation results for Gaussian profile ($M = N = 1$, $a = b = 0.2$).

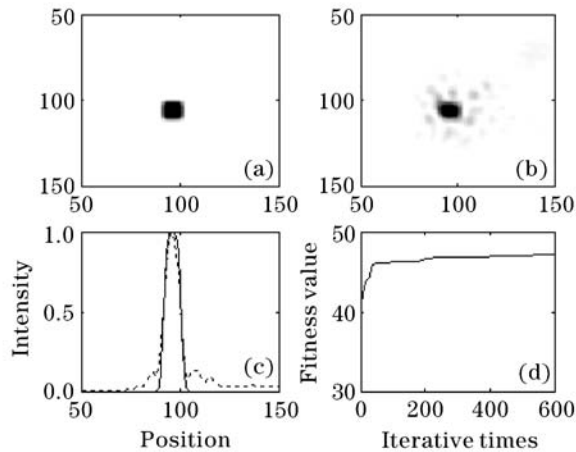


Fig. 4. Beam shaping simulation results for super-Gaussian profile ($M = N = 2$, $a = b = 0.2$).

parameters of super-Gaussian profiles. The layouts of Figs. 4 – 6 are similar to those of Fig. 3. From Figs. 3 – 6 we can know that in all cases, the beam intensity profile with phase aberrations can be well shaped close to Gaussian or super-Gaussian target profile. After several hundred times iterative running (it is about 30 minutes based on a Pentium computer with a 2.8-GHz CPU) the GA can well converge to a nearly global optimum value. Determined by the population scale and iterative times, it will take about

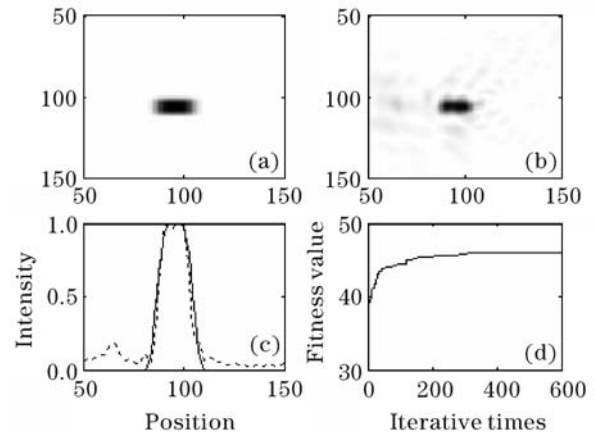


Fig. 5. Beam shaping simulation results for super-Gaussian profile ($M = N = 2$, $a = 0.1$, $b = 0.2$).

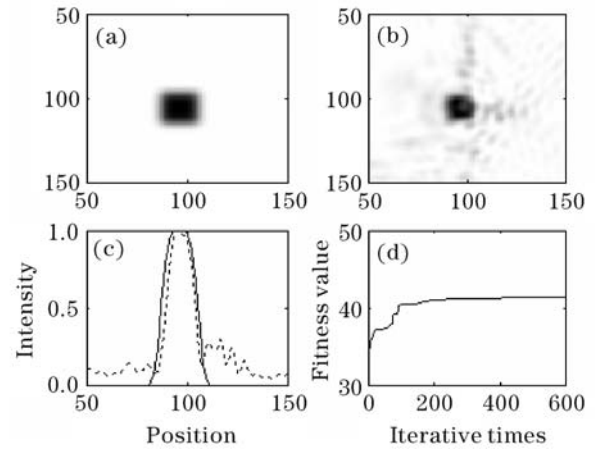


Fig. 6. Beam shaping simulation results for super-Gaussian profile ($M = N = 2$, $a = b = 0.1$).

