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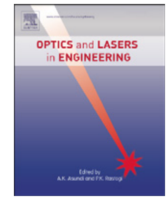

New design of beam expanding unit for excimer laser

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ABSTRACT

The excimer laser beam is used widespread in the areas of photolithography, ophthalmic operations, cold working and others, because of its high power, high homogeneity and high stability. However, based on the rectangular cross-section distribution characteristic of the laser, it must be expanded in one dimension first to achieve square cross-section distribution for further use. The reported beam expanding units has the deficiencies of serious speckle effect of coherence and the strict tolerance of alignment, respectively. A kind of multi-components parallel reflective expander was proposed based on the shortages above. The structures of such beam expanding units were determined by calculating linear system of equations, and two kind of them were selected by analyzing the feasibilities of different structures due to the solves of equations. A synthesis comparison was executed at the aspects of tolerance analyzing, transmission efficiencies and uniformities of output beam. According to the results of simulations, the designed four components beam expanding unit is proven to be an optimal scheme because of the evident declines of the tolerance sensitivities and speckle effects. Meanwhile, the homogeneity of output beam is improved.

1. Introduction

Excimer laser is widespread used recently with the enhancements of both homogeneity and pulse stability. This type of laser has some applications as follows: first, it can be used to achieve cold-working by breaking chemical bonds of materials, because there is almost no thermal responsive area on the interacting interface [1–3]. That is to say, the boundaries of etching holes are distinct enough to guarantee high accurate manufacturing. Second, it has the maximum pulse power and average power in the range of ultraviolet band, which can be used as a source of lithography to achieve 90 nm, 65 nm, 45 nm and even 32 nm nodal points of chips for grand scale integration circuits [4]. On the other hand, it also can be used to execute ophthalmic operations.

It is obviously that high degree homogeneity of excimer is one of the most important factors to be used comprehensively. Actually, the substance of excimer laser is a kind of unstable chemical compounds at excitation state, and at ground state, it decomposes to two kinds of atoms rapidly. This characteristic leads to the intensity distribution of excimer laser is non-uniform, and the cross section size of it has the magnitude of millimeter. For example, as the source of DUV lithography, the rectangular cross section size of excimer laser is 12 mm × 2 mm, and the intensity distributions at long side and short size are like flat-toping type and Gauss type, respectively. These features of excimer laser determine the design of beam homogenizing unit is very difficult. In order to reduce the difficulties, it is necessary to locate a kind of beam expanding unit before homogenizing unit to adjust the rectangular cross section to a square one. There are two kinds of methods which are based on the physics optics and geometrical optics, respectively, to design the one dimension beam expanding unit. The former method uses diffraction optics element to accurately control beam distribution [5–8]. The latter one uses refraction or reflection optics elements, and the difficulties of manufacturing are much smaller than the former [9–11]. So, in this paper, the design of beam expanding unit with geometrical optics method is discussed only. Generally, there are two kinds of configurations to be used, cylindrical lens and graded transmission plate. The advantages of cylindrical lens are the easy fabrication, and the expanding ratio can be designed arbitrarily. In term of laser beam, the evident speckle effects can be produced by superimposing interference when multi-beams output from homogeneity unit [12]. Fortunately, the said speckle effects can be reduced tremendously by using to eliminate temporal coherence. The disadvantages of graded transmission plates are the difficult coating and aligning, which increase costs and assembling time greatly.

Above all, a multi-components parallel mirror groups was proposed by improving the structures of the graded transmission plates. A linear equation group to calculate the transmission ratio of each reflective component was deduced, assuming that

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the value of transmission ratio of each component was an element of a matrix. Two feasible configurations were obtained according to the equation solves, and the optimum one was selected by synthesized analyzing tolerances, structures and homogeneities. At last, the simulation results showed that, the homogeneity of the designed beam expanding unit was 30%, which was better than the prior two configurations. The coherent effects and the alignment difficulties were also reduced.

2. Methods of one dimension beam expanding for excimer laser

A kind of representative ArF excimer laser is GT40A, which is produced by Gigaphoton Ltd [13]. The distributions of beams are shown in Fig. 1. According to the size, the expanding ratio is six in Y direction. Furthermore, the central wavelength is 193.368 nm, and the band width is 0.7 pm.

