Optik 125 (2014) 4308–4312

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

Measurement of refractive index homogeneity of parallel optical component

Xu Liu, Yong Liu, Hongzhen Jiang*, Huan Ren, Hua Ma, Liqun Chai, Xiaoyu Yang, Bo Chen

Research Center of Laser Fusion, China Academy of Engineering Physics, Mianyang, 621900 Sichuan, China

ARTICLE INFO

Article history:
Received 18 August 2013
Accepted 10 March 2014

Keywords:
Refractive index homogeneity
Parallel optical components
Fringe analysis

ABSTRACT

In this paper, we present a method for enhancing the measurement capability of refractive index homogeneity for parallel optical components, which phase-shifting interferometry cannot handle with. With the help of wavelength-modulation phase-shifting interferometry, a series of multiple-surface interference fringes are obtained and analyzed by Fourier transform. Based on the fact that the interference fringe corresponding to each interference cavity has its own variation frequency, the wavefront aberrations induced by each interference cavity are obtained and the refractive index homogeneity is then obtained. It is proved by experiment that the enhanced method can measure the refractive index homogeneity of parallel optical components more accurately and conveniently compared with the traditional measurement approach. Therefore, it will have potential application forwards in optical measurement field.

1. Introduction

Refractive index homogeneity of optical material is one of the key factors that affect the quality of wavefront in high powered laser systems, and local changes in the refractive index of the order of 10^{-6} must be detected to guarantee the output beam quality. A technique given by Twyman and Perry [1] separated refractive index deviations from surface deformations, and this technique has been improved by Roberts and Langenbeck [2], who obtained results that are free from the influence of the interferometer components. An alternative method is given by Johannes Schwider [3], in which the variations of the refractive index apart from a linear slope, as well as the thickness variations of the glass block can be measured and displayed with the help of four interferograms, and this method is called traditional measurement approach in this paper. However, this method cannot be used to measure the refractive index homogeneity of parallel optical components because the wedge angle is usually less than 30″. In this case, the light reflected from the sample's front and back surfaces will interfere with the reference light simultaneously and produce multiple-surface interference fringes. To solve this problem, an available approach [4] is to fill oil on one surface of the sample to reduce its reflection and measure the wavefront aberrations caused by the other surface. But the surface of the sample might be destroyed during the oil-filling procedure and the measurement accuracy will be influenced by the uniformity of the oil layer.

As none of the mentioned methods can deal with the measurement of refractive index homogeneity of parallel optical components effectively, in this paper, we propose an enhanced method based on the multiple-surface interference fringes analysis [5–14] and the wavelength modulated phase-shifting interferometer. The method can accurately measure the refractive index homogeneity of optical components with wedge angle less than 30″.

2. Principles

2.1. Description for measuring refractive index homogeneity

For the sample to be measured, its thickness can be expressed as:

$$h(x, y) = h_0 + h_1(x, y) + h_2(x, y), \qquad (1)$$

where the subscript x and y denote individual pixel locations in each image, as shown in Fig. 1. In Eq. (1), h_0 is the mean thickness of the sample, $h_1(x, y)$ and $h_2(x, y)$ stand for the surface deviations of sample. As the refractive index homogeneity $\Delta n(x, y)$ is assumed to be small compared with the mean refractive index n_0, the refractive index of the sample can be written as:

$$n(x, y) = n_0 + \Delta n(x, y). \qquad (2)$$

* Corresponding author.
E-mail address: zjuliuxu@gmail.com (X. Liu).

http://dx.doi.org/10.1016/j.ijleo.2014.03.034

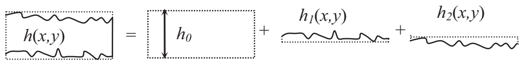

Fig. 1. Model of parallel optical component.

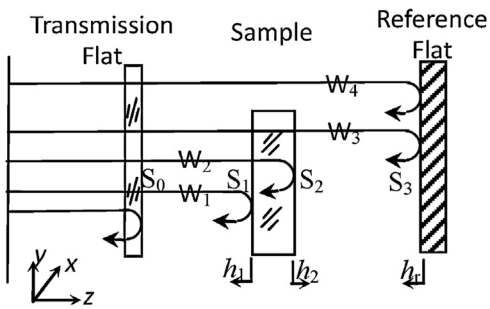

Fig. 2. Measurement of refractive index homogeneity by Fizeau interferometry.

According to the traditional measurement approach, four wavefront aberrations should be measured by Fizeau interferometry, as shown in Fig. 2. They can be written as follows [3]:

$$\begin{cases} W_1(x,y) = W_0(x,y) + 2h_1(x,y) \\ W_2(x,y) = W_0(x,y) - 2(n_0-1)h_1(x,y) - 2n_0h_2(x,y) - 2h_0\Delta n(x,y) \\ W_3(x,y) = W_0(x,y) - 2(n_0-1)[h_1(x,y)+h_2(x,y)] - 2h_0\Delta n(x,y) + 2h_r(x,y) \\ W_4(x,y) = W_0(x,y) + 2hr(x,y) \end{cases} \tag{3}$$

