Application of genetic algorithm on optimization of laser beam shaping

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Abstract: This study proposes a newly developed optimization method for an aspherical lens system employed in a refractive laser beam shaping system, which performs transformations on laser spots such that they are transformed into flat-tops of any size. In this paper, a genetic algorithm (GA) with multipoint search is proposed as the optimization method, together with macro language in optical simulation software, in order to search for ideal and optimized parameters. In comparison to a traditional two-dimensional (2D) computational method, using the one-dimensional (1D) computation for laser beam shaping can search for the optimal solution approximately twice as fast (after experiments). The optimal results show that when the laser spot shrinks from 3 mm to 1.07 mm, 88% uniformity is achieved, and when the laser spot increases from 3 mm to 5.273 mm, 90% uniformity is achieved. The distances between the lenses for both systems described above are even smaller than the thickness for the first lens, enabling us to conclude that our design objectives of extra light and slimness in the system are achieved.

OCIS codes: (140.3300) Laser beam shaping; (220.2740) Geometric optical design

References and links

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1. Introduction

A laser beam has the following properties: it is high powered, directional, coherent, and monochromatic. Laser beams also exhibit a Gaussian distribution. However, technologies involving laser welding, laser processing, and laser medical applications are affected the uneven energy distribution of laser beams which can cause material damage due to localized overheating. To avoid affecting the subsequent processes, laser beam shaping is necessary. In recent years, laser beam shaping technology has become an important research topic due to the increasing demand for it from various applications. One of the most commonly used laser beam shaping technologies is called flat-top. Through optical design [1–3], the Gaussian distribution [4] of the laser beam energy is converted to uniform distribution. A uniformly distributed laser beam can be obtained by shaping systems that are refractive [5–8] and reflective [9–11]. Laser shaping designs are often based on derived methods [5]. However, the thickness between lenses is often assumed to be large enough to simplify the derivation and to reduce the design difficulties associated with aspherical parameters, making the overall length of the system continuously increase. If the gap between the two lenses is not significantly larger than the thickness of the first lens during the derivation process, laser shaping cannot be achieved. In addition, most laser shaping systems assume that the incident beam is collimated [7,8] for ease of derivation. Not all systems are designed to use laser beams with a collimated light source [12]. Even if a divergent light source is used, most systems focus on transforming the light source into collimation, and consider uniformity less. Although some non-sequential optical softwares support the optimization process, they usually focuses on one target during optimization process. The spot size and collimation could not be optimized at the same time when running optimization. However, the laser beam shaping often concerns about the spot size and collimation simultaneously. The optimization method with genetic algorithm (GA) offers a great solution to optimize multiple targets when executing the optimization process especially for laser beam optimization. In our study, a GA is used for optimization, and our laser beam shaping design is based on a refractive system. A one-dimensional (1D) computation is undertaken, instead of a two-dimensional computation (2D) to speed up the optimization. As a result, the GA with 1D computation can effectively transform a laser with Gaussian distribution into a laser with uniform distribution. Our study is divided into five sections: an introductory section, the GA optimization for a laser shaping system, different calculation methods for optimization, simulation results for the laser beam shaping system, and a conclusion.

2. Genetic algorithm in laser shaping optimization

The GA can simultaneously search multiple variables in multiple modal spaces to improve the limitations of the searching domain, which can solve the problems raised by complexity and discontinuity. Most of the conventional searching methods have the deterministic characteristic that the direction of the next searching point is based on a point within the searching domain. Such point-to-point searching methods easily become trapped in a local optimal solution. With its random and adaptive characteristics, a GA can consider multiple object points in the domain simultaneously, instead of focusing on only a single object point. A more complete and thorough survey is performed to avoid becoming trapped in a local optimal solution. The main framework in which GAs solve problems consists of three compartments: a selection mechanism, crossover operation, and mutation operation. The process flow for the GA used in our study is shown in Fig. 1.

