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LETTER

Research on a wavefront aberration calculation method for a laser energy gradient attenuator

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Abstract
When a laser energy gradient attenuator is working, there is an inhomogeneous temperature distribution in the whole of the glass because of the non-uniform light energy absorption. This will lead to optical performance reduction. An integrated opto-thermal–mechanical method is proposed to calculate the wavefront aberration for analysis of the thermal effect of the system. Non-sequential optical analysis is used for computing the absorbed energy distribution. The finite element analysis program solves the temperature distribution and the deformations of nodes on the surfaces. An interface routine is created to fit the surface shape and the index field, and extended Zernike polynomials are introduced to get a higher fitting precision. Finally, the parameters are imported to the CodeV optical design program automatically, and the user defined gradient index material is ray traced to obtain the wavefront aberration. The method can also be used in other optical systems for thermal effect analysis.

(Some figures may appear in colour only in the online journal)

1. Introduction

In the application of laser target simulation, the light intensity of the laser needs to be attenuated continuously. The laser energy gradient attenuator is based on the absorption characteristics of the material to achieve this purpose. When the attenuator is working, light energy is absorbed and converted into thermal energy, which causes a gradient temperature distribution in the material. This temperature difference will not only produce surface deformations, but also cause a refractive index gradient in the optical elements. As a result, aberration is produced and may affect the optical performance seriously. Therefore, it is necessary to consider the thermal effect by evaluating the wavefront deformations of the system.

The light energy absorbed by the glass follows the Beer–Lambert law. For an optical system, it is usually difficult to calculate the absorbed flux in the glass directly because of the complex light path and source attributes. Non-sequential optical analysis is a suitable tool to solve the problem.

General optical analysis considers that the internal temperature of a lens is homogeneous. Some optical design programs, such as Zemax and CodeV, support the user to set

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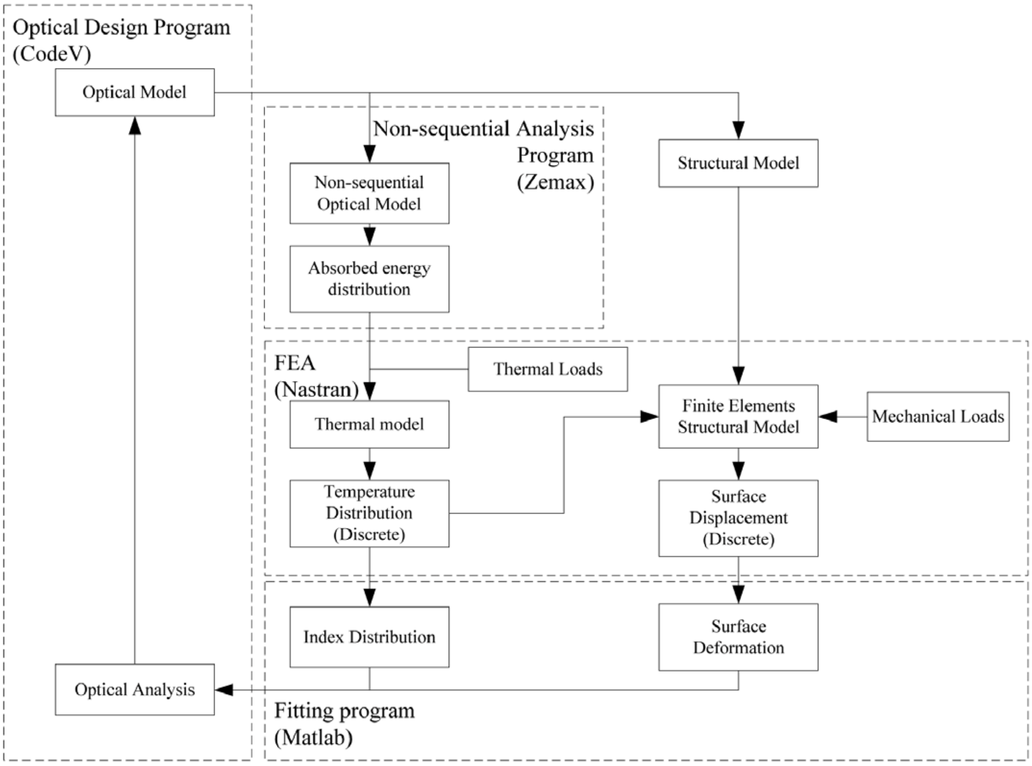

Figure 1. The flow chart.

the temperature of the system, the lens or the surfaces, but the distribution form is usually regular and simple, and so it is less accurate when the index gradient is large and the distribution is complex.