There are two kinds of configurations for one dimension defocusing beam expanding unit by the geometry optics methods. One is called cylindrical lens group [14,15]. The schematic diagram is shown in Fig. 2(a). The group consists of positive-negative power cylindrical lenses which have curvatures in only one direction. Incident beams are diverged first, and then collimated to make expand. According to the definition of Etendue, the beam divergent angle reduces when the beam size increasing. On the other hand, the relationship between spatial coherent length X_s and divergent angle θ is shown in Eq. (1).

$$X_s = \frac{2\lambda}{\theta} \tag{1}$$

where λ is the wavelength. So, beam expanding reduces the divergent angle, and increases spatial coherence of output beams. Meanwhile, temporal coherence is also evident due to the narrow band width. These two kinds of coherences lead to evident speckle effects which reduce the homogeneities. Therefore, cylindrical lens group is not suitable to be the laser beam expander. Similarly, prisms combination can also be used as beam expanding unit with the same principle, as shown in Fig. 2(b). However, it not only has evident speckle effects as cylindrical lens, but also has severe fresnel reflective losses because of the large incident angles. Therefore, prisms combination is not suitable for excimer laser beam expanding application.

Ref. [16] proposed graded transmission plates to reduce speckle effects. The theory is shown in Fig. 3. The number of sub-unit of M_2, such as a, b in Fig. 3, is changeable according to expanding ratio. The principle of this configuration is as follows: the rectangular beam emitted from laser source was reflected and

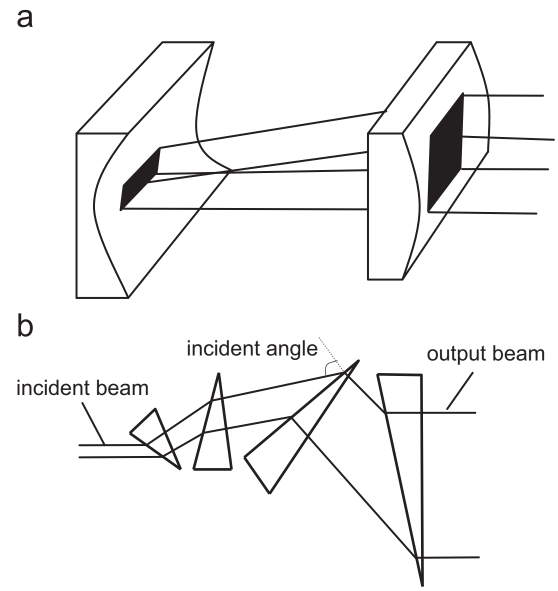


Fig. 2. Cylindrical lens beam expanding unit (a) and prisms combination beam expanding unit with the same principle (b).

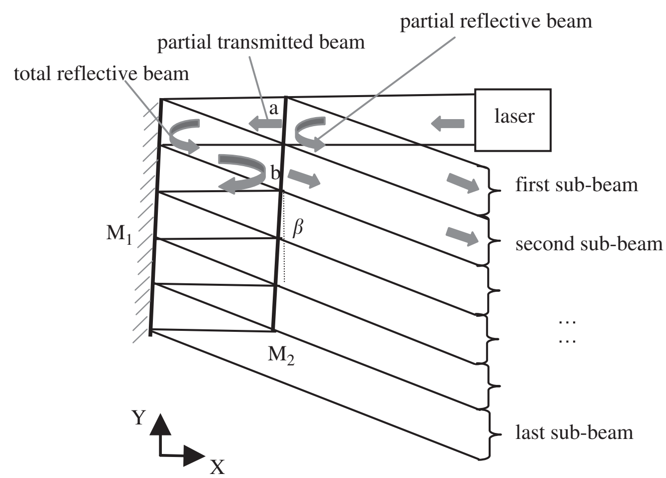


Fig. 3. Graded transmission plates beam expanding unit. M_1 is a total reflective mirror, M_2 is multi-transmission plate. M_1 and M_2 are parallel strictly, and they are tilt β angle to Y axis.

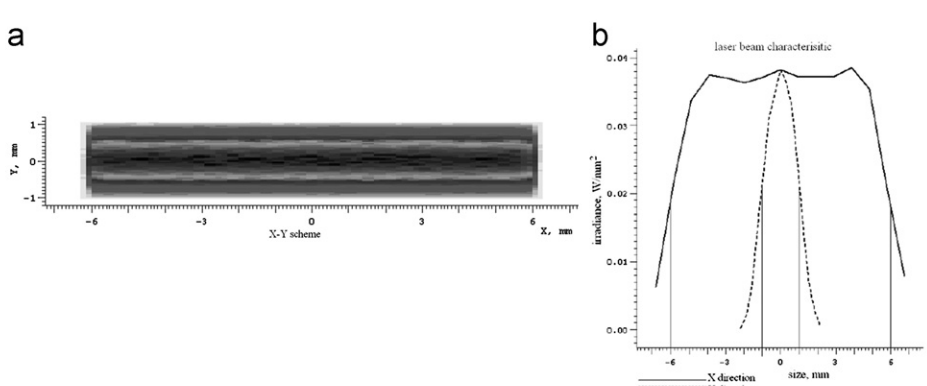


Fig. 1. Intensity distributions of excimer laser source in two demensions, (a) and at two orthogonal directions, there are two types of distributions: flat-topping and Gauss cross section; (b). The size is 12 mm × 2 mm corresponding to flat-topping and Gauss distributions, and the angles of divergence are 2.5 mrad × 1.5 mrad.