where $W_0(x, y)$ stands for the wavefront aberrations generated in the interferometer itself. $W_1(x, y)$ stands for the wavefront aberrations caused by the sample's front surface (surface S_1) and $W_0(x, y)$. $W_2(x, y)$ denotes for the wavefront aberrations caused by the sample's front surface, refractive index homogeneity, back surface (surface S_2) and $W_0(x, y)$. The measuring light passes through the sample and be reflected by reference flat (RF), forming the wavefront aberration of $W_3(x, y)$. Specially, $W_4(x, y)$ stands for the wavefront aberrations caused by the reference flat (surface S_3) and $W_0(x, y)$, in which $h_r(x, y)$ denotes for the surface deviation of the reference flat. Combined with the wavefront aberrations information, both the refractive index homogeneity (Δn) and thickness variation (Δh) can be calculated from Eq. (3), which can be expressed as:

$$\begin{cases} \Delta n(x,y) = \dfrac{1}{2h_0}[(n_0-1)(W_2-W_1) - n_0(W_3-W_4)] \\ \Delta h(x,y) = h_1(x,y) + h_2(x,y) = \dfrac{1}{2}[(W_3-W_4)-(W_2-W_1)] \end{cases} \tag{4}$$

2.2. Wavefront aberrations measurement

Fig. 3 shows the principle of wavelength-modulated phase-shifting Fizeau interferometry, in which S_0 is the transmission flat, S_1 is the front surface of the sample, S_2 is the back surface of the sample and S_3 is the reference flat. Based on the fact that each interference cavity (S_0: S_1, S_1: S_2, S_0: S_2, S_0: S_3, S_1: S_3 and S_2: S_3) has a unique OPD, as shown in Fig. 3, we use wavelength modulated phase-shifting interferometry to separate and evaluate each of the interference patterns. By gradually varying the wavelength of the laser source during measuring procedure, a series of multiple-surface interference fringes can be collected. Then according to the fact that each interference cavity has a unique modulation frequency, we can now simultaneously measure and evaluate all the wavefront aberrations shown in Eq. (3).

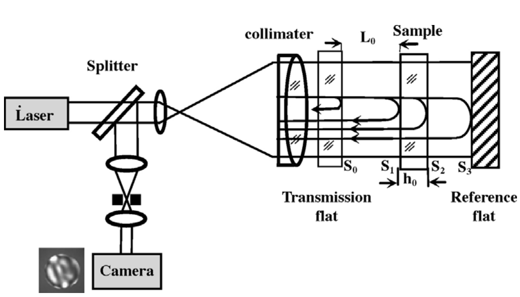

Fig. 3. Principle of wavelength-modulated phase-shifting interferometry.

When the wavelength of the laser source changes from λ_0 to $\lambda_0 + k\Delta\lambda$ (k = 1, 2,. . ., $M-1$), the interference intensity for the kth frame of multiple-surface interference fringes can be expressed as:

$$I(x,y,k) = \sum_{i=0}^{5} a_i(x,y) + \sum_{i=0}^{5}\left\{b_i(x,y)\cos\left[\frac{4\pi L_i(x,y)}{\lambda_0 + k\cdot\Delta\lambda}\right]\right\}, \tag{5}$$

where the subscript i denotes the ith group interference fringe (i = 0, 1, 2, 3, 4, 5), and the parameter x and y denotes the individual pixel locations in each image. In Eq. (5), a_i is the background intensity, b_i is the modulation amplitude, $L_i(x, y)$ is the OPD of the interference cavity corresponding to the ith group fringe. The variation of wavelength ($k\,\Delta\lambda$) is assumed to be further small compared with the initial wavelength λ_0 (about 10^{-5}:1 in experiment), so Eq. (5) can be expressed as:

$$I(x,y,k) = a(x,y) + \sum_{i=0}^{5}\left\{b_i(x,y)\cos[\phi_i(x,y) - \frac{4\pi L_i(x,y)}{\lambda_0^2}\cdot k\cdot\Delta\lambda]\right\} \tag{6}$$

where $\phi_i(x, y) = 4\pi L_i(x, y)/\lambda_0$, and $a(x, y)$ stands for the total intensity of background for the kth frame.

2.3. Determination of unique modulation frequency for each interference cavity

Consider again the interference cavity shown in Fig. 3. The sample is positioned at the specific distance from the reference flat and transmission flat, where the relationship between L_0, n_0 and h_0 can be expressed as:

$$\varepsilon_0 = \frac{n_0h_0}{L_0}, \quad \gamma = \frac{L_3}{L_0}, \tag{7}$$

where ε_0 and γ are constants, L_0 and L_3 stand for the OPD corresponding to the interference cavity (S_0: S_1) and (S_0: S_3), respectively. In order to obtain the wavefront aberrations we needed, we should analyze their corresponding frequencies about parameter k, which can be obtained from the following equations:

$$\begin{cases} \upsilon_0(x,y) = \dfrac{2L_0(x,y)}{\lambda_0^2}\Delta\lambda \\ \upsilon_1(x,y) = \dfrac{2n_0(x,y)h_0}{\lambda_0^2}\Delta\lambda = \varepsilon_0\upsilon_0 \\ \upsilon_2(x,y) = \dfrac{2[n_0(x,y)h_0 + L_0(x,y)]}{\lambda_0^2}\Delta\lambda = (\varepsilon_0+1)\upsilon_0 \\ \upsilon_2(x,y) = \gamma\upsilon_0 \end{cases} \tag{8}$$