Integrated opto-mechanical analysis has been widely used to evaluate the optical aberration of a system with surface deformation caused by temperature change [1–7]. Few previous studies have paid attention to the performance reduction caused by the index gradient in the transmission system [8, 9].

The opto-mechanical analysis software Sigfit is based on finite element analysis (FEA). It evaluates the optical performance by the FEA results which include the optical surface deformation and temperature distribution. It analyzes the thermo-optic effects using an optical path difference (OPD) map. The OPD map is created by integrating the $\mathrm{d}n/\mathrm{d}t$ effect through each optical element [10]. It ignores the direction changes caused by the gradient index to obtain a fast computing speed. Therefore, if the temperature gradient is great, the accuracy is reduced.

To get a more accurate result, an integrated opto-thermal–mechanical method (figure 1) is proposed. The non-sequential ray trace software (Zemax) is used to calculate the energy absorbed by the glass. Then the result is imported to finite element analysis software, such as Nastran, to solve the displacements of the surface nodes and the temperature of the nodes, and then the data are fitted and expressed. An extended Zernike polynomial function is proposed to fit the temperature field. Finally, the parameters are imported to the optical design software (CodeV) by the interface routine automatically, and the wavefront aberration can be computed by the ray trace.

2. Integrated opto-thermal–mechanical analysis

2.1. Light energy absorption analysis

When a laser beam passes through a glass, the light energy will be gradually attenuated with increase of incident depth; the energy lost is absorbed by the material and converted to heat. It can be expressed by Beer–Lambert law

$$I = I_0\,\mathrm{e}^{-\alpha l} \tag{1}$$

where I_0 and I are the intensities of the incident light and the transmitted light respectively. α is the absorption coefficient and l is the path length through the glass along the light path.

When the surface shape and the source attribution are complicated, calculation of the absorbed energy at each position in the glass is difficult. Fortunately, a non-sequential optical analysis program, e.g. Zemax, can solve the problem by a numerical method.

The whole non-sequential model can be considered to be an assemblage of many tiny elements. Each ray represents part of the source energy, and they are traced one by one. If the nth ray hits in the ith element, the path length $\Delta l_{n,i}$ is known and the incident light intensity I_{i0} can be found from the front element computation result. The energy of the ray absorbed by the ith element can be calculated easily. If the number of rays traced (n_{trace}) is large, the sum of the energy absorbed by

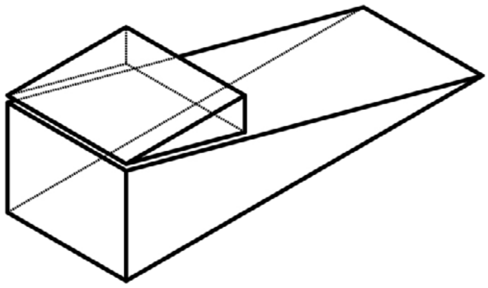

Figure 2. The attenuator.

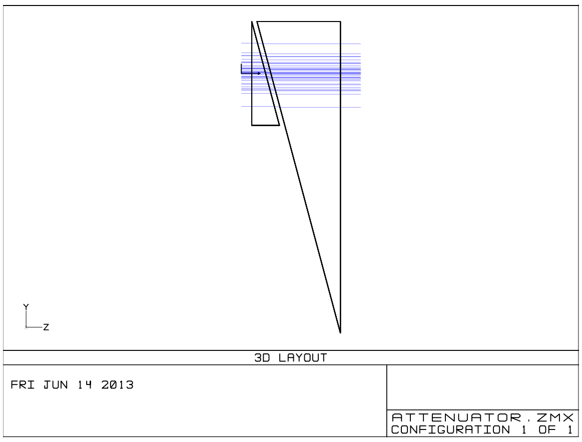

Figure 3. The optical path layout.