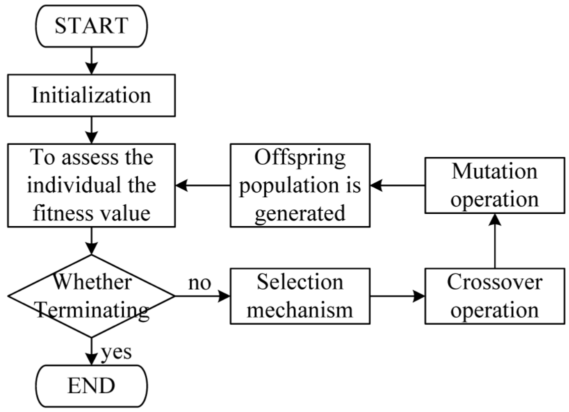

Fig. 1. GA process flow.

In the GA process, a function is used to investigate what the fitness level is for each individual within a population. A higher fitness value for an individual means more ability to fit. The GA can identify the fitter individuals on the basis of the fitness function. The fitness function of the proposal is believed to optimize uniformity, the size of the laser spot, and collimation. The definition of the fitness function is presented in two parts, as described below:

2.1 Definition of fitness function

For the optimization method used in our study, an object value r_T is defined before the simulation starts. Two fitness values, r_1 and $r_{2,}$ gradually approach the target according to the GA process. In other words, we obtain the optimal solution according to how close the fitness values are to the target, as shown in Fig. 2. The object functions for uniformity and spot size are defined as

$$M_1 = \exp\left\{\left[\sum_{i=1}^{Mesh}\left(\left|r_1 - r_T\right| + \left|r_2 - r_T\right|\right)\right]\times Q\right\}, \tag{1}$$

where *Mesh* is the number of grids for the detection surface. In this study it is 51x51. r_1 is the simulated grid value of the detection surface. r_2 is the simulated grid value of the detection surface on the back of the second lens. r_T is the target value. Q is the weight. Since the object value is respected as exponential, the closer it is to the value 1 the closer it is to the ideal value. In terms of weighting, the computation required is excessive if we perform a calculation in 2D. After evaluation and verification, it is set to 0.0001 if we are performing the calculation in 2D, but 0.003 if we are performing the calculation in 1D.

The definition of the target function for collimation is

$$M_2 = \exp\left\{\frac{1}{N}\left[\sum_{i=1}^{N}\left(1-\cos\theta_i\right)\right]\right\}, \tag{2}$$

where N is the number of all beams on the detection surface. The θ_i is the direction cosine angle at the detection surface. The total average value is then obtained as exponentiation. A value closer to 1 shows that the beam is more collimated to the optical axis. In order to approach the target, multiplication is used to calculate the optimal object: that is

$$fit(i) = \frac{1}{M_1 \times M_2}, \tag{3}$$

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A larger value for the optimized target means a larger value for the fitness function, and hence an easier target to select.

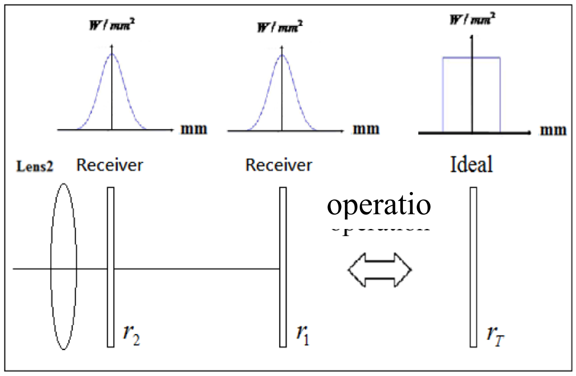

Fig. 2. Simulated calculations.

2.2 Selection mechanism

The fitness value is respected in the selection mechanism to produce offspring from the population. The best-known selection method is roulette wheel selection. Each individual is treated as a region in a wheel. The size of the region is proportional to the fitness value of the individual. A higher fitness value has a larger region representing the individual, which results in a higher probability of selection. The equation used for roulette wheel selection is

$$P_M = \sum_{i=1}^{M} fit(i) \Big/ \sum_{i=1}^{Pop\_size} fit(i) \text{ for } M = 1, 2, \ldots, Pop\_size, \tag{4}$$

where P_0 is zero. When a random number between $P_{M\text{-}1}$ and P_M is generated, the individual with number M is selected to perform the operation crossover.

