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Study on the consistency of the voxel of two photon polymerization with inclined beam

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ABSTRACT

In the process of two photon polymerization, the focused beam should be perpendicular to the materials to be processed. But actually it is hard to control, because of the errors of the optical system and the three-dimensional motion platform. So, the inconsistencies of voxels in size and angle due to the errors mentioned above will seriously impact the surface quality of the products. In this paper, the size, angle and location of the titled voxels formed by inclined beam are simulated according to matrix optics and polymerization theory. According to the simulation results, a method for angle errors compensation with the aid of scanning galvanometer is proposed. Although the angle of the voxels can be controlled by scanning galvanometer, but the deflection angles of the scanning galvanometer have a certain range, it should be lower than 3°, or the deformation of the voxels will be serious. Therefore the consistency of the voxel in both size and angle will be ensured.

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1. Introduction

Two photon polymerization processing is done by sacking layers of voxels, so the size, angle and location of voxels severely impact the quality of our products. K. Takada et al. point out different sizes of voxels can be obtained by different laser parameters, which induce the variation of surface roughness [1]. D. Wu, M. Malinauskas and Y.L. Zhang et al. also find that the inconsistency of voxels would lead to products' degradation. Therefore the high reputation of the voxels could further improve the surface accuracy [2–4]. The tilting of the peak intensity distribution in the focal spot of the focused beam can play important roles in some applications such as femtosecond laser micromachining and bio-imaging [5]. In the ideal situation, the focused beam should be perpendicular to the materials to be processed. But actually, by reasons of the installation error and the angle errors of the three-dimensional motion platform, the focused beam usually slightly incline with the axis of optical system which makes the voxels titled and size inconsistent. Therefore, the objective of this paper is to find the proper parameters to make sure the consistency of the voxels by researching the impacts of inclined incident beam on the consistence of voxels.

2. The model of voxel

The generalized Huygens-Fresnel diffraction integral formula, also known as Collins formula, combines the diffraction integral of complete optical system with ABCD matrix. Due to this combination, on the one hand, the applications of matrix optical method are extended, and on the other hand, the development of the theory of diffraction has been promoted [6]. In this paper, the focus situation with inclined incident beam is quantitatively analyzed by this method. Thus the variations of the angle, location and size of the titled voxels could be got.

2.1. The angle and location of titled voxels

Fig. 1 shows the focus effect of an arbitrary beam passes through scanning galvanometer and focus lens. First, the beam is supposed to along the optical axis of the system, so the scanning galvanometer is the unique reason for angle variation. Then the projections of the beam in the xoz and yoz planes are obtained, which is easier to understand the changes in angle of the beam. The intensity distribution of focused beam [7–9] and the angles of the titled voxels can be obtained by giving the wavelength and waist of the laser beam, the structure parameters of the scanning galvanometer and the focus lens and the deflection angles of the scanning galvanometer θ_x and θ_y, shown as Eqs. (1) and (2),

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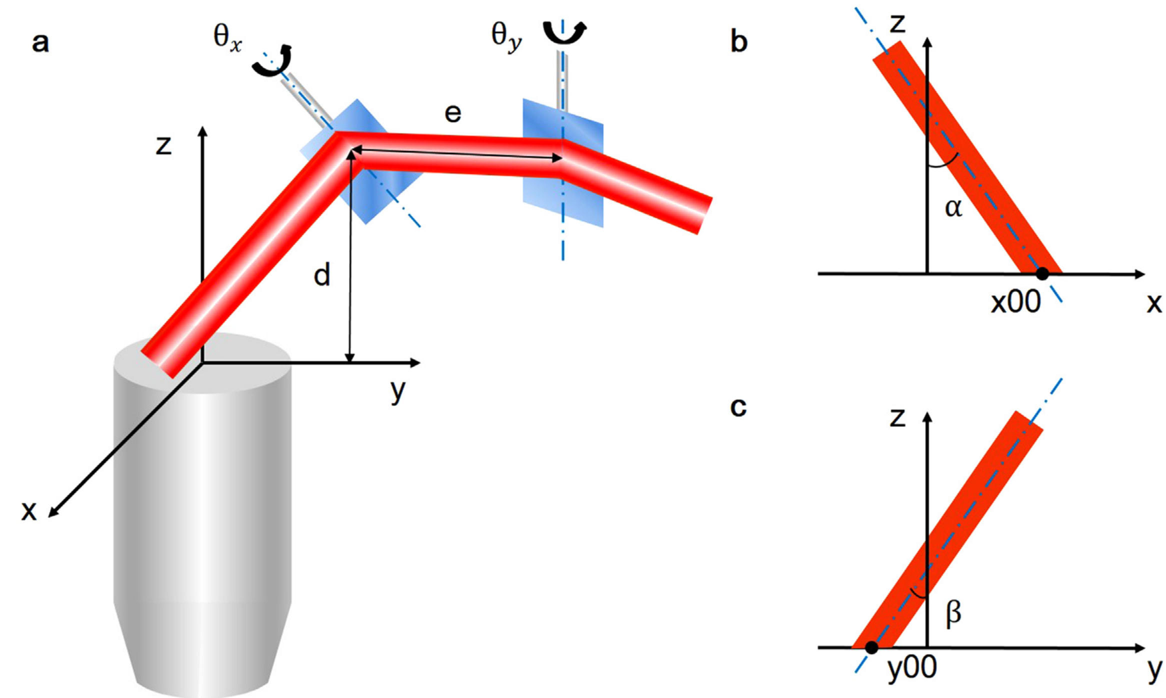