the element (I_i) is approximately the same as the actual value, and the analysis will obtain a reliable result,

$$I_i = \sum_{n=1}^{N_{\text{trace}}} I_{i0}\, \mathrm{e}^{-\alpha \Delta l_{n,i}}. \tag{2}$$

By using the theory, the laser energy gradient attenuator is a transmission light intensity adjustment device. The light source is a continuous laser. The input is a collimated Gaussian beam, and the beam diameter is 15 mm. The attenuator is made up of two wedges: the small wedge is fixed and the other wedge moves parallel to its slope. The material is a kind of neutral density glass named ZAB50; the transmission in the visible wavelength range is about 50% for a thickness of 2 mm. The model is shown in figure 2 and the optical path layout is shown in figure 3.

With the Zemax software, the whole work space is divided into 12 000 elements, and 1 000 000 rays are traced. The volumetric absorbed flux in each element is computed and output. The result at the section $z = 10$ is shown in figure 4.

2.2. Finite element analysis (FEA)

Finite element analysis is used in this method for solving the temperature distribution and the surface deformation.

The energy absorbed by the glass provides the heat input for the system. Therefore, the result computed previously is input into the FEA program, and the discrete data are interpolated as the heat load at each element (figure 5). Water-cooled equipment is used to keep the non-working surface at 20 °C. Moreover, radiation and conduction are

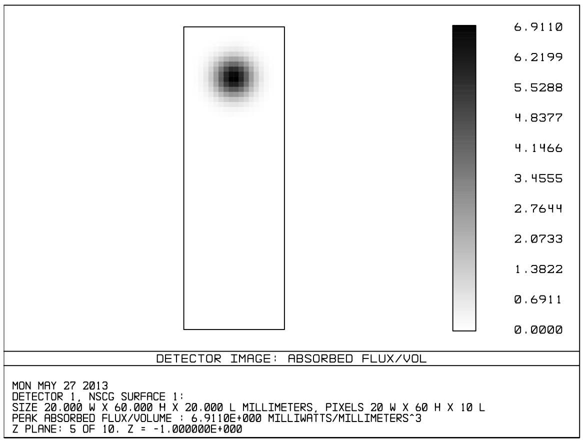

Figure 4. The absorbed energy distribution ($z = 10$).

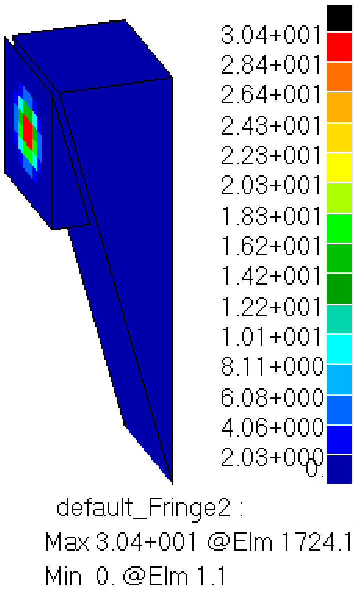

Figure 5. The heat load.

considered. The temperature distribution can be solved by the FEA program and the result is shown in figure 6.

From the analysis, we can see that the maximum temperature of the glass is 81.1 °C, and the minimum is only 20 °C. The difference in temperature is 61.1 °C. This will lead to a large index gradient for the optical system.

Then, the displacement of each node can be solved by the thermo-elastic calculation (figure 7).

2.3. Surface fitting

The FEA result contains the location information for the nodes on the surfaces, but these are discrete data. Further optical analysis not only needs the position of an arbitrary point on the surface, but also needs the gradient of the surface at this point. Therefore the data require to be fitted to a differentiable surface.

