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Genetic-Algorithm-Based Method to Optimize Spatial Profile Utilizing Characteristics of Electrostatic Actuator Deformable Mirror

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Arbitrary spatial beam shaping was demonstrated with a membrane electrostatic actuator type deformable mirror (DM). An automatic closed loop system must optimize such beam shapes as flattop. Well-characterized short pulse laser beam is widely required for a photocathode RF gun or for microscopic processing, etc. We propose a new sophisticated optimizing method based on a genetic algorithm (GA) for spatial shaping. A membrane type DM is driven by electrostatic attraction power, and applied electrode voltages vs displacement of membrane surface have a square function relationship. We prepare discrete electrode voltages to linearly change displacement as a utilized gene of the initial population in GA. Using uniform crossover without mutation in this method, we can make an arbitrary spatial beam shape quasi-flattop.

Key words: beam quality control, Ti:sapphire laser, terawatt femtosecond laser, spatial shaping, adaptive optics, three-dimensional pulse shaping, deformable mirror (DM), genetic algorithm (GA), future light sources, photocathode RF gun

1. Introduction

Laser systems, which are used for many applications in various fields, have been developed for specific purposes. Some laser systems use complex sets of optical units or elements (lens, mirrors, crystals, etc.). These optical elements or complex systems sometimes cause such undesired effects as aberration, wave front distortion, and beam profile unbalance. Thus, many beam shaping techniques and devices have been studied.[1–6] Diffractive optical element (DOE) and micro lens array (MA) as a passive device with a geometrical method or computer-generated design are necessary for fine shaping, but they are limited to static beam input. Further, spatial light modulator (SLM) and deformable mirror (DM) as an active beam shaper can treat arbitrary beam input or changing beam input.

However, changing the distorted beam into a flattop beam is not always simple, because the laser beam from the table top terawatt laser fluctuates with depending on aberrations.

We have been developing a spatial beam shaper for a UV-laser light source for a photocathode RF gun at SPring-8.[7] A UV-laser, which is required for this gun's copper cathode, is generated as a third-harmonic of a Ti:sapphire terawatt laser. This UV-laser spatial profile must be flattop (top hat, i.e., homogeneous intensity in the cross section) on the photocathode as a light target plane with a diameter of 1.0 mm and circular cross section. The laser beam thus has high peak intensity, but the shaping device must not cause a nonlinear effect. Furthermore, we must change the beam diameter at the target plane. Active optics with a closed loop system[8] enables us to treat beam shaping when the input beam profile is changed. We selected membrane type DM, which does not cause a nonlinear effect.

It is necessary to select a proper algorithm for the automatic control in case of using the DM in closed system. An enormous conbination of voltages and electrodes may be optimized.

There are many genetic algorithms (GA),[9–11] for example, to correct the wave front of a femtosecond laser, but no one uses DM characteristics. These methods include many different ways of DM voltage optimization. Therefore, we propose an algorithm using membrane DM characteristics. With certain initial conditions for GA, GA convergence improves. The algorithm is used for generating a flattop beam using the third-harmonic beam of Ti:sapphire terawatt laser output.

2. Membrane Type Deformable Mirror and Characteristic

2.1 Membrane type deformable mirror

With an electrostatic actuator, we used a membrane type DM whose construction is shown in Fig. 1(a). The DM consists of an aluminum-coated, multilayer silicon nitride membrane and 59 small mirror actuators behind the reflective membrane with a center-to-center distance of 1.75 mm between the actuators. The outermost layer of the reflective membrane is protected with MgF_2 coating to maintain about 60–70% reflectivity in the ultraviolet region. Adjusting voltages between the control electrodes on the boundary actuators results in fine adjustment of each mirror actuator; the adjustable region of the control voltages is between 0 and 250 V in 1 V steps, making it possible to arbitrarily shape the laser spatial profile for a total of 250^{59} ($\sim 10^{141}$) forming possibilities. To control all electrode voltages, the DM needs other subsystems, a PC with a DA converter interface, an external high