refracted simultaneously when passing sub-unit *a*. The reflected part composes the first sub-beam, and the refracted part is totally reflected by M_1. On sub-unit *b* which is adjacent to *a*, occurs reflection and refraction again, and the refracted part is called the second sub-beam. Light beams propagate between M_1 and M_2 continuously to achieve beam expanding. There is no temporal coherence between adjacent sub-beam by making the distance of M_1 and M_2 larger than the half of the coherent length. Furthermore, the beam size itself is not amplified with this method, but just jointed, so spatial coherence does not increase, which reduces the speckle effects.

The disadvantages of the graded transmission plates are that they are hard to coat and align. In order to meet the needs of each sub-beam has the same intensity, it must be coated by different transmission ratios films on different sub-unit. There are two common coating methods: one is vapor-deposited coating, which coats different films for each sub-unit on the whole M_2 plate. But it expends a long time and costs. The other one is coating each sub-unit separately and then, jointing them together to make M_2 plate. This method simplifies coating process, nevertheless, aligning difficult increases greatly. So, the two coating methods both have big deficiencies.

3. Design of multi-components beam expanding unit

In order to overcome the difficulties of coating and aligning for graded transmission plates, a kind of multi-components parallel mirror beam expanding unit was proposed. Fig. 4 shows the principle of the designing. The idea is as follows: based on the said graded transmission plates, adding several more components like M_2 along *X* direction, as can be seen in Fig. 4, and keep each component parallel strictly. In order to discuss conveniently, assuming that each component along the beam propagation direction corresponds to a row of a matrix. Each illuminated area of each component is divided into *j* units, and each sub-unit has the transmission ratio labeled as τ_{ij}. Comparing to the graded transmission plates, some units of the proposed configuration are utilized as both reflective ones (where reflection ratio is $(1-\tau_{ij})$) and refractive ones (where refraction ratio is (τ_{ij})) simultaneously. Therefore, the utilization ratio of these units is enhanced to reduce the number of different transmission ratios, which improves the performances of beam expanding unit.

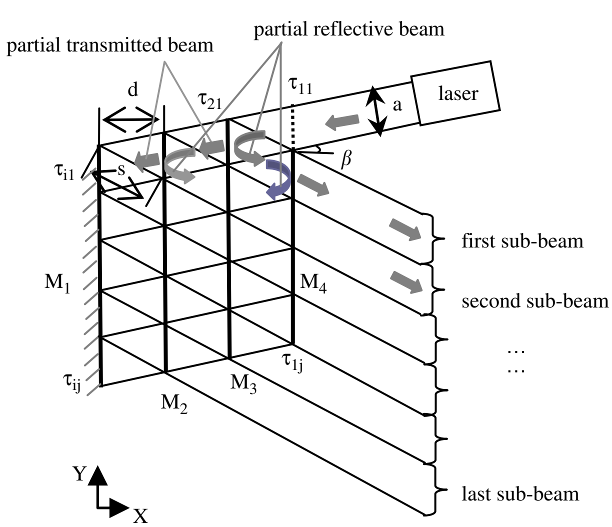


Fig. 4. Multi-components parallel reflective beam expanding unit.

3.1. Calculation of distances between each component

The calculation equation of coherent length is:

$$l=\frac{\bar{\lambda}^2}{\Delta\lambda} \tag{2}$$

where $\bar{\lambda}$ is average wavelength, which equals central wavelength after adding weight calculation. $\Delta\lambda$ is band width. So *l* equals 53.4 mm by Eq. (2). Caution that *l* must be larger than half distance between each sub-unit.

The distance between each component is represented by *d*, the angle between incident beam and *X* axis is β, and the width of incident beam in *Y* axis is *a*. There is a relationship as follows:

$$d=\frac{a}{2\sin\beta} \tag{3}$$

The optical path difference (OPD) between two adjacent components is represented by *e*:

$$e=2s=\frac{2d}{\cos\beta} \tag{4}$$

It is known that $a=2$ mm, and $e\geq l$. Simultaneous Eqs. (3) and (4) to get a quartic equation, and the solve is that $d\geq 26.68$ mm after rounding-off negative value. Notice: value of *d* cannot too large; otherwise the requirements of fabrication accuracy increase greatly for the very small angle β. Therefore, when *d* is chosen as 30 mm, then β equals 1.91° as a result.