The Zernike polynomial is a useful mathematic tool for analyzing the performance of an optical system [8–11],

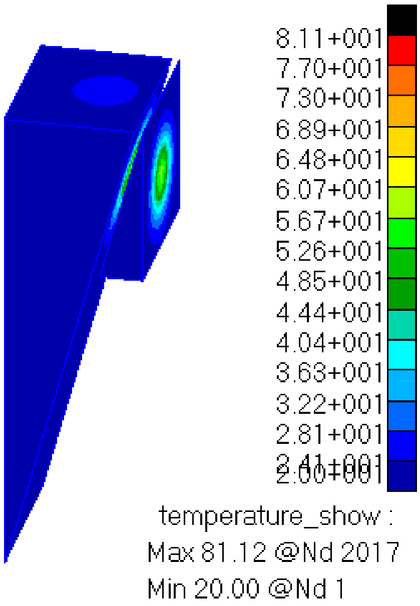

Figure 6. The temperature distribution.

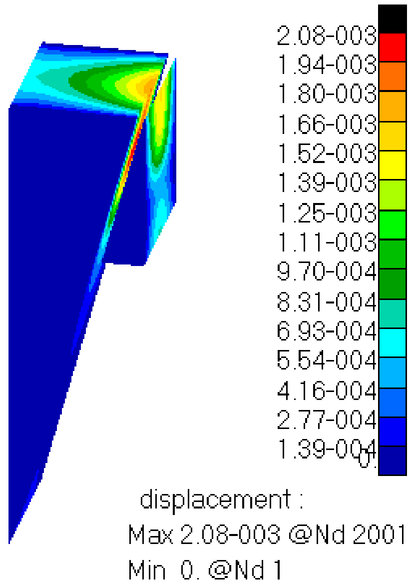

Figure 7. Thermal elastic deformation.

because each Zernike term corresponds to a kind of Seidel aberration. Additionally, Zernike polynomials can represent a surface or a deformation accurately with only dozens of coefficients.

The Zernike polynomial is of the form

$$S(\rho,\theta) = \sum_{n=1}^{\infty}\left\{A_n R_n^0(\rho) + \sum_{m=1}^{n}[B_{nm}R_n^m(\rho)\cos(m\theta) + C_{nm}R_n^m(\rho)\sin(m\theta)]\right\}$$

$$\text{where } R_n^m(\rho) = \sum_{s=0}^{n-m}(-1)^s \frac{(2n-m-s)!}{s!(n-s)!(n-m-s)!}\rho^{2(n-s)-m}. \quad (3)$$

Here, A_n, B_{nm} and C_{nm} are the Zernike polynomial coefficients, $\rho = \sqrt{x^2+y^2}$ is the normalized radial ray coordinate, and $\theta = \arctan(y/x)$ is the angular ray coordinate.

Generally, aspheric terms are added to represent the original surface; the Zernike terms represent the deformation, which can be expressed by

$$z(\rho,\theta) = \frac{cr^2}{1+\sqrt{1-(1+k)c^2r^2}} + \sum_{i=1}^{n}\alpha_i r^{2i} + \sum_{i=1}^{N} A_i Z_i(\rho,\theta) \quad (4)$$

where c is the curvature of the surface, r is the radial ray coordinate, k is the conic constant, n is the number of aspheric coefficients, α_i is the coefficient of the ith term, N is the number of Zernike coefficients in the series, and A_i is the coefficient of the ith Zernike polynomial.

The least-squares method is used to fit the Zernike coefficients from the discrete data. The Zernike coefficients are solved and the surface is reconstructed (figure 8). As the plot diagrams show, the reconstructed surface (mesh surface) represents the FEA result data accurately.

2.4. Index distribution fitting

There are two ways to get the index at an arbitrary position in the glass.

(1) Fit the node temperature data to a continuous temperature distribution, then calculate the index at the position of the ray trace needed.

(2) Compute the indices at the nodes in the FEA model according to the thermal effect of the glass, and then fit them to get a continuous index distribution.

Method (2) is used in this letter to reduce the computational complexity of the following optical analysis.

Generally, for an optical system, the direction of light is approximately along the optical axis. Therefore, the temperature along the optical axis can be expressed by polynomials. However, for the section vertical to the axis, because of the complicated circumstances, the temperature distribution varies. An extended Zernike polynomial function is proposed to fit the three-dimensional distribution, which is given by

$$n(\rho,\theta,z) = \sum_{i=1}^{\infty}\left[\left(\sum_{j=0}^{n} c_{ij}z^j\right) Z_i(\rho,\theta)\right] \quad (5)$$

where $Z_i(\rho,\theta)$ is the value of the ith Zernike polynomial at (ρ,θ) in the aperture and c_{ij} is the polynomial coefficient.