2.3 Crossover operation

In the case of crossover, two individuals from the GA parent generation are randomly selected using the selection mechanism. An individual is produced after merging data from the parents. It is mainly used to select the good genes accumulated from the previous generation with the intention that these genes will produce even better individuals. The offspring genes are then produced by merging the parents' genes based on the exchange rate; that is, a random value (α). The crossover rate refers to the ratio between the parents' generation and the next generation. If we assume that the parent generation has a value of 100, and a crossover rate of 0.8, then 80 offspring will be produced as a result of crossover. The exchange rate refers to the ratio of gene exchange. Suppose two individuals $A = (a_1, a_2, \ldots, a_n)$ and $B = (b_1, b_2, \ldots, b_n)$ are selected from the parent generation; each pair of genes undergoes crossover according to the exchange rate. The gene of offspring $C = (c_1, c_2, \ldots, c_n)$ is produced as

$$c_i = a_i \text{x} a + b_i \text{x} (1 - \alpha). \tag{5}$$

where the exchange rate is a random value between 0 and 1.

2.4 Mutation Operation

If the GA relies simply on crossover to reproduce the offspring, the individual cannot evolve with new features. This is because the new individuals merely inherit various characteristics as a result of merging the genes from the parents. This not only slows down their evolution, but also limits the results to only a few particular points. Generally speaking, if the mutation

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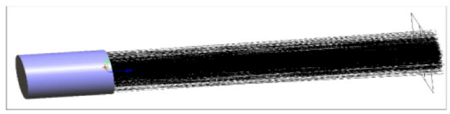
rate is high, it is not easy for them to converge for optimization. The mutation rate should be set within a reasonable range. We use the multipoint random mutation method, with the mutation rate set to 0.2. When the randomly generated value (β) is less than 0.2, the mutation requirement is satisfied to randomly generate a new gene which is within the specified range. The three operations: selection, crossover and mutation, are iteratively performed in the GA process to optimize the laser beam shaping system. Without setting termination conditions, the GA process continues to evolve endlessly. The termination condition is set to 100 evolutionary generations. Analysis is performed for each generation until the search reaches the generation specified.

3. Calculation methods of fitness value



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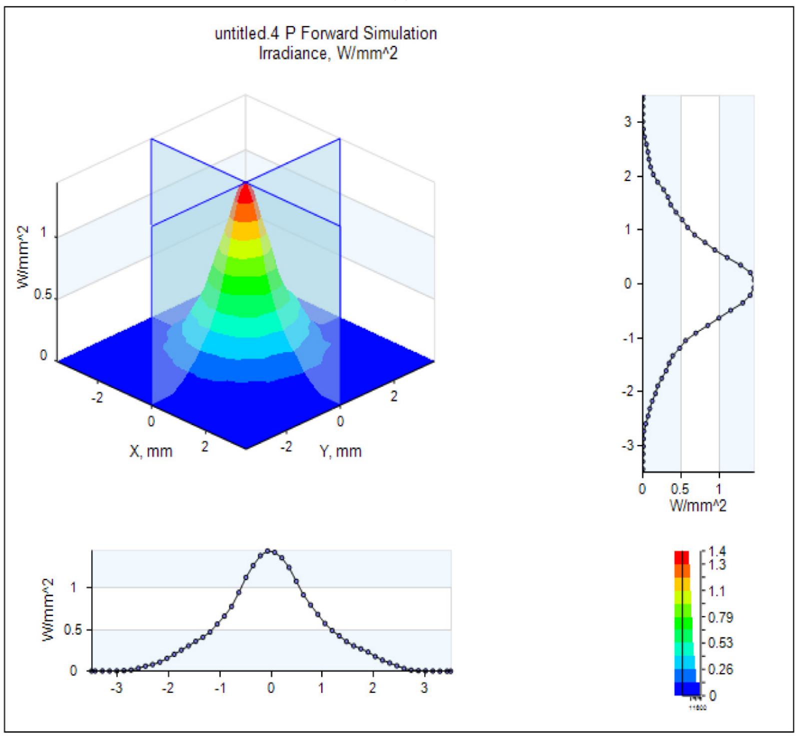

(b)

Fig. 3. Initial simulation of laser source (a) Tracing diagram for the laser beams (b) Laser spot irradiation.