3.2. Calculations of transmission ratio of each component

Transmission ratios of each sub-unit of graded transmission plates can be calculated by

$$\tau_i=1-\frac{1}{R}\left(1-\frac{I_0}{nI^R_{i-1}}\right) \tag{5}$$

where τ_i and I^R_{i-1} are the *i*th transmission ratio of M_2 and the $(i-1)$th reflection beam intensity, respectively; *R* is the reflective ratio of M_1; *n* is the number of sub-unit of M_2. According to the requirements in this paper, $R=1$, $n=6$, and $I_0=1$. The calculation results are shown in Table 1. However, Eq. (5) is not suitable to apply to multi-components beam expanding unit because of the repetitive-use of some sub-units. So, the calculation method for our design will be discussed in detail below.

Assuming the intensity of incident beam equals 1 and ignores the intensity losses which are absorbed by material for the sake of simplifying, so the intensity of each sub-beam is 1/6. In order to meet the restraint of single transmission ratio for each component, τ_{11} must equal to 1, otherwise τ_{11} equals to 5/6 identically. In that case, there is no solves for the above restraint. But τ_{11} is also considered as a variable to meet the requirement of discussing solves of Eq. (6) as the restraint condition is soften later. The area corresponding to τ_{11} in Fig. 4 is shown with imaginary line. Eq. (6) with $i=4$ can be obtained according to Fig. 4, where the first equality indicates the incident beam passes the first sub-unit

Table 1
Transmission ratios of each sub-unit on M_2.

i	τ_i	I_i^R	I_i^T
1	0.1667	0.8333	0.1667
2	0.2	0.6667	0.1667
3	0.25	0.5	0.1667
4	0.3333	0.3332	0.1667
5	0.5	0.1665	0.1667
6	0	0	0.1667

of $M_4(\tau_{11})$, then it is reflected on M_3 $(1-\tau_{21})$, the reflected beam passes the second sub-unit of $M_4(\tau_{12})$ to get the first sub-beam, which equals to 1/6. The other equalities are deduced accordingly. The case of *i* equals other values will be discussed later. Notice: if considering all the effects of reflective and refractive for the incident beam on all the illuminated areas of all components, the equation is very complex and there is no regularity at all. So it will be very difficult to solve this type of equation. Therefore, only some possible conditions are considered to make up Eq. (6), where some other complex possible conditions are omitted. It is feasible to use this simplified method because it is indeed obtain some kinds of simple beam expanding configurations as can be seen in later discussions.

$$\begin{cases} \tau_{11}(1-\tau_{21})\tau_{12} = \frac{1}{6} \\ \tau_{11}\tau_{21}(1-\tau_{31})\tau_{22}\tau_{13} = \frac{1}{6} \\ \tau_{11}(1-\tau_{21})(1-\tau_{12})\tau_{22}(1-\tau_{32})\tau_{23}\tau_{14} = \frac{1}{6} \\ \tau_{11}\cdot\tau_{21}(1-\tau_{31})\tau_{22}(1-\tau_{13})\tau_{23}(1-\tau_{33})\tau_{24}\tau_{15} = \frac{1}{6} \\ \tau_{11}(1-\tau_{21})(1-\tau_{12})\tau_{22}(1-\tau_{32})\tau_{23}(1-\tau_{14})\tau_{24}(1-\tau_{34})\tau_{25}\tau_{16} = \frac{1}{6} \\ \tau_{11}\tau_{21}(1-\tau_{31})\tau_{22}(1-\tau_{13})\tau_{23}(1-\tau_{33})\tau_{24}(1-\tau_{15})\tau_{25}(1-\tau_{35})\tau_{26}\tau_{17} = \frac{1}{6} \end{cases} \quad (6)$$

Now, the relationships between transmission ratios and the number of components according to solves of Eq. (6) will be discussed. First, assuming $\tau_{11}=0$, then, defining $\tau_{1m}=x$, $m=2, 3\ldots$, $\tau_{2n}=y$, $n=1, 2\ldots$, $\tau_{3k}=z$, $k=1, 2\ldots$, and at last, the final component is a mirror, so $\tau_{4t}=0$, $t=1, 2\ldots$. The solves of Eq. (6) are $\tau_{1m}=1/2$, $m=2,3,4$; $\tau_{2n}=2/3$, $n=1$; $\tau_{3k}=1/2$, $k=1$, and the configuration is shown in Fig. 5. This structure is called four components unit.

On the other hand, when *i* equals 5, there is also only one kind of transmission ratio for each component, however, the size at *X* direction increases. So this scheme is not an optimum one.

When *i* equals 3, Eq. (6) has no solves when requiring only one transmission ratio for one component. But there is an advantage that the size at *X* direction reduces. In terms of this point, the restraint of single transmission is eased, and the solves are $\tau_{1m}=1/3$, $m=2,3$; $\tau_{1m}=1/2$, $m=4,5$; $\tau_{2n}=1/2$, $n=1$; $\tau_{3k}=0$, $k=1,2\ldots$. In this case, as can be seen in Fig. 6, there are two kinds of transmission ratios for the first component. This configuration is called as three components unit.

