Optik 127 (2016) 7973–7977

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

Phase error evaluation technique based on Fourier transform for refractive index detection limit of microfluidic differential refractometer

Weibang Ji [a,b,*,1], Jianguo Zhang [a,b]

[a] Key Laboratory of Advanced Transducers and Intelligent Control System (Ministry of Education), TaiYuan University of Technology, TaiYuan 030024, China
[b] Department of Physics and Optoelectronics, TaiYuan University of Technology, TaiYuan 030024, China

ARTICLE INFO

Article history:
Received 7 April 2016
Accepted 31 May 2016

Keywords:
Fourier analysis
Phase error evaluation
Microfluidic
Differential refractometer,

ABSTRACT

A novel phase error evaluation technique based on Fourier Transform Method is presented to estimate the phase error resolution from the spatial interference pattern. The highest phase error resolution is $3.4 \times 10^{-8} \times 2\pi\, rad$ in simulation. The simulation has shown the validity of the proposed technique compared to the result in real experiment. The influence of bit depth, size of the pixel and the spatial period of the interference fringe on the phase error resolution is also discussed in detail. The results are helpful for choosing the suitable parameters of CCD camera and controlling the whole size of the integrated microfluidic differential refractometer.

Integrated optical differential refractometers refer to the measurement of small changes in the refractive index (RI) of liquids and gases, offering solutions to a broad range of scientific and technical problems and applications. In an optical interferometric system for RI detection, the measured detection limit is encoded in the phase error of interference fringe patterns. The phase error is related to the corresponding changes in refractive index of the sample. The relationship is expressed by the following expression:

$$\Delta\phi = \frac{2\pi}{\lambda} OPD = \frac{2\pi L}{\lambda} \Delta n$$

where $\Delta n$is the change in refractive index of the sample, L is the optical length, and the λ is the wavelength of laser. There exit several methods for the phase extraction from interference fringe patterns such as Fourier transform method (FTM) [1], Windowed Fourier transform method [2], wavelet transform (WT) method [3], phase-shifting (PS) technique [4], curve fitting method [5] etc. Among these methods, Fourier transform for fringe pattern analysis is more tolerant to noise, especially more effective for decreasing the influence of nonstationary noise. This method has already been used for various kinds of interferometric techniques, such as holographic interferometry, shearography and moire interferometry. Furthermore, it has been applied to refractive index detection by fringe analysis [6–8]

* Corresponding author at: Key Laboratory of Advanced Transducers and Intelligent Control System (Ministry of Education), TaiYuan University of Technology, TaiYuan 030024, China.
E-mail address: jiweibang@tyut.edu.cn (W. Ji).
1 Supported by the National Natural Science Foundation of China No. 51404165.

http://dx.doi.org/10.1016/j.ijleo.2016.05.160
0030-4026/

Following Takeda [1] the principle of the FTM may be summarized as follows. An interference fringe pattern can be described as

$$I(x) = a + b[\cos(2\pi f_0 x + \phi_0)] \tag{1}$$

where the coefficients a and b is the background and fringe amplitude respectively, f is the spatial frequency and ϕ_0 is the initial phase.We can rewrite the Eq. (1) as

$$I(x) = a + c(x)\exp(i2\pi f_0 x) + c^*(x)\exp(-i2\pi f_0 x) \tag{2}$$

with the definition

$$c(x) = \frac{1}{2} b \exp(i\phi_0) \tag{3}$$

and the $c^*(x)$ is the complex conjugate of $c(x)$. Then Fourier Transform of Eq. (2), the result is given by

$$I(f) = A(f) + C(f - f_0) + C^*(f + f_0) \tag{4}$$

where the capital letters denote the transforms of the corresponding functions and f is the spatial frequency domain. The phase ϕ is given by

$$\phi = \tan^{-1}\{Re[c(x)]/Im[c(x)]\} \tag{5}$$

where $Re[c(x)]$ refers to the real part of $c(x)$ and $Im[c(x)]$ to the imaginary part. Usually, the detected phase in Eq. (5) is discontinuous and ranges from $-\pi \sim \pi$, so the true phase will be obtained only after the phase in Eq. (5).