Table 1. Laser light source specifications.

Wavelength	Beam diameter	Beam divergence	power	Laser mode
355nm	5 mm	0.5°	7 W	TEM_{00}

To optimize the original 2D calculation method in the laser beam shaping requires excessive computation. All grid values (51x51) from the detection surface are used in the calculation. To lower the computation cost, we attempt to take advantage of the rotationally symmetric property in refractive shaping systems to convert the 2D GA calculation into a 1D calculation.

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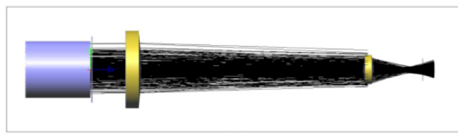
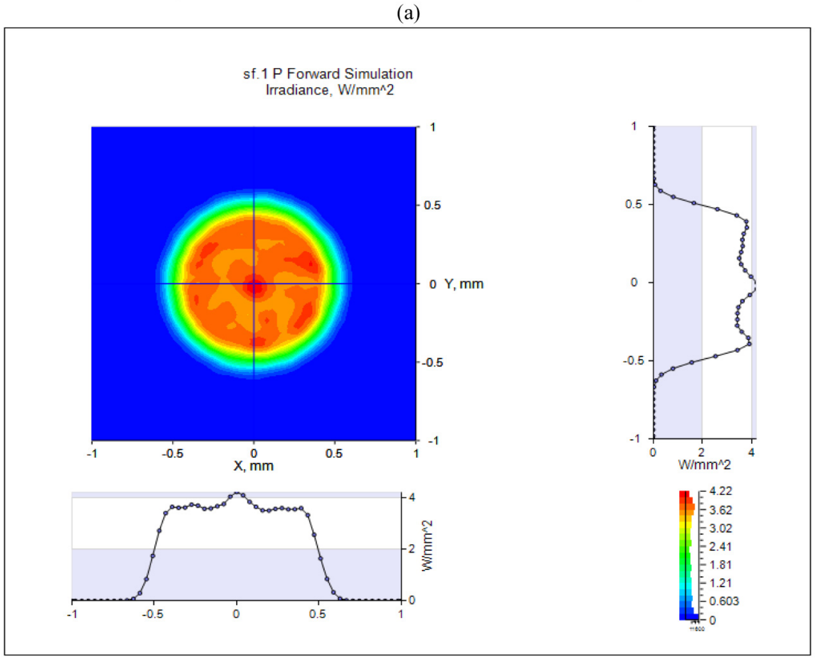
Only part of the detection surface (51x1) is calculated, to reduce the computation cost. These two calculation methods are used to reach optimization in comparing the results for laser beam shaping. Aspherical lens architecture was used to reduce the laser spot from 5 mm to 1 mm with a uniform flat-top laser beam. The settings for the laser light source had to be configured in the simulation software before the optimization was performed. The energy distribution for the laser source is usually circular, and therefore the laser source is designed to be cylindrical in the system. Table 1 shows the settings for the laser light source. The incident light source is configured to be 7 W. However, the detected value of 3.5 W at the detection surface is the one mainly used because the light source is coherent. Light Tools simulation software was then used to verify the characteristics of the laser source on the detection surface. One million laser beam rays are used in the following simulations. The initial tracing diagram for the laser beams is shown in Fig. 3(a). Figure 3(b) shows the initial laser spot irradiation.

3.1 2D calculation method



(a)



(b)

Fig. 4. Simulation by 2D calculation (a) Trace diagram for the laser beams (b) Laser spot irradiation.

Table2. Detection surface data of 2D calculation.