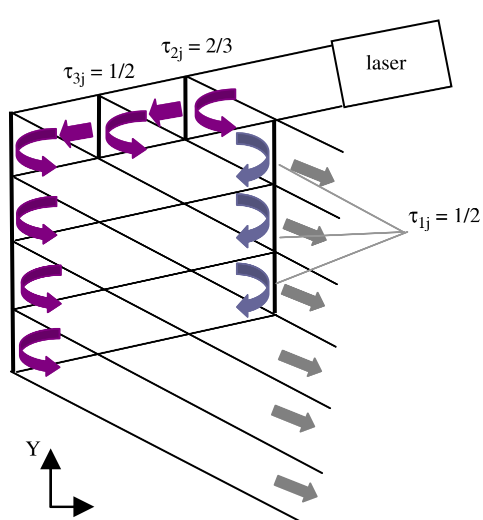


Fig. 5. Four components beam expanding unit.

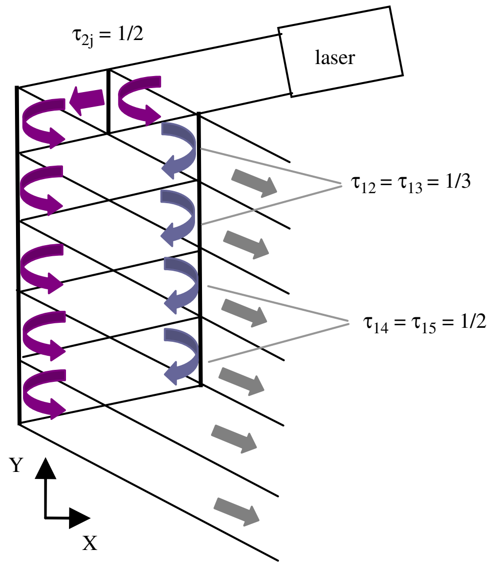


Fig. 6. Three components beam expanding unit.

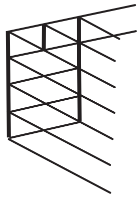
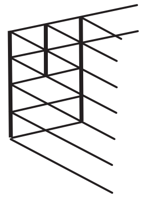
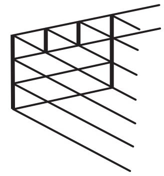
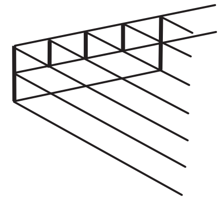
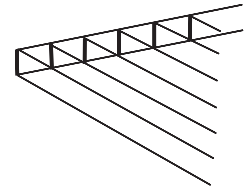
On the other hand, when easing the restraint of single transmission, τ_{11} is not necessarily to be zero. In that case some solves and the corresponding configurations are listed at Table 2. It is known after comparing that A3 structure is equivalent to three components unit; A3′ structure has four kind of transmission ratios; A4 structure has more kinds of transmission ratio than four components unit; both A5 and A6 have larger spatial sizes and more components. As a comparison result, A3 is the best one in Table 2. Above all, four components unit and three components unit are better schemes.

4. Comparisons of different beam expanding units

The performances of cylindrical lens, graded transmission plates, the designed three components unit and four components unit are compared to show which the best one is. Tolerances of each structure are analyzed by CODE *V* to compare the alignment difficulties. Due to beam expanding units belong to non-image optics, so it is necessary to put a convergent lens group after the beam expanding unit to research tolerance sensitivities. The reason why not using "perfect lens" instead of convergent lens group in CODE *V* is that the "perfect lens" ignores all the aberrations because of its idealization. This leads to the wrong results of tolerance analysis. Take the graded transmission plates as an example to interpret the procedures of tolerance analyzing as follows: The configuration and modulate transform function (MTF) are shown in Fig. 7. The last sub-beam contains the accumulated tolerances of all the components, so the alignment tolerances information can be obtained by evaluating it. There are different evaluation criterions of the beam performances for analyzing tolerances at tangential (TAN) or radial (RAD) direction about the curves of MTF. The imaging quality in TAN direction is better than that in RAD direction for the sake of the size in TAN direction is smaller than that in the RAD, so the sphere aberration in RAD direction is evidently large. Owing to each beam expanding unit uses the same convergent lens group in simulation, the residual aberrations of the convergent lens group are no-effect on analyzing tolerances of each unit.

Generally, defocus and decenters of the image are selected to be compensators, and the results of tolerances analyses with the same misalignments are shown in Fig. 8. Only tolerances at RAD

Table 2
Structures and parameters of the solves of beam expanding unit.