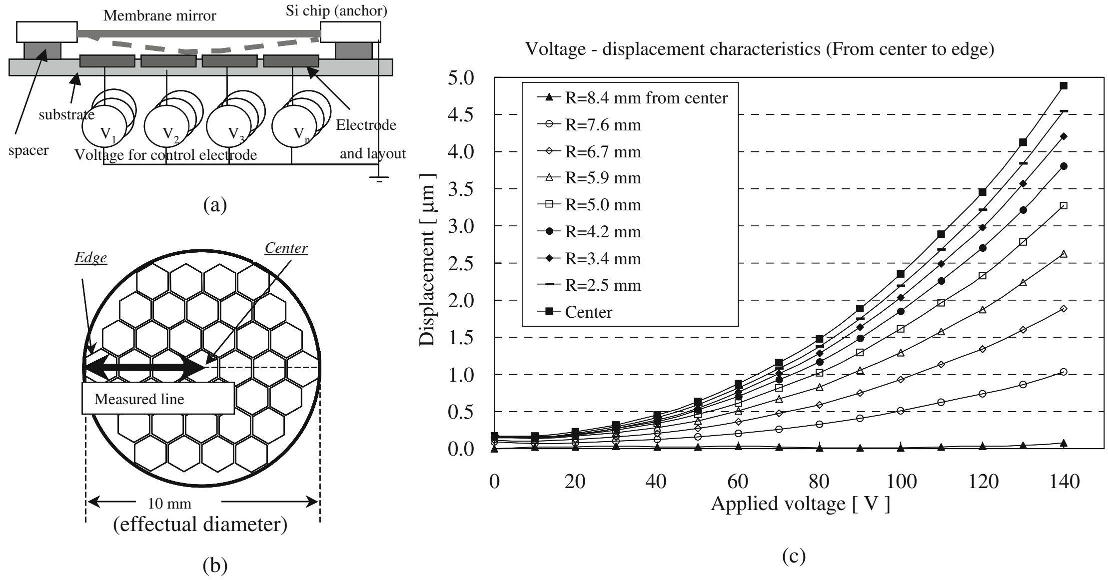


Fig. 1. Membrane type deformable mirror and its characteristics. (a) Sectional plane of deformable mirror. (b) Measured points on center line. (c) Voltage–displacement characteristics of membrane surface.

voltage power supply, and a control board that amplifies voltage to high. Signals for the control electrode voltages are prepared in the PC as voltage array and are next sent to the DM by a DA converter and a control board that applies high voltage.

2.2 *Basic characteristics of deformable mirror*

Each corresponding electrode can bend the membrane surface of the DM. Since the wave front is corrected, the spatial profile is transformed in the far field.

To obtain the basic characteristics, we measured surface displacement while changing the applied electrode voltages of two types of DM, 37 and 59ch DM, using a noncontact three-dimension measuring system (Mitaka Kohki Co. NH-3) and focusing the He–Ne laser light at the membrane surface. In this experiment, the electrode voltages were all set identically from 0 V to max voltage (140 V for 37ch DM and 250 V for 59ch DM), and we measured 11 points on the center line of the DM membrane surface, from the center to the edge (near the anchor) inside the effectual DM diameter. Figure 1(b) shows the DM layout; hexagons denote electrodes behind the surface.

The result is shown in Fig. 1(c). Since all points are on the conic line, the relationship of the applied electrode voltages vs surface displacement (V–D) can be expressed in square function ($D = CV^2$, where C is a constant) for all measured points from the center to the edge of the DM. The displacement center comes up to 5 µm for the 37ch DM, while edge displacement is limited below 1 µm because the membrane edge is fixed to the anchor. Additionally, the displacement of changing the electrode voltage from 0 to 70 V was much smaller than from 70 to 140 V. In a similar experiment for 59ch DM, the displacement of the center electrode was 7 µm when the same voltage was applied to all electrodes.