Fig. 1. The scanning galvanometer and focusing systems. (a) The whole structure of this system is shown. θ_x and θ_y are the deflection angles of the scanning galvanometer, respectively. (e) and (d) Are the distance between two mirrors of the scanning galvanometer(blue) and the distance between the second mirror and incident plane of the focus lens(silver), respectively. (b) and (c) The projections of the beam in the xoz and yoz planes are got. In these planes, the angles between the beam and z axis are α and β, respectively. When the beam arrive at the front surface of focusing lens, $x00$ and $y00$ are the distances between the intersections of the beam and x axis and y axis and the origin of coordinates, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

respectively.

$$\mathrm{I} = E_2E_2^* = \frac{2P}{\pi w_2^2(z)} exp\left\{-2\frac{(x - x_d - \frac{z}{z_{20}}x_0)^2 + (y - y_d - \frac{z}{z_{20}}y_0)^2}{w_2^2(z)}\right\} \quad (1)$$

$$\begin{cases} \phi_x = arctan(Cx_{00}) = arctan(C(e + d\sec 2\theta_y)\tan 2\theta_x) \\ \phi_y = arctan(Cy_{00}) = arctan(Cd\tan 2\theta_y) \end{cases} \quad (2)$$

where $x_d = \frac{Dx_{00}}{D^2 + C^2{z_0}^2/\cos\alpha^4}$, $x_0 = \frac{Cx_{00}z_0/\cos\alpha^2}{D^2 + C^2{z_0}^2/\cos\alpha^4}$, $y_d = \frac{Dy_{00}}{D^2 + C^2{z_0}^2/\cos\beta^4}$, $y_0 = \frac{Cy_{00}z_0/\cos\beta^2}{D^2 + C^2{z_0}^2/\cos\beta^4}$, $\alpha = arctan\left(\frac{\tan 2\theta_x}{\cos 2\theta_y}\right)$, $\beta = arctan(\tan 2\theta_y)$. ω_0 and ω_{20} are the waists of the beam before and after it through the optical system. $\omega_2(z)$ is the radius of beam when the reference plane is z from the waist in image space. z_0 is the Rayleigh length of incident beam. C and D are from the ABCD matrix of the focus lens. e and d are the distance between two mirrors of the scanning galvanometer and the distance between the second mirror and incident plane of the focus lens, respectively. x_d and y_d are the offsets of the center of the focused beam in x and y axis, respectively, which are used to define the location of the voxels.

Eq. (2) shows that the deflection angles of the focused beam are influenced by both the angle of incident beam and the properties of scanning galvanometer and focused lens. They are also the angles of the titled voxels. Then combining the intensity distribution of the focused beam and the polymerization threshold of the materials, the diameter and the length of the voxels can be solved.

2.2. The size of titled voxels

In order to obtain the size of titled voxels, the intensity distribution of the titled focusing beam is necessary. The changes of the beam before and after focusing is shown in Fig. 2a. The projection of the focused beam in the xoz and yoz planes are got by coordinate transform, illustrated in Fig. 2b and c, respectively. For convenience, only the variation of the focused beam in the xoz plane is studied. Therefore, the intensity distribution in the xoz plane can be simplified to Eq. (3), P is the laser power.

$$I(x, z) = \frac{2P}{\pi w_2^2(z)}\mathrm{exp}\left\{-2\frac{(x - x_d - \frac{z}{z_{20}}x_0)^2}{w_2^2(z)}\right\} \quad (3)$$

Then using coordinate transformation, the intensity distribution in x′oz′ coordinate is shown as Eq. (4) [7–9]:

$$\mathrm{I}(x', z') = \frac{2P\cos^2\phi_x}{\pi\omega_2'^2(z')}\mathrm{exp}\left\{-2\frac{x'^2}{\omega_2'^2(z')}\right\} \quad (4)$$

where

$$x' = (x - x_d)\cos\phi_x - z\sin\phi_x$$
$$z' = (x - x_d)\sin\phi_x + z\cos\phi_x$$

Hence the diameter and length of voxels can be solved with Eq. (4) and the two-photon polymerization threshold, shown as Eq. (5) [10–13]. Therefore, the size of voxels of inclined incident beam depends on the power of laser P, exposure time t, the parameters of focused lens and the incident angles of the beam ϕ_x and ϕ_y.

$$\begin{cases} d = \omega_{20}'\left(\ln\frac{4P^2t\cos^4\phi_x}{\pi^2E_{th}\omega_{20}'^4}\right)^{\frac{1}{2}} \\ l = \frac{2\pi\omega_{20}'^2}{\lambda}\left(\left(\frac{4P^2t\cos^4\phi_x}{\pi^2E_{th}\omega_{20}'^4}\right)^{\frac{1}{2}} - 1\right)^{\frac{1}{2}} \end{cases} \quad (5)$$

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