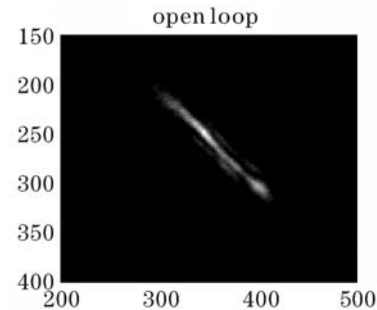


Fig. 7. Starting beam profile with astigmatism aberrations.

10 – 50 minutes to find the global optimum value. We also find that, as the target profile size increases, the shaping performance decreases accordingly. This phenomenon can be attributed to the limit deflection range of the DM. Although the stroke of the DM can reach 4 μm , it still may not satisfy our demands.

Figure 7 is the far-field beam profile with static astigmatism aberrations. This far-field profile is acquired by the image acquisition card within an industrial computer and used as the starting profile for shaping a standard Gaussian profile. Figure 8 is the corresponding experimental shaping result. Similarly, Fig. 9 is another starting profile with complex static aberrations for shaping

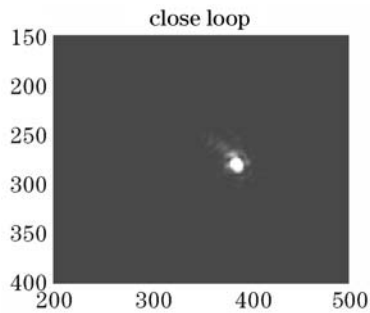


Fig. 8. Experimental shaping result for Gaussian object profile ($M = N = 1$, $a = b = 0.3$).

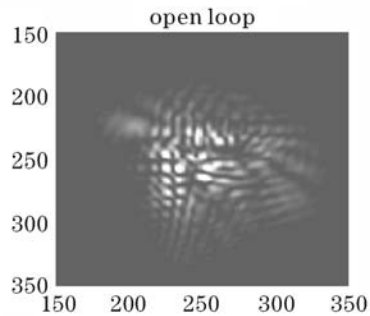


Fig. 9. Starting beam profile with complex phase aberrations.

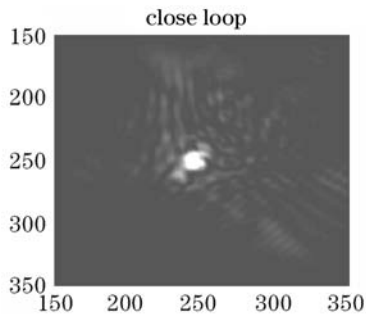


Fig. 10. Experimental shaping results for super-Gaussian object profile ($M = N = 2$, $a = b = 0.1$).

a super-Gaussian beam profile. Figure 10 is the experimental shaping results corresponding to Fig. 9. It takes 22 and 28 minutes to obtain the shaping results of Figs. 8 and 10 respectively based on the industrial computer with a 2-GHz CPU. What we can see from Figs. 8 and 10 is that GA can be used to shape actual laser beam to a Gaussian or super-Gaussian beam.

We have provided a method for controlling DM to shape the intensity profile of light beam. Both simulated and experimental results prove that it is feasible to form a Gaussian or a super-Gaussian intensity profile in the far field by changing the surface shape of the DM based on a global GA. Through selecting proper genetic operators and fitness function carefully, this GA is proved to be a powerful method for obtaining the optimum results. Simulation results show that it is possible to shape the intensity profile of beams with phase aberrations to well match the target intensity profile. Experimental results also prove that this GA can be applied to shape the actual laser beam with static phase aberrations to Gaussian or super-Gaussian beam. Therefore, we believe that this method will open a way of shaping the beam intensity profile of many lasers for industrial application, such as laser machining, ICF, and so on. Although the target intensity function in this paper is Gaussian or super-Gaussian one, it does not mean that our technique is restricted by it. In fact, it can nearly be used for any specified intensity shaping fields. To speed the convergence of GA and save the operation time, this adaptive beam shaping technique will be realized through hardware approach and it will be used in a solid-state laser system in our laboratory in the near future.

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