3. Experimental Setup for Spatial Profile Transformation

3.1 *GA algorithm*

This spatial shaping method with adaptive optics requires a sophisticated algorithm. We developed software based on a GA to automatically optimize DM deformation. The set of voltages of whole DM-electrodes is treated as chromosomes in GA application.

The basic GA operation has several steps. After preparing the initial population consisting of a number of chromosomes by coding electrode voltage as a parameter, iteration starts, and then the following steps are taken: selection, crossover (generally including mutation), and evaluation by a fitness function followed by selection (surviving chromosomes). Selection is used to reduce digenesis by the minimal generation gap (MGG) method and also to reduce the calculation load. In the next section, our procedure for GA operation is described.

3.2 *Automatic closed loop system*

A set array of electrode voltages in a PC easily drives the DM manually, but a combination problem exists when automatically optimizing beam spatial shaping. Therefore, a closed loop system for beam shaping is essential to optimize DM electrode voltages. We control the DM's electrode voltage by PC and measure the profile with a laser profile monitor (Spiricon LBA300-PC[12]). Laser light is reflected by DM, and after passing a set of optical lens and mirror, partial light is inserted to profile the monitor whose analyzing program can provide many parameters of beam profiles (see Fig. 2). The program is remote controlled by Active X, so we can control DM by monitoring laser beam parameters.

The original laser beam is generated from a Ti:sapphire terawatt laser system and penetrates THG and a fused silica

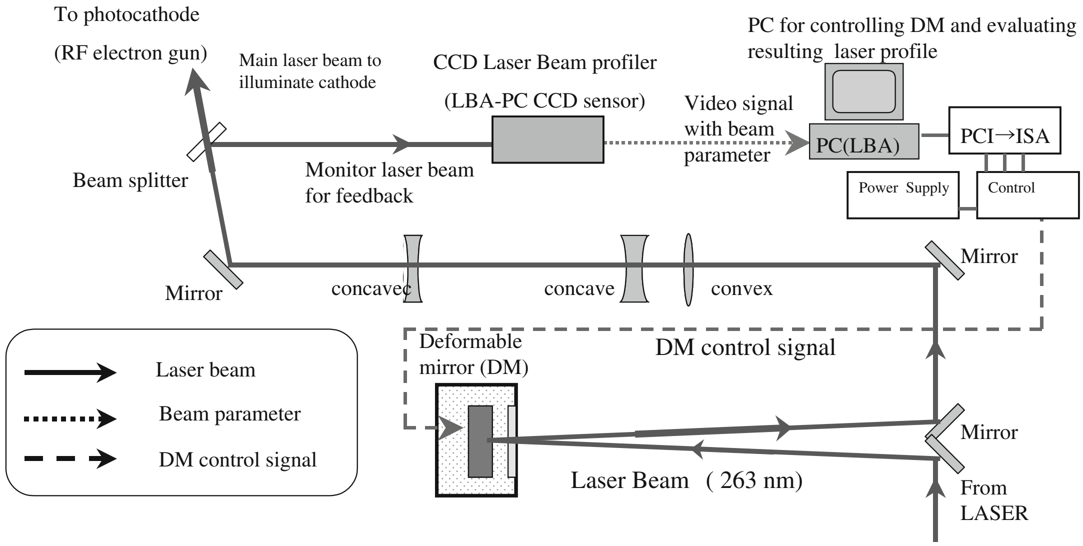


Fig. 2. Experimental setup for spatial beam shaping.

rod due to wavelength requirements (263 nm) and pulse duration (2.5 ps). It has an aberrated beam profile. Our aim is to make a flattop on the photocathode as a light target plane with a diameter of 1.0 mm and circular cross section after beam shaping.

