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Focusing error detection based on astigmatic method with a double cylindrical lens group

Zhen Bai [a,b], Jingsong Wei [a,*]

[a] Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, Shanghai 201800, China
[b] University of Chinese Academy of Sciences, Beijing 100049, China

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ABSTRACT

Autofocusing and autotracking are widely used in maskless laser lithography, optical imaging, and recording and readout of optical information storage. With the development of optoelectronic techniques, the accuracy of autofocusing and autotracking thus needs to be improved to the nanoscale, and the autotracking range also needs to be extended to tens of micrometers. In this work, an astigmatic method with two cylindrical lenses is proposed, where the focusing error signal is extracted to detect the focusing error. A theoretical analysis and simulation are carried out, accordingly. A focusing error detection system is established to demonstrate the theoretical analysis. The experimental results indicate that the focusing error signal curves present good "S" characteristics. The linear tracking range is up to 18 μm, and the tracking accuracy is approximately 50 nm. The theoretical and experimental results indicate that the astigmatic method with two cylindrical lenses is a good method for autofocusing and autotracking with both high accuracy and large dynamic range. This work is useful in the fields of high-resolution maskless laser lithography and optical imaging.

1. Introduction

Autofocusing and autotracking are widely used in maskless laser lithography, optical imaging, and recording and readout of optical information storage, when the laser beam is focused on a small spot with an objective lens having a high numerical aperture (NA) and short depth of focus [1–10]. In autofocusing and autotracking, one of the critical factors is focusing error detection [11–17]. For focusing error detection, the astigmatic method is widely used owing to its simple operation and low cost, in which only one cylindrical lens and four-quadrant detector (FQD) are usually required [18–21]. The basic principle of the astigmatic method is as follows: when the sample is out of focus, the cylindrical lens changes the distribution of the reflected laser beam, resulting in a different spot shape on the FQD. By measuring the focusing error signal on the FQD, one can calculate the defocus amount. Then, autofocusing and autotracking are realized by compensating the defocus amount, which may be conducted through servo systems.

With the development of optoelectronic techniques, the objective lenses with high NA are being used in the autotracking unit of maskless laser lithography and optical imaging systems. The depth of focus (DOF) of systems can be estimated as $\mathrm{DOF} = 0.5\lambda/(\mathrm{NA})^2$ [11], where NA and λ are numerical aperture of objective lens and laser wavelength of the system, respectively. The DOF is becoming smaller and smaller for the maskless laser lithography and optical imaging systems. For example, the DOF is about 200 nm for a system with NA of 0.95 and laser wavelength of $\lambda = 405$ nm. The DOF is shortened to about 100 nm when the NA of objective lens is increased to 1.40 [22,23]. The accuracy of focusing and tracking of the objective lens is required to be improved to the nanoscale, and the tracking range is also required to be extended to tens of micrometers, accordingly. However, to our knowledge, the astigmatic method with a single cylindrical lens does not meet the requirements [24–26]. This is because the high accuracy is accompanied by a short linear range. The short linear range means a very small dynamic autotracking range. In contrast, the accuracy is too low when the dynamic range is large enough.

In this work, an astigmatic method is proposed in which a double cylinder lens group replaces the single cylinder lens. Focusing error detection is carried out using a combination of the double cylinder lens group and FQD. With this method, the linear dynamic tracking range can reach up to approximately 18 μm, and the focusing accuracy is improved to 50 nm theoretically and experimentally. The proposed method provides a good way of autofocusing and autotracking with both higher accuracy and larger dynamic range.

* Corresponding author.
E-mail address: weijingsong@siom.ac.cn (J. Wei).

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2. Theory of astigmatic method with a double cylindrical lens group

The schematic of the optical path in the proposed method is presented in Fig. 1a, where two cylindrical lenses (marked as CL_x and CL_y) are used as astigmatic elements. The focal lengths of CL_x and CL_y are marked as f_x and f_y, respectively. The cylindrical lenses CL_x and CL_y are placed into a mutually orthogonal system. CL_x tunes the x-directional optical axis of spot on the FQD and CL_y changes the y-directional optical axis of spot on the FQD. Thus, CL_x and CL_y together form a double cylindrical lens group (*DCLG*). The FQD, which is placed behind the *DCLG*, is used as the signal detection element and acquires the focusing error signal (FES). L_o is the objective lens with a focal length of f_o, and is used to focus the laser beam onto a spot. P_f is the focal plane of L_o, while P_a and P_p are the apofocal plane and perifocal plane of L_o, respectively. In Fig. 1a, the *DCLG* actually functions as an astigmatic element and generates the FES. The generation principle of FES is as follows. When the sample is placed on the focal plane P_f of L_o, the reflected light passes through L_o and *DCLG*, then arrives at the FQD. The spot on the FQD is circular (shown in Fig. 1b-b$_2$). The spot on the FQD becomes an upright ellipse when the sample is placed on the plane P_a (apofocus) of L_o (shown in Fig. 1b-b$_1$). A horizontal elliptical spot can be formed if the sample is placed on the plane P_p (perifocus) of L_o (shown in Fig. 1b-b$_3$).