	Uniformity (%)	Collimation (degree)	spot size (mm)	Conversion efficiency (%)	Rate of shrinkage (%)
Simulated values	81	12.139	0.983	87	20

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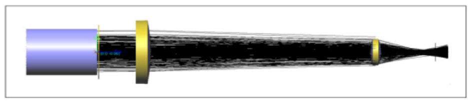
The fitness value was 1/1.547 after performing 2D GA optimization on an aspherical lens system. The simulated trace diagram of 2D calculation for the laser beam shaping system is shown in Fig. 4(a). The largest illumination value out of the 13 detection points on the detection surface was 4.221 W/mm^2, and the smallest value was 3.432 W/mm^2. The uniformity is therefore 81%. Figure 4(b) shows the laser spot irradiation of 2D calculation at the detection surface for the system. According to the program, the calculated average angle for all light when passing through the detection surface is 12.139 degrees. The total amount of radiation obtained is 3.034 W. The initial incident energy was 3.5 W. The conversion efficiency was 87%. The size of the laser spot was set to be full width half maximum (FWHM), which was 0.983 mm. The calculated shrinking rate for the laser spot was 20%. The simulated values for the detection surface are listed in Table 2.

3.2 1D calculation method



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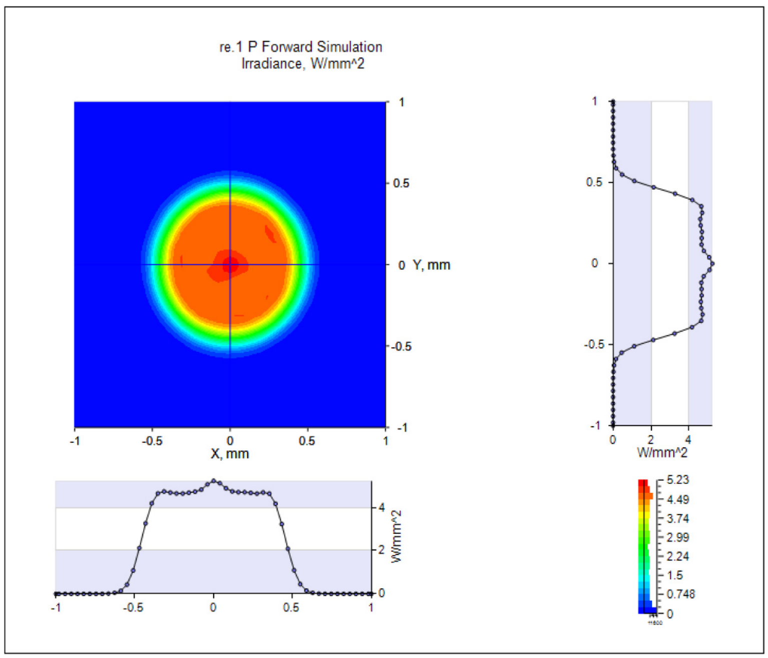


(b)

Fig. 5. Simulation by 1D calculation (a) Trace diagram for the laser beams (b)Laser spot irradiation.

Table 3. Detection surface data of 1D calculation.

	Uniformity (%)	Collimation (degree)	Laser spot size (mm)	Conversion efficiency (%)	Shrinking rate (%)
Simulated values	88	11.026	0.908	93	18

The aspherical lens used in the laser shaping process is rotationally symmetrical in refractive optics systems. The chromosome used in the 2D is same as that of the 1D. The difference between the 1D calculation and the 2D calculation is the number of mesh grid. We reach success in use only a (51x1) grid to speed up the optimization instead of calculating the result

#237245 - $15.00 USD Received 1 Apr 2015; revised 14 May 2015; accepted 19 May 2015; published 8 Jun 2015

from the (51x51) grids. By using a (51x1) grid calculation the fitness value became 1/1.522. Figure 5 (a) shows the simulated trace diagram of 1D calculation for the laser beam shaping system. The largest and smallest illumination values were 5.174 W/mm^2 and 4.551 W/mm^2 on the detection surface, respectively, giving a uniformity of 88%. There is an 11.026 degree divergence angle through averaging the angle of the rays on the detection surface. The 3.264 W total amount of radiation results in 93% the conversion efficiency. The laser spot size of the detection surface at FWHM was 0.908 mm to receive 18% of the shrinkage rate for the laser spot. The simulated values for the detection surface are listed in Table 3.

