Optics and Lasers in Engineering 86 (2016) 125–131

Contents lists available at ScienceDirect

Optics and Lasers in Engineering

journal homepage: www.elsevier.com/locate/optlaseng

A novel integrated fiber-optic interferometer model and its application in micro-displacement measurement

Chi Wang [a,b,c], Long-long Xu [a], Jun Zhu [b,*], Zhi-wen Yuan [b], Ying-jie Yu [a], Anand K. Asundi [d]

[a] Department of Precision Mechanical Engineering, Shanghai University, Shanghai 200072, China
[b] Science and Technology on Near-surface Detection Laboratory, Wuxi 214035, China
[c] State Key Lab of Precision Measuring Technology and Instruments, Tianjin University, Tianjin 300072, China
[d] School of Mechanical and Aerospace Engineering, Nanyang Technological University, Singapore 639798, Singapore

ARTICLE INFO

Article history:
Received 7 March 2016
Received in revised form
23 April 2016
Accepted 17 May 2016
Available online 6 June 2016

Keywords:
Self-focusing lens
Fiber optical probe
Interferometer
Micro-displacement

ABSTRACT

We conducted an investigation in a novel integrated fiber-optic interferometer model based on ultra-small self-focusing optical fiber probe and the method of its application in micro-displacement measurement. Firstly, we proposed the structure model of integrated fiber-optic interferometer and established its input–output mathematical model applied in micro-displacement measurement. Secondly, we established the hardware system of the integrated fiber-optic interferometer. Finally, we analyzed the fitting result of experimental data of micro-displacement measurement and some error factors and defined the linear working range. The experimental results indicate that, under the given experimental conditions, the linear measurement range, linearity and sensitivity of the integrated fiber-optic interferometer were 10 μm, 1.36% and 8.8 mv/μm respectively.

1. Introduction

In recent years, with the development of science and technology and modern industrial manufacturing, the development of precision measuring instruments gradually tended towards miniaturization, integration and intelligence. Thanks to its advantages such as non-contact measurement, small size, light weight, resistance to electromagnetic interference, high resolution and low cost, interferometers which transmit light based on optical fiber are widely used in the field of precision measurement, and they can be used to measure parameters such as displacement, vibration, speed, strain, pressure and temperature, etc. [1–4]. The organic combination of ultra-small optical probe and fiber-optic interferometer is an important technical way to achieve miniaturization, integration and high-precision of precision measuring instruments. Among them, the self-focusing lens (gradient index lens), due to its self-focusing properties and small size, are widely used in fiber-optic sensing system. For example, Tan et al. proposed the confocal measurement system based on self-focusing lens [5]; Xie et al. developed the fiber-optic Michelson interferometer based on GRIN lens, achieving vibration and displacement measurement successfully [6,7]. However, the different external dimensions of GRIN lens and optical fiber, increase the package size of probe and make the bonding process relatively complicated and the interface transmission quality unstable. As a matter of fact, ultra-small and highly integrated fiber-optic interferometer cannot be really realized.

Due to ultra-small structural dimensions and superior focusing performance of the ultra-small self-focusing optical fiber probe (Gradient index fiber probe, GRIN fiber probe), an all-fiber optical probe consisting of single-mode fiber, non-core fiber and self-focusing fiber [8,9], can be integrated with the signal arm of fiber-optic interferometer through the fusing process directly, and this type of probes have been favored by scholars in recent years. For example, in the research area of OCT (optical coherence tomography) systems, Mao et al. studied the production of GRIN optical fiber probe and the method to detect light transmission performance [10,11]; Fang et al. studied the feasibility to use OCT systems based on such probe in measurement of lungs, muscle and other biological tissue [12,13]. As far as we know, the measurement systems based on ultra-small GRIN fiber probe are more concentrated in the field of OCT technology, only limited systematic analysis and theoretical study can be found regarding integrated interferometer based on such probe. In the precision industrial measurement, Schmitt [14,15] studied the Fizeau interferometer based on an ultra-small GRIN optical fiber lens and discussed the feasibility to detect micro-bore in the engine nozzle. However, the optical probe is composed of GRIN fiber and single-mode fiber which are welded together, and the working distance is

* Corresponding author at: Science and Technology on Near-surface Detection Laboratory, Wuxi 214035, China.
E-mail address: zwyuan_2015@126.com (J. Zhu).

http://dx.doi.org/10.1016/j.optlaseng.2016.05.012
0143-8166/

relatively small due to the limited mode field diameter of single-mode fiber.

Based on the existing research results of ultra-small GRIN fiber optical probe, this paper develops an integrated fiber-optic interferometer based on the ultra-small GRIN fiber optical probe, establishes its physical model, analyzes its application methods in micro-displacement measurement and builds fiber optical sensing experiment system for micro-displacement measurement. The micro-displacement measurement results show that, under the given experimental conditions, the sensitivity and the linear measurement range of the integrated fiber optical interferometer are 8.8 mv/μm and 10 μm respectively, which demonstrates the characteristics of miniaturization, integration and high precision of the integrated fiber-optic interferometer. In addition, it is of great application potential in the field of detecting microdeep hole and microvibration.

2. Model of integrated fiber-optic interferometer and principle of micro-displacement measurement

Fig. 1 shows the physical model diagram of integrated fiber optical interferometer studied in this paper, in which the signal arm of the interferometer is welded onto an ultra-small GRIN