3.3 Preparation (coding to chromosomes)

In the first step of GA, a number of chromosomes must be prepared as the coded initial population. Although in the early years, 8-bit binary values were used on gene chromosomes, recently, an electrode voltage parameter has been directly used. We selected the latter for preparation due to efficient movement based on experiments for 59ch DM, whose results are shown Fig. 3(a).

In this type of DM (electrostatic actuator), displacement in the central region of the membrane is proportional to the square of the electrode voltage. The dotted line shows displacement corresponding to the voltage, and voltage for the 0.5 µm steps is shown by solid lines. Both lines are for the center of the DM, but voltage steps are common property for all electrodes, as shown in Fig. 1(c). Thus, to linearly change displacement, electrode voltages were randomly selected from a set of discrete voltages (0, 42, 70, 93, 113, 131, 147, 162, 176, 189, 201, 213, 225, 236, and 250 V), and each value corresponds to vertical step lines in Fig. 3(a). To use a set of discrete voltages, standard deviation for controlling DM capability is improved on the corresponding normally random generation of elements in GA.

We prepared 50 chromosomes as the initial population. The 59 DM-electrode voltages were applied independently in a range of 0 to 250 V and coded to 59 elements per chromosome [shown in Fig. 3(b)].

3.4 GA procedure in MGG method

In the GA procedure, chromosomes are treated as follows [Fig. 4(a)].

(1) Make a Family consisting of four chromosomes: Two chromosomes are selected randomly from the initial population to make a "Family", and these chromosomes are labeled "Parents". Then, the other two chromosomes labeled "Children" are generated through the crossover of the chromosomes of the "Parents". Thus, four chromosomes are prepared and treated as a "Family", which is called "Generation" in GA.

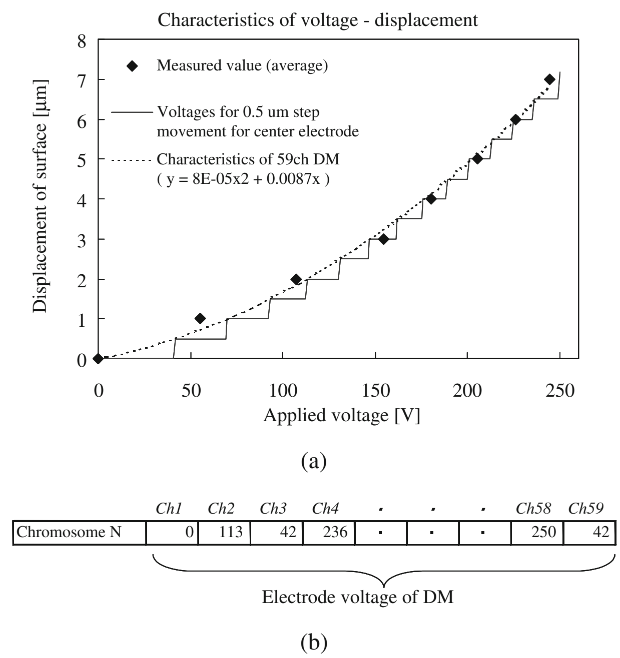


Fig. 3. Preparation for GA: 59 chromosome elements are used as step electrode values. (a) Discrete voltage step for DM. (b) Coding for chromosomes.

(2) Drive the deformable mirror and obtain results of the laser parameters from measurements of the laser's spatial profile: In the MGG method, the four chosen chromosomes in the Family are compared, and the two best survive. Drive DM by setting the chromosomes of the four members of the "Family" (in the order "Father", "Mother", and two