3.3 Comparison between 2D and 1D calculations

We compare the computational cost used for optimizing 100 evolution generation and 100 groups. The results show that the 2D optimization spent about 70 - 80 hours while the 1D optimization requires only 30 - 40 hours. The GA optimization process includes three operators, that is, selection, crossover and mutation. The 1D optimization also executes these three operators during the optimization process. After a generation, the new genes are respected as the lens parameters that are inputted into the software to create lens model for acquiring the fitness value. These processes are basic computation cost for the GA optimization. The GA optimization spend most of time for these basic computation cost, especially for lens model creation. That is the reason that the computation cost of 1D optimization is almost twice as fast as that of 2D optimization. It also shows that the 1D optimization produces better results in less time even when the sampling regions are smaller, as shown in Fig. 6. When we investigate the solution spaces of these two optimization, we can find that the solution space of 2D optimization is much larger than that of 1D optimization. That implies that the 2D optimization must spend much effort to look for the optimal solution. Using 1D optimization with small solution space could have high opportunity to search the well solution. That is why the result of 1D optimization is better than that of 2D optimization. In the following optimization design, the 1D calculation is applied for the laser beam shaping system. As we can see, the 1D calculation method can speed up the optimization without lowering the specification requirement.

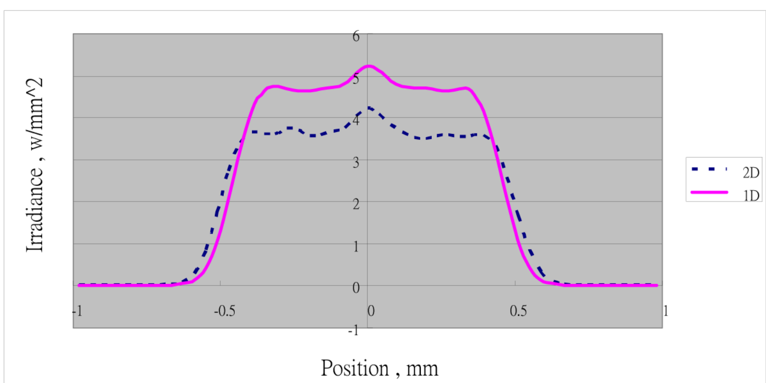


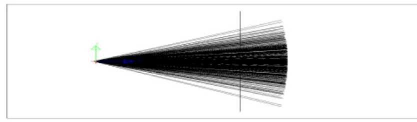
Fig. 6. Comparison between 2D and 1D simulated results.

4. Laser beam shaping results based on 1D calculation

We demonstrated converting the laser spot to any size with uniform energy distribution based on 1D calculation through GA optimization. The simulated laser source was known to be near ultraviolet lasers with a wavelength of 355 nm. The diameter is relatively small, since the light source has a larger divergence angle. Table 4 lists the setting specifications. The coherent mode is active to simulate the laser property by using the optical software. Figure 7 (a) shows the initial tracing diagram for the laser source with a larger divergence angle. Its

#237245 - $15.00 USD Received 1 Apr 2015; revised 14 May 2015; accepted 19 May 2015; published 8 Jun 2015

spot irradiation with Gaussian profile is shown in Fig. 7(b). For coherence, the detection surface receives only 3.5W, which is regarded as a reference during the GA optimization. By using the multi-point searching feature of GA optimization, the laser beam shaping system can be designed to be as light and slim as possible.