The coefficients of the standard Zernike polynomials are replaced by a series of polynomials. The distribution is a polynomial about z in the axial direction and a Zernike polynomial in the vertical axial direction for a better

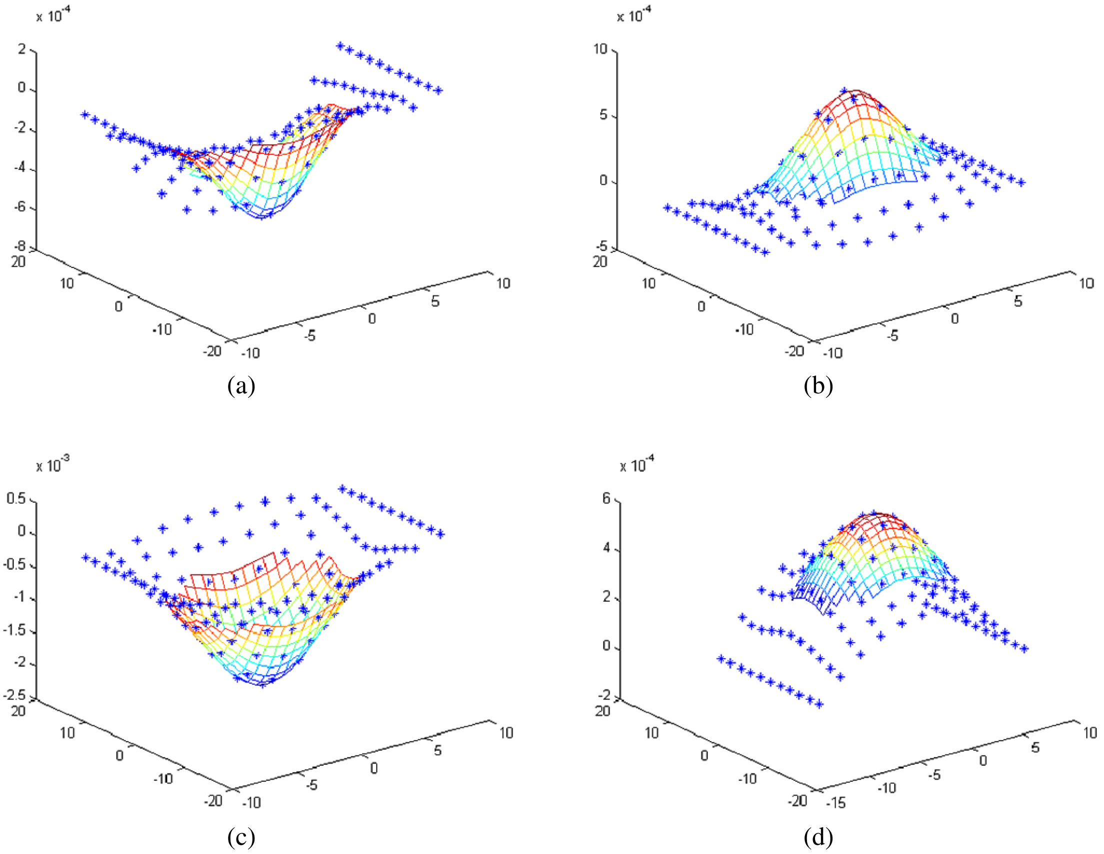

Figure 8. Plot of the surface deformation (represented by '*') and the reconstructed surfaces. (a) Surface 1. (b) Surface 2. (c) Surface 3. (d) Surface 4.

Table 1. Fitting precision comparison.

Simple polynomials			Extended Zernike polynomials		
Number of coefficients	PV (°C)	RMS (°C)	Number of coefficients	PV (°C)	RMS (°C)
27 (3 × 3 × 3)	0.4708	0.1050	20 (10 × 2)	0.4015	0.0918
48 (4 × 4 × 3)	0.4148	0.0855	45 (15 × 3)	0.2244	0.0462
147 (7 × 7 × 3)	0.1781	0.0239	135 (45 × 3)	8.810×10^{-7}	1.042×10^{-7}

expression compared to simple polynomials like the following one [11]:

$$n(x, y, z) = \sum_{i=0}^{ni} \sum_{j=0}^{nj} \sum_{k=0}^{nk} C_{ijk} x^i y^j z^k. \tag{6}$$

A test was performed and the result (table 1) showed that a fitting using extended Zernike polynomials can obtain a more accurate approximation with fewer coefficients.