The FES can be analyzed as follows: A_1, A_2, A_3, and A_4 are the areas of the spot on each quadrant of the FQD, as shown in Fig. 2, with intensities of I_1, I_2, I_3, and I_4, respectively. r_x and r_y are the radii of the x-axis and y-axis of the spot on the FQD, respectively. The FES is defined as:

$$FES = \frac{-I_1 + I_2 - I_3 + I_4}{I_1 + I_2 + I_3 + I_4} \tag{1}$$

Let us assume that the spot on the FQD has a uniform intensity distribution; then, one can obtain

$$I_i = CA_i \quad (i = 1, 2, 3, 4) \tag{2}$$

where C is a constant. Considering the symmetry of the spot,

$$A_1 = A_3, A_2 = A_4 \tag{3}$$

Based on Eqs. (1)–(3) and geometrical relationship of the spot, one can calculate FES as follows:

$$FES = \frac{2}{\pi}\left[\arcsin\frac{|r_x|}{\sqrt{r_x^2 + r_y^2}} - \arcsin\frac{|r_y|}{\sqrt{r_x^2 + r_y^2}}\right] \tag{4}$$

The values of r_x and r_y can be obtained through the imaging principle, where the light is reflected by the sample, as shown in Fig. 3. The reflected light goes through L_o and *DCLG*, before arriving at the FQD. a_o and b_o are the object and image distances of L_o, respectively. a_x and b_x are the object and image distances of CL_x, respectively. a_y and b_y are object and image distances of CL_y, respectively. l_{xy} is the distance between CL_x and CL_y. In order to calculate the r_x value, one can consider CL_y as a glass plate, as is shown Fig. 3a, where r_o and r_{clx} the radii of light beam onto L_o and CL_x, respectively. m_x is the distance between CL_x and the FQD. Based on the Gaussian imaging formula, one can obtain

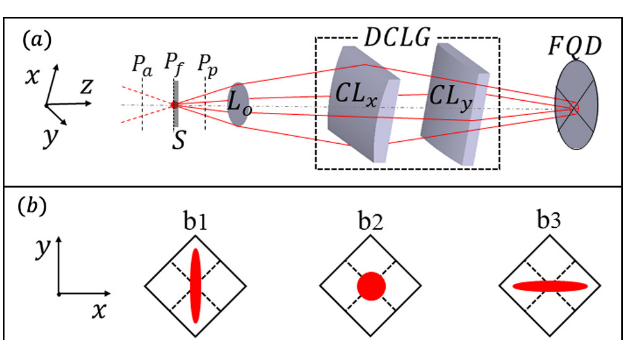

Fig. 1. Schematic of astigmatic method with a double cylindrical lens group. (a) Optical path and (b) shape change of spot on the FQD.

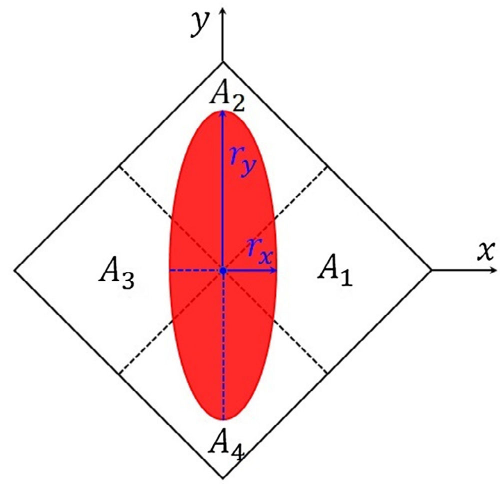

Fig. 2. The spot profile onto the FQD.

$$1/a_o + 1/b_o = 1/f_o, \quad -1/a_x + 1/b_x = 1/f_x \tag{5}$$

Based on the homothetic triangle theory, one can obtain:

$$r_x/r_{clx} = (m_x - b_x)/b_x, \quad r_{clx}/r_o = a_x/b_o \tag{6}$$

Then r_x can be calculated as:

$$r_x = \frac{m_x - b_x}{b_x} r_{clx} = r_o \frac{m_x - b_x}{b_x}\frac{a_x}{b_o} \tag{7}$$

From Eqs. (5) and (7), one can obtain:

$$r_x = r_o\left[\frac{m_x}{f_x} + \frac{m_x(a_o - f_o)}{a_o f_o - l_x a_o + l_x f_o} - 1\right]\left[1 - \frac{l_x(a_o - f_o)}{a_o f_o}\right] \tag{8}$$

Similarly, r_y can be calculated by considering CL_x as a glass plate, as is shown in Fig. 3b, where the r_{cly} is the radius of light beam onto the CL_y and m_y is the distance between CL_y and the FQD. Using a series of mathematical operations, one has

$$r_y = r_o\left[\frac{m_y}{f_y} + \frac{m_y(a_o - f_o)}{a_o f_o - l_y a_o + l_y f_o} - 1\right]\left[1 - \frac{l_y(a_o - f_o)}{a_o f_o}\right] \tag{9}$$

Based on Fig. 3, one can see that $m_y = m_x - l_{xy}$, $l_y = l_x + l_{xy}$, hence Eq. (9) can be further written as

$$r_y = r_o\left[\frac{m_x - l_{xy}}{f_y} + \frac{(m_x - l_{xy})(a_o - f_o)}{a_o f_o - (l_x + l_{xy})a_o + (l_x + l_{xy})f_o} - 1\right]\left[1 - \frac{(l_x + l_{xy})(a_o - f_o)}{a_o f_o}\right] \tag{10}$$

Therefore, one can obtain the dependences of the FES, r_x, and r_y on the defocus amount of Δa_0 through the Eqs. (4), (8), and (10), respectively, where Δa_0 is defined as the change in the amount of a_o. The relation between FES and Δa_0 is called as "S" curve. The maximum of r_x and r_y are marked as R_x and R_y, respectively. In practical applications, the values of R_x and R_y are also limited by the size of the FQD.