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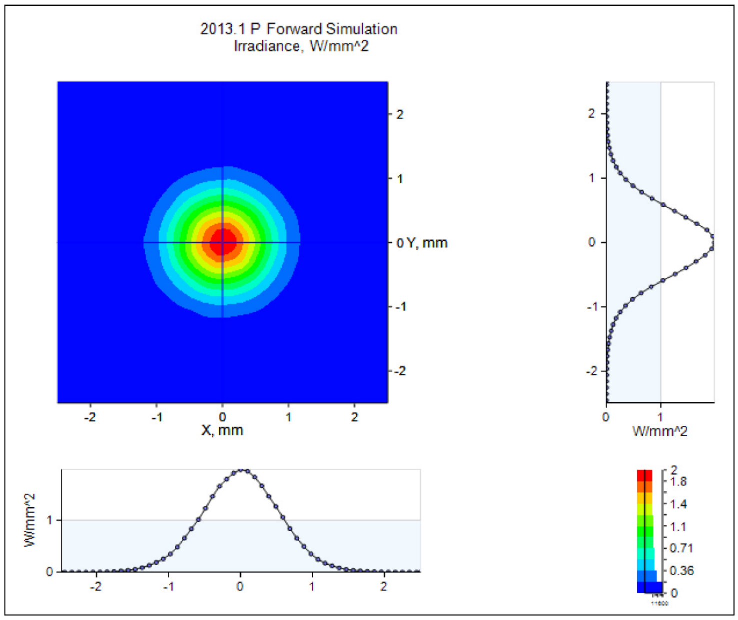

(b)

Fig. 7. Initial simulation of laser source with a larger divergence angle (a) Tracing diagram for the laser beams (b) Laser spot irradiation.

Table 4. The specifications of laser source with a larger divergence angle.

Wavelength	Beam divergence	Power	Laser mode
355nm	10°	7 w	TEM_{00}

4.1. Beam expander design

Table 5. Detection surface data by optimization of the beam expander.

	Uniformity (%)	Collimation (degree)	spot size (mm)	Conversion efficiency (%)	Enlarging rate (%)
Simulated values	90	5.797	5.273	80	176

Two aspherical lens elements were employed to expand the laser spot from 3 mm to 5 mm. The GA optimization gaining the best fitness value is 1/1.021. Figure 8 (a) shows the simulated trace diagram for the laser beam shaping system after the beam expander optimization. According to the data collected, the average angle for all light when passing through the detection surface was 5.797 degrees. Figure 8 (b) shows the laser spot irradiation for the beam expander design. Among the 13 detection points on the detection surface, the

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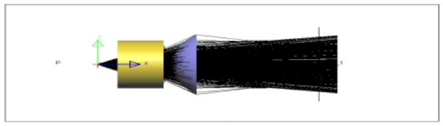
largest and the smallest illuminations were 0.134 W/mm^2 and 0.119 W/mm^2, respectively, which results in 90% of uniform distribution. Receiving 2.79W of the radiation power gained 80% of conversion efficiency at the detection surface. The size of the laser spot was 5.273 mm so that the enlarging rate for the laser spot was 176%. Table 5 shows the optimization results.



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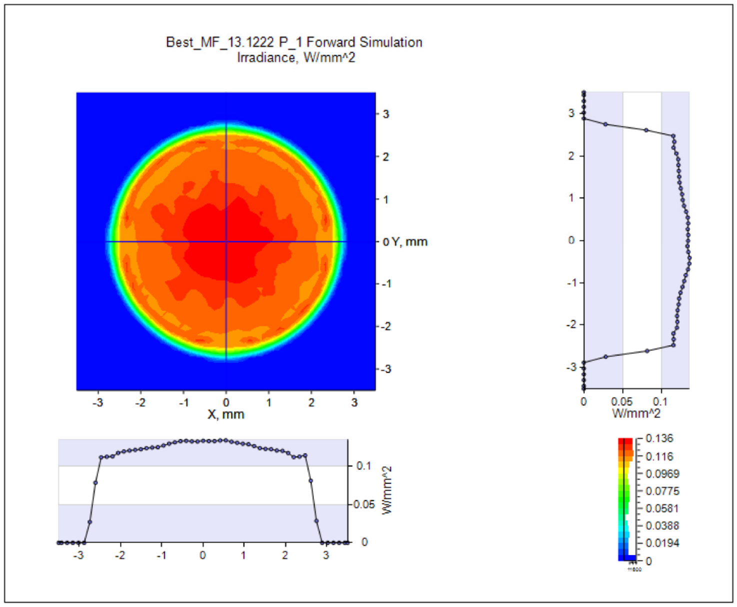


(b)

Fig. 8. Optimization for beam expander (a) Tracing diagram for the laser beams (b) Laser spot irradiation.