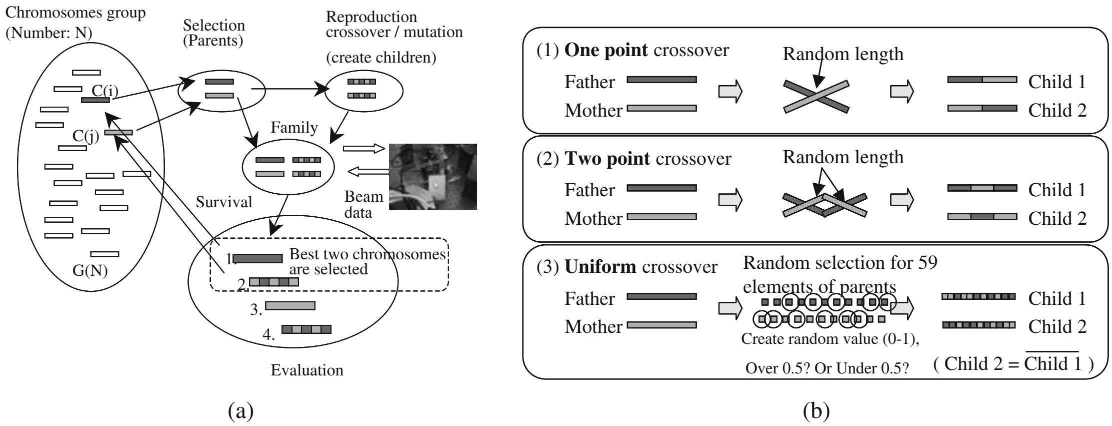


Fig. 4. Flow of GA procedure. (a) Flow of GA procedure for deformable mirror; selection, crossover, evaluation, and selection step. (b) Differences of three crossovers.

Table 1. Set parameters and usages for fitting function to evaluate spatial profile optimization to flattop shaping.

Parameters of fitting function for flattop shaping	
Beam Center	Minimize difference from initial center position (x, y)
Top hat factor[12)]	Maximize top hat factor (0–1) (Flattop: THF = 1.0)
Aperture energy	Maximize integrated energy within set circle area
Effective diameter	Minimize difference from diameter of set circle
Flatness (SD/mean)	Minimize standard deviation divided by average in flattop area
Peak-to-peak	Minimize difference between max and min in a flattop area
Beam diameter	Minimize difference from set diameter
Hot spot (max.)	Minimize max. in flattop area
Dark spot (min.)	Maximize min. in flattop area

“Children”), and obtain each result of the beam parameters calculated from the analysis program of the laser profile monitor. The beam parameters of the laser’s spatial profile are obtained for evaluation in the following step.

(3) Evaluate the resulting parameters using a fitness function: These results are scored by a fitness function defined by flattop beam shaping. The fitness function is a linear combination of the nine parameters[7)] shown in Table 1 with each coefficient as weight. If a chromosome is more highly scored in the evaluation of the fitness function for flattop, it will be promoted to a higher position in the “Family” ranking. Thus, in this ranking, chromosomes are ordered by comparing fitness function values.

(4) The best two chromosomes are selected as superior and then returned to the population. This procedure makes one generation step forward, and the population is renewed to initiate the next generation.

3.5 *Crossover and mutation*

In our program, we prepared three different ways of crossover: uniform (in our case “58-point crossover”), one-point, and two-point. In the MGG method, high scoring chromosomes are returned to the population by a fitness function as the next generation. A condition in which “Children” is quite different from “Parents” is convenient for seeking the optimized solution. Uniform crossover is also available in programming to generate “Children”. For example, a random number from 0 to 1 is generated, and when the number is over 0.5, a gene for Child 1 is extracted from “Father” and “Child 2’s” is taken from “Mother”. In the other case, reverse sets are extracted, and Child 2 is conjugative for “Child 1” [Fig. 4(b)].

Mutation is not used because uniform crossover widely searches the GA solution, and the genes of the chromosomes in the initial population are based on DM characteristics. The other crossover and mutation methods are still debatable.

4. Experimental Results and Discussion

4.1 *Beam profile parameters for fitness function*

A fitness function is used to evaluate the flattop profiles for GA. We chose nine beam parameters[5)] to evaluate the profiles in a closed loop system. These beam parameters and their functions are shown in Table 1 and Fig. 5.