Values of i	$i=3$		$i=4$	$i=5$	$i=6$
Structure chart					
Symbol	A3	A3′	A4	A5	A6
Transmission rate	$\tau_{11}=5/6$; $\tau_{1m}=1/2$, $m=2,3,4$; $\tau_{21}=3/5$.	$\tau_{11}=5/6$; $\tau_{12}=2/5$; $\tau_{1m}=1/2$, $m=3,4$; $\tau_{2n}=1/2$, $n=1,2$;	$\tau_{11}=5/6$; $\tau_{1m}=1/2$, $m=2,3$; $\tau_{21}=3/5$; $\tau_{31}=1/3$.	$\tau_{11}=5/6$; $\tau_{12}=1/2$; $\tau_{21}=3/5$; $\tau_{31}=2/3$; $\tau_{41}=1/2$.	$\tau_{11}=5/6$; $\tau_{21}=4/5$; $\tau_{31}=3/4$; $\tau_{41}=2/3$; $\tau_{51}=1/2$.
No. of sub-units	3	3	4	5	5
Size (mm^3)	$9\times12\times60$	$9\times12\times60$	$8\times12\times90$	$6\times12\times120$	$6\times12\times150$

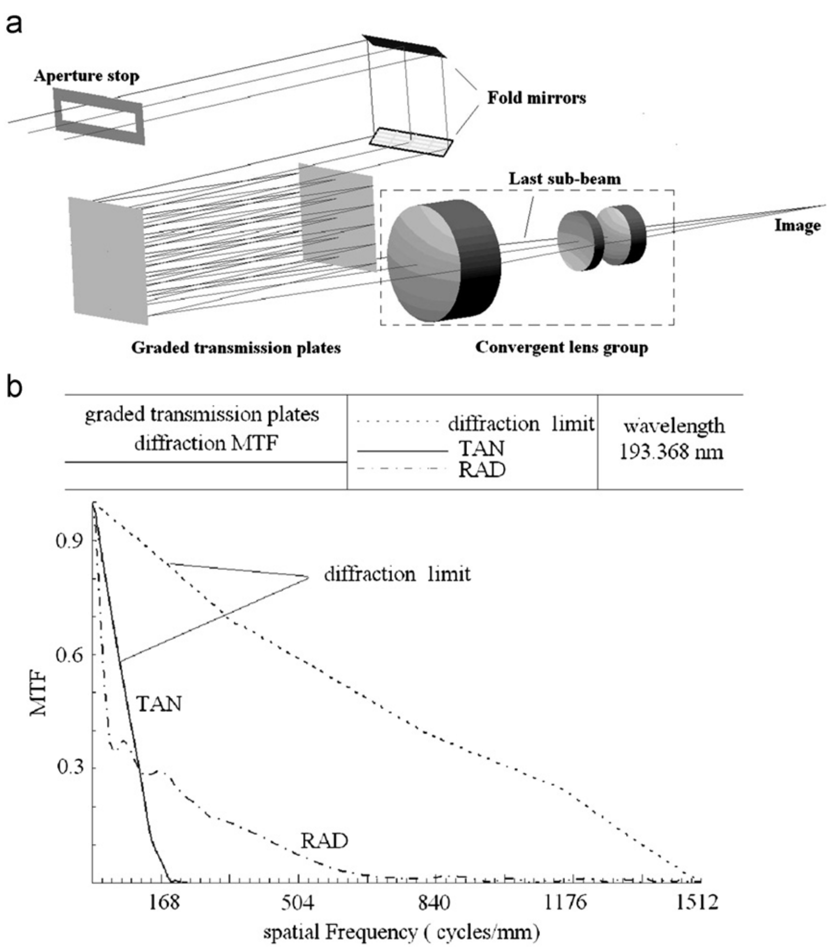


Fig. 7. Graded transmission plates model (a) and its MTF curves (b). Caution that the introduction of convergent lens group is only used to analyze the tolerance sensitivities because CODE V only makes tolerance analysis for the imaging system. The designed beam expanding unit is a non-image system, so the convergent lens group is framed by dotted line.

direction which are more sensitive are considered so that it is easier to evaluate the difficulties of alignment. In Fig. 8, four components unit and three components unit have approximate difficulties of alignment for their configurations and numbers of components are close. The graded transmission plates have the largest number of sub-units so that their tolerances are the strictest ones. The cylindrical lens has the most loosen tolerances for its simple structure.