4.2 Narrower beam design

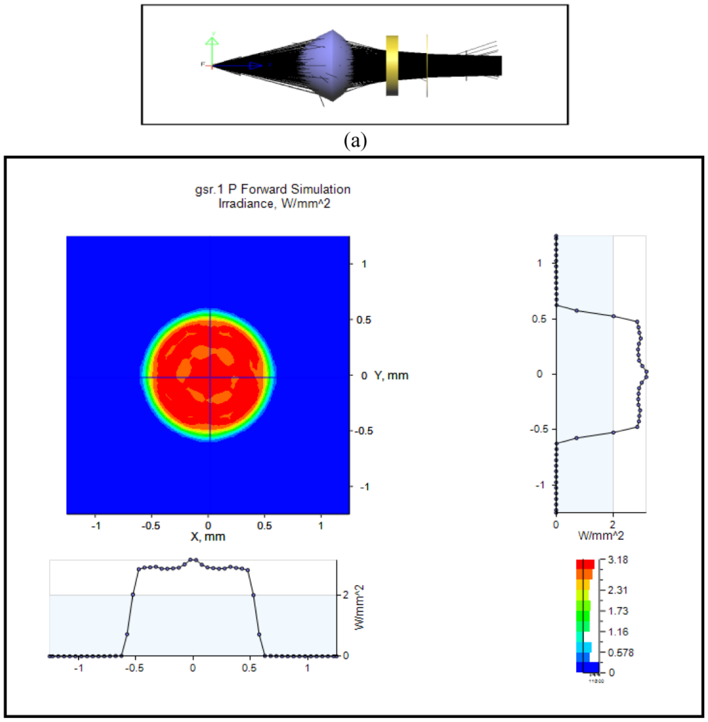
Table 6. Detection surface data by optimization of narrower beam.

	Uniformity (%)	Collimation (degree)	spot size (mm)	Conversion efficiency (%)	Shrinking rate (%)
Simulated values	88	3.14	1.076	78	36

A laser spot shrunk from 3mm to 1mm demonstrated the GA optimization by using two aspherical lens elements. The best result in the optimization obtained 1/1.235 fitness. Figure 9 (a) shows a 3.14° divergence angle after GA optimization. Figure 9 (b) shows its spot irradiation. The detection surface gained 88% of uniform distribution such that the largest and smallest illumination values were 3.20^2 W/mm^2 and 2.829 W/mm^2, respectively. The total amount of radiation obtained was 2.759 W, gaining 78% of the conversion efficiency. The laser spot was 1.076 mm, resulting in 36% of the shrinkage rate. The simulation results are listed in Table 6. Whether an expanding or narrowing system was used for the laser spot, at least 88% of uniform distribution can be optimized by using GA for a laser source with a divergence angle. Another important point is that during the conventional derivation process for laser beam shaping, the gap between the two lenses must be long enough for easy

#237245 - $15.00 USD Received 1 Apr 2015; revised 14 May 2015; accepted 19 May 2015; published 8 Jun 2015

derivation. We used the GA on a laser source with a divergence angle that could optimize the laser beam shaping. The results show that, for both laser spot expanding and laser spot narrowing, the distance between the two lenses can be minimal for laser shaping. As a result, the system can be both light and slim.



(a)

(b)

Fig. 9. Optimization for narrower beam (a) Tracing diagram for the laser beams (b) Laser spot irradiation.

5. Conclusion

Laser shaping systems with various spot size design goals can be efficiently optimized the basis of genetic algorithm (GA) optimization, according to experiments in this research. The rotationally symmetric property of the refractive shaping system replaces the original 2D calculation by a 1D calculation to improve the computation cost, e.g., approximately twice as fast. The laser source with a divergence angle delivered the results of laser shaping through GA with 1D calculation: laser spots shaped from 3mm to 5mm gained 90% of uniformity. When the laser spot was reduced from 3 mm to 1.076 mm, the uniformity was 88%. The distance was even smaller than the thickness of the first lens. It is concluded that our proposed method enables the system to be both light and slim thanks to the employment of GA optimization, which is flexibly achieved with the multi-point searching feature for the best laser shaping system.

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