Because the function is linear, the derivatives can be calculated by

$$\begin{aligned}
\frac{\partial n(x, y, z)}{\partial x} &= \sum_{i=1}^{\infty} \left[\left(\sum_{j=0}^{n} c_{ij} z^j \right) \frac{\partial Z_i(x, y)}{\partial x} \right] \\
\frac{\partial n\,(x, y, z)}{\partial y} &= \sum_{i=1}^{\infty} \left[\left(\sum_{j=0}^{n} c_{ij} z^j \right) \frac{\partial Z_i(x, y)}{\partial y} \right] \\
\frac{\partial n(x, y, z)}{\partial z} &= \sum_{i=1}^{\infty} \left[\left(\sum_{j=0}^{n} \mathrm{j} c_{ij} z^{j-1} \right) Z_i(x, y) \right].
\end{aligned} \tag{7}$$

2.5. Wavefront aberration

Wavefront aberration is a useful optical performance evaluation tool. It can be obtained by tracing rays from an object point to the exit pupil and comparing the optical path length to that of the chief ray. If the system is aberrated, the wavefront will deviate from the spherical wavefront. The deviation represents the aberration of the system.

If the index of the material is not homogeneous, the light will not travel in straight lines. The path is curved because of the index gradient. This needs to be solved by a numerical method. CodeV software provides the computational functionality by the high speed Sharma method [12].

A user defined gradient index material with the index form introduced earlier is created in the CodeV program by a user defined subroutine. The subroutine gets the coefficients automatically from the data file produced by the fitting program, and calculates the index when the ray tracing

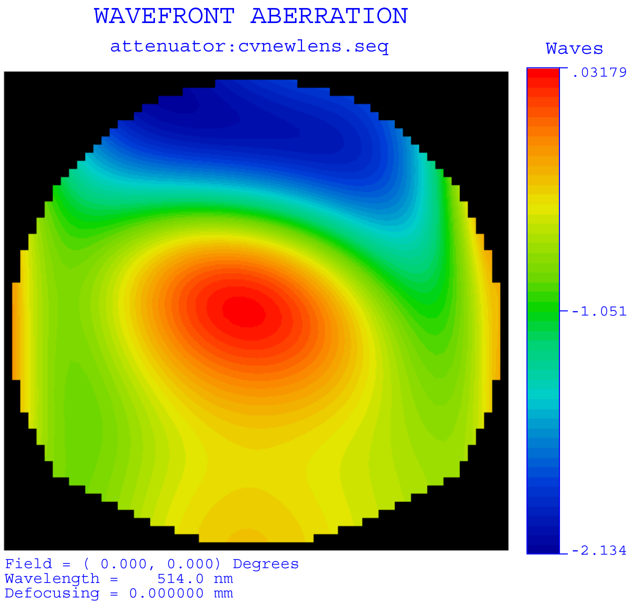

Figure 9. Diagram of the wavefront aberration.

process is required. The surface type is set to Zernike polynomial, and the coefficients are also set by the surface fitting program automatically for convenience.

The CodeV program traces the rays and computes the wavefront aberration; the analysis result is shown in figure 9. From the figure, we can see that the PV value is 2.166 waves and the RMS value is 0.537 waves. Note that the distribution is not exactly symmetrical; this is caused by the non-uniform sampling of the non-sequential analysis and the FEA solution.

3. Conclusion

The integrated opto-thermal–mechanical method applies different theories of different fields to analyze the thermal effect of the laser energy gradient attenuator. It is applicable to wavefront aberration analysis caused by the thermal effect, and is especially aimed at the condition where the material absorbs energy and causes a large index gradient. The extended Zernike polynomials are proved to be effective in obtaining a higher fitting precision. A self-built program working as the interface between non-sequential analysis, FEA and optical design software is effective and convenient.

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