However, the phase evaluation with the FTM produces noticeable inaccuracies because of many error sources. For instance, the error from incorrect frequency domain filtering operations; the error from random noise, disturbances of the environment and vibrations; and the errors due to incorrect phase unwrapping. These errors will enhance the inaccuracy of phase error from the interference fringe. Those mentioned methods [1–5] have proposed some methods to improve the resolution of phase error, but they were very complex and have limitations.

In this Letter, a new signal processing algorithm is proposed to estimate the phase error resolution from the spatial interference pattern without noise. The method avoids complexity of those mentioned methods above. The detected limit of the differential refractometer can be obtained from the phase error. We also investigate the influences of the CCD camera bit depth by quantization principles, pixel width and distance between silt and CCD camera of integrated optical interferometer. This study shows a simple method capable of detecting the detection limit of the integrated optical interferometer from the fringe pattern. The three important parameters of the system which can affect the resolution of RI detection are also investigated in this article. It shows that the optimal parameters for an integrated differential refractometer.

The phase extraction process and the phase error evaluation process are demonstrated as follows. Firstly, a simulated interference fringe is presented by the sinusoidal function. The Fourier spectrum is transformed by FFT, and the terms A, C, and C* of Eq. (4) are separably placed as three peaks in the frequency domain. A phase distribution curve is obtained by using Eq. (5). Fig. 1(a),(b) and (c) shows a simulated pattern, the modulus of the discrete spectrum and the phase distribution. The spectrum is displayed as frequency ranges from 0 to 2048 in Fig. 1(b), where 2048 is the number of CCD pixels. Fig. 1(c) shows the unwrapped phase distribution.

Then we mark the position of maximum value of term C* and extract the phase information at the same position from phase distribution curve. Thirdly, we replace ϕ_0 with ϕ_i in Eq. (1), where $\phi_i = \phi_0 + \sum_i \Delta\phi_i$, and $\Delta\phi_i$ represent the step. Then we repeat the phase extraction procedure with ϕ_i. A phase point is obtained and stored. A series of phase values are calculated with many times. Some phases would not be changed in a range from N to N + M because of the limitation of system. The value of M is phase error resolution of the optical interference system. The proposed method was verified by computer simulation. All the calculations have been done in the Matlab environment. The calculation parameters have been adjusted according to real experimental conditions: a pixel size of 14 μm, a laser wavelength of 632.8 nm, a distance between two silts of 1.3 mm.

We assume the initial phase of Eq. (1) $\phi_0 = 0$ and the value of $\phi_i$changes from $1 \times 10^{-7} \times 2\pi$ rad to $1 \times 10^{-3} \times 2\pi$ rad with step $\Delta\phi_i = 1 \times 10^{-9} \times 2\pi$ rad. The phase value distributes from 2.154861 to 2.155044 as shown in Fig. 2(a). The details of "phase line" are shown in Fig. 2(b). It shows that some points of phases are in the same location. The number of unchanged value of phase represents the phase error resolution of the interference system. The detection limit can be estimated by using the phase error resolution. Compared to the experimental detection limit in article [9], the proposed method can be proved to be efficient in noiseless case.

To measure the detection limit using the proposed method, the fringe patterns are digitized by a CCD camera. Hence, the phase error resolution due to the quantization is simulated by computer. Quantization error determines limitations of the acquisition devices in the measurement system and plays an important role in the calculation of system accuracy. The effect of quantization was first investigated by Koliopoulos [10] for the phase stepping technique using a four-frame (three-step) algorithm and was then further analyzed by Brophy [11]. RI detection limit is also affected by the CCD structures such as bit depth, pixel width, shot noise [12] and so on. Jin Hongzhen et al. [13] investigated the influence of size of pixel, sampling interval and sensitive area on the reconstruction image. When the fringe patterns are recorded by a digital camera,