Simultaneously using plural beam parameters requires adequate weight for fitness function as a coefficient. To determine these coefficients, we used a ratio of converged value after 500 steps of the GA experiment. First, the converged values for one beam parameter measured experimentally. Next, they were modified using a combination of beam parameters. Sometimes too many beam parameters carried undesired effects. If the “flatness” of the parameter is excessive, the intensity of the beam profile is decreased to the noise level. In this case, the coefficient must be adjusted.

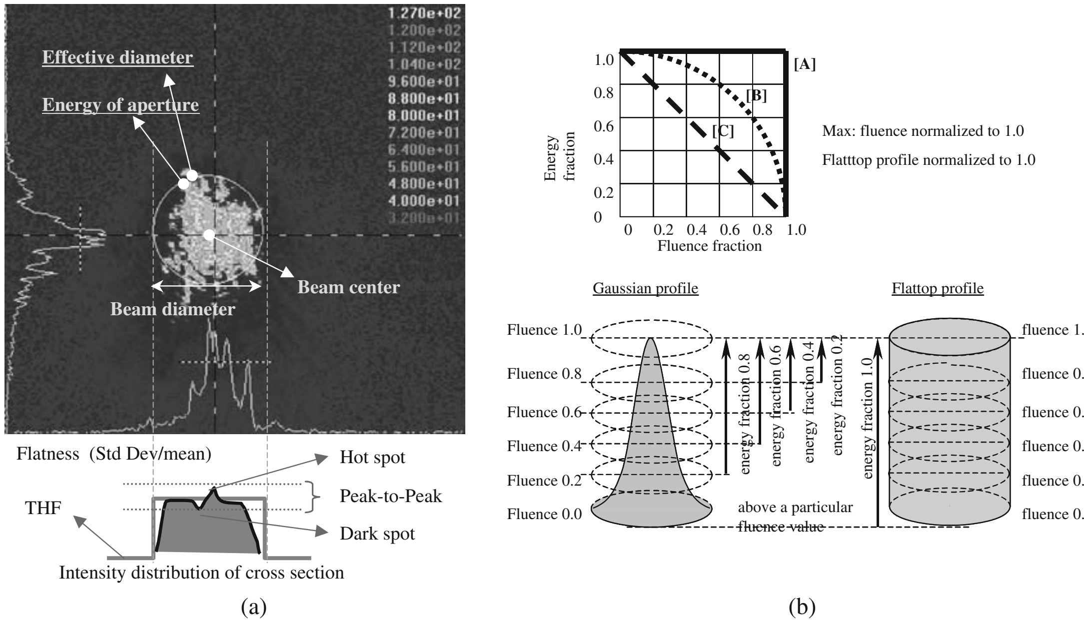


Fig. 5. Parameters for spatial beam shaping and explanation of top hat factor. (a) Laser beam profile during optimization and parameters for flattop shaping. (b) THF: Energy fraction defined as fraction of total energy above a particular fluence value; Perfect Top Hat has single fluence value comprised of 100% energy and plots curve [A]. Gaussian beam plots curve labeled [C].

The fitness function is comprised of the linear combination of these parameters and is used as an index for the sophisticated program-based genetic algorithm.

The closer the laser profile is to the target profile (flattop), the higher the fitness function score is. This is calculated for the spatial profile corresponding to each chromosome to evaluate the spatial profile, the spot-size diameter, and the center position of the profile. Maximizing the value of the fitness function with the GA program, a computer-aided DM optimizes the profile toward a target spatial profile such as the flattop. The most important parameter is the top hat factor (THF),[12] which is defined as an integral function of energy fraction, as shown in Fig. 5(b).

4.2 *Spatial beam shaping experiments*

A flattop beam profile is accomplished by proper combination of three parameters; energy of aperture, THF, and standard deviation by mean (SD/mean). Since the automatic control system based on genetic algorithm stops when the step number reaches an appointed number, we stored parameters and the results of converged chromosomes as initial population for the next experiment. The first was started from the initial distorted beam. The next three experiments were started with the results of previous converged chromosomes as a population. The last test was 1000 GA steps. Finally, the total steps were a maximum of 3000.