Now, the losses of the energy by substrates absorbing are considered. The material of all the substrates of components is fused silica and the losses of absorbing of each surface are about 1%, assuming LaF_3 and MgF_2 films are coated. Four components unit, three components unit and graded transmission plates are compared in Fig. 9. There are many reflection and refraction times on the third component of four components unit so that the energy losses are great on that component as shown in Fig. 9. On

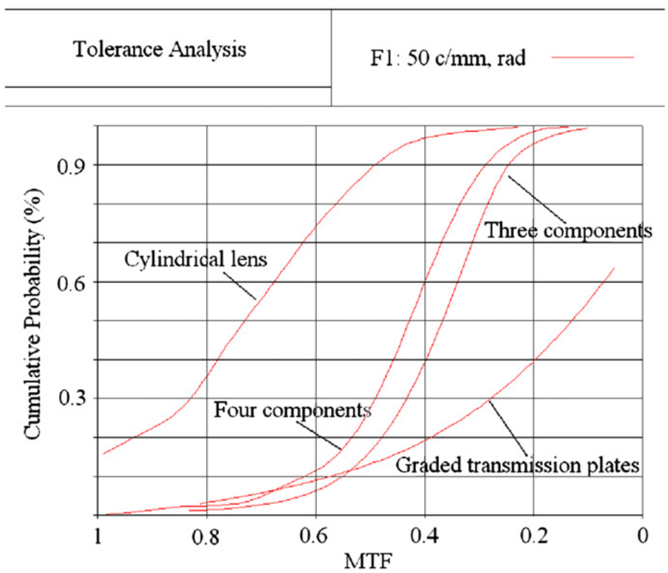


Fig. 8. Tolerance curves of four kinds of beam expanding units.

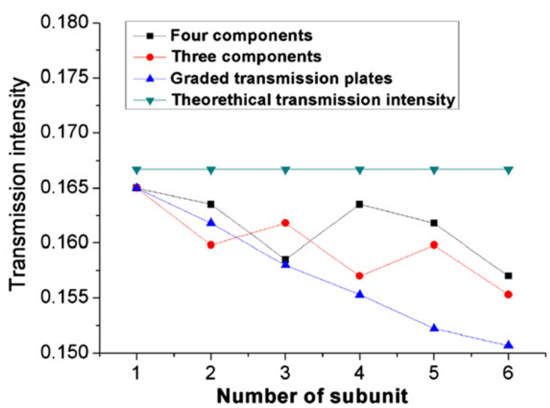


Fig. 9. Intensity distributions of each sub-beam.

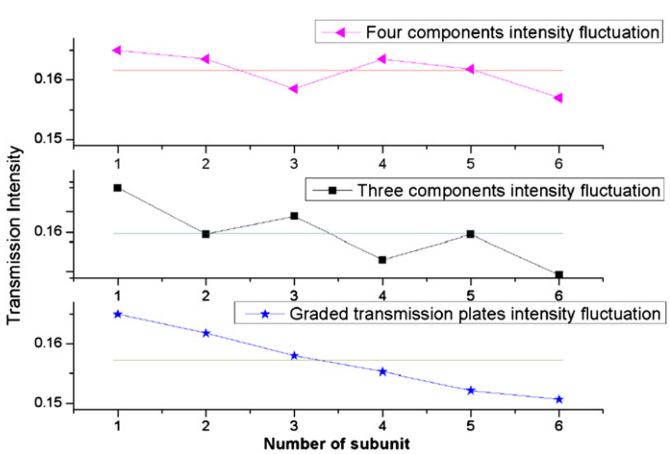


Fig. 10. Intensity fluctuations of each sub-beam.

the other hand, the characteristic of graded transmission plates is that the output intensity of sequential adjacent sub-unit reduces step-by-step. After comparing, the fluctuation of intensities of four components unit is minimal as shown in Fig. 10.

In terms of temporal coherence, all the three kinds of reflective type units consider how to reduce speckle effects. At last, the configuration size at *X* direction of cylindrical lens group is maximal, and reversely, the size of graded transmission plates is minimal, the size of four components unit is moderate. The performances of each beam expanding unit are listed on Table 3, where the term ''system tolerance'' means the reduction of MTF resulted by the fabrication tolerances. The homogeneity is calculated by

Table 3
Comparisons of four kind of beam expanding unit.

	Cylindrical lens	Graded transmission plates	Four components	Three components
Number of subunit	–	6	4	3
System tolerance	−0.5299	−0.9591	−0.7807	−0.8076
Total transmission	86.8%	83.7%	87.6%	88.5%
Uniformity η	67.7%	25%	24%	30%
Temporal coherence	Yes	No	No	No
Size (mm^3)	$12\times12\times135$	$12\times12\times30$	$8\times12\times90$	$10\times12\times60$

$$\eta=\frac{I_{max}-I_{min}}{I_{max}+I_{min}}\times100\% \quad (7)$$

where I_{max} and I_{min} represent the maximum and minimum intensity at image.

5. Simulations

A 3D modeling software LightTools is used to simulate the four kinds of beam expanding units said above, the number of tracing rays is 200,000, and the results are shown in Fig. 11.