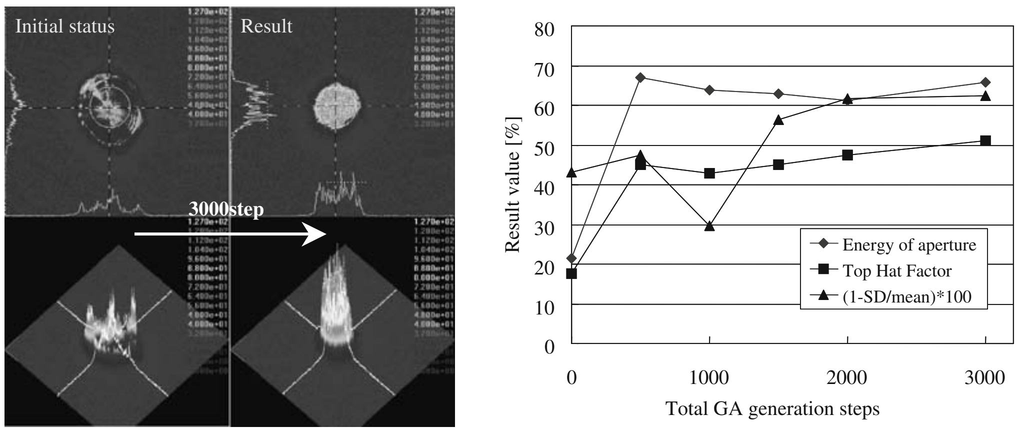
As a result, the laser profile was spatially shaped to a profile shown in Fig. 6. It shows an optimization process with a GA-based method up to 3000. The upper and lower images show 2D and 3D views, respectively. While energy is concentrated and fitted into a set circle, Fig. 6(a) shows that the spiky noise of the flattop area is not yet completely deleted. Three of the fitness function parameters are shown in Fig. 6(b) as evaluated parameter in each step. The value of 0–1 is changed to 0–100 to express percentage. The "SD/mean" must be minimized, so it is expressed as $(1 - \mathrm{SD/mean}) \times 100$ in Fig. 6(b). The parameters close to flattop are located in the upper part. Individually, these parameters show little improvement, but the experiment leads to completely balanced results.

5. Conclusions

We used a computer-aided DM as a spatial shaper for a high stabilized tripled Ti:sapphire laser beam (263 nm). This automatic optimization with a DM is a powerful method with genetic algorithms if the ideal profile is within its search range.

DM has capability for beam shaping due to its adjustable region of control voltages and electrodes set. On the other hand, it causes a complex combination problem. Since a DM membrane is attracted by electrostatic power, membrane surface displacement is proportional to the square of the electrode voltage. We linearly changed the discrete voltages for displacement with 0.5 μm steps to retain the movement range of the membrane surface. These voltages are selected semi-randomly and used as genes to make the initial population. To hold the discrete voltages and to search a wide space, we selected uniform crossover without mutation.

Utilizing DM characteristics for an optimizing program based on GA is considered an efficient method to restrict combination patterns against wide search ranges. We simultaneously used plural parameters that required adequate weight for fitness function, so there is still room for more optimization.



(a) (b)

Fig. 6. Optimization process with GA based method up to 3000 steps. (a) Evolution of spatial beam shaping. (b) Changes of evaluated parameter in each step.

We have a plan to improve the search range and the potential of this system with sophisticated fitness function in the future. Moreover, it should directly optimize specific values in each application. For instance, directly monitored emittance of electron beams is a sufficient value to optimize a high brightness RF gun and such processing parameters as depth progress rates for laser material processing. Our final purpose is to build a rapid searching solution system that optimizes progress to obtain the best results for several systems.

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