It can be seen that the homogeneity of cylindrical lens is very bad, which increases the difficulties of designing uniformity unit for illumination system. Other three units have relative good homogeneities.

Owing to the intensity distributions at the edge of sub-beams have the characteristic of Gauss beam, two reflection fold mirrors called mirror A and mirror B are introduced in the unit to superpose adjacent sub-beams to improve the homogeneity further. Since there is no temporal coherence of each adjacent sub-beam, this method of overlapping beam dose not introduce speckle effects.

Finally, though the cylindrical lens group has the simplest structure, the uniformity and the space size are not so good, especially in terms of the illumination of lithography, the requirement of uniformity is extremely high. So, after synthetic analysis discussed above, the four components unit is chosen as the optimal structure.

6. Conclusions

A new type of excimer laser beam expanding unit was designed in this paper. A kind of multi-component beam expanding unit was proposed after comparing the prior common used beam expanding units. The performances of designed two configurations and the prior ones were simulated and evaluated. At last, the four component unit was chosen as the optimal one. The method of obtaining the configurations by solving linear equations can also be applied to calculate other beam expanding units for laser source. On the other hand, the angle or distance between each component can be varied to overlap the edges of Gauss

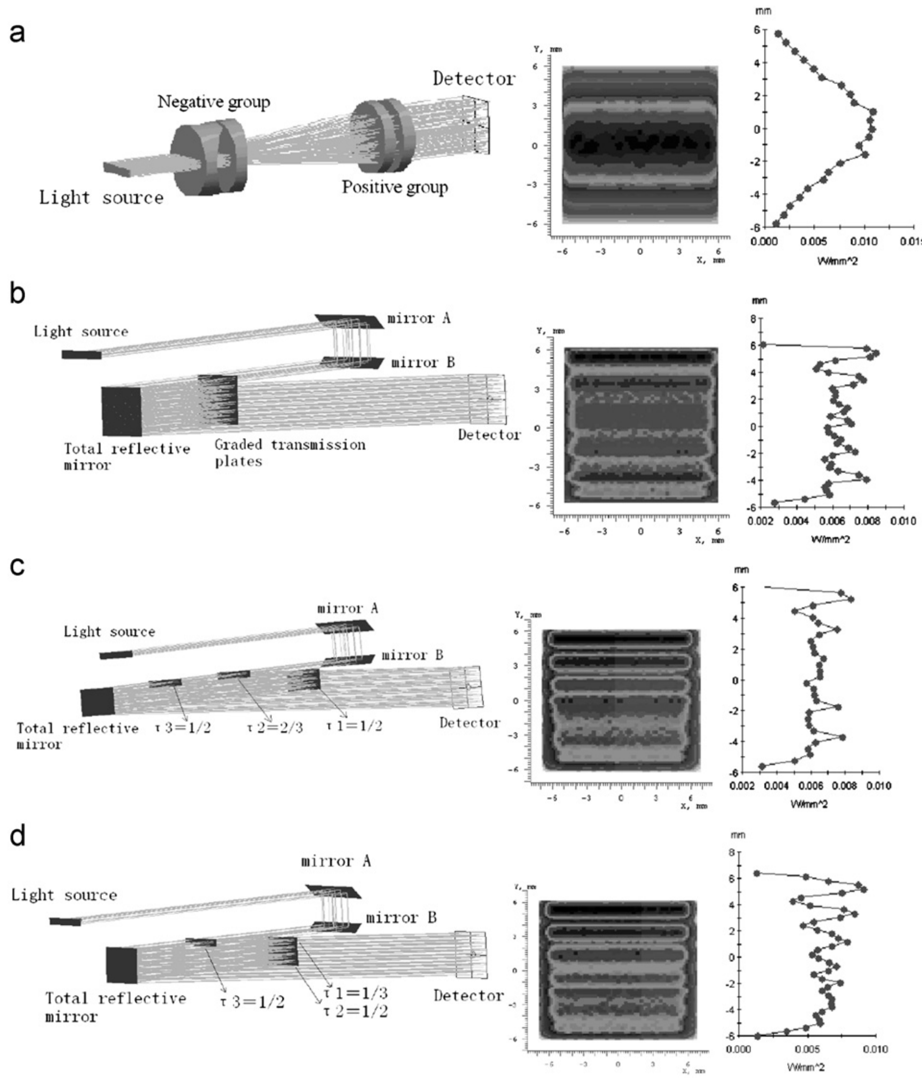


Fig. 11. Simulation results of cylindrical lens (a), graded transmission plates (b), four components (c) and three components (d) beam expanding units. The sampling points' distributions on the right side are used to calculate the uniformity η. The selection of $I_{\min}$ omits the edge points which have very low intensity to affect uniformities greatly.

beam to enhance homogeneity further. This part of work will be researched sequentially.

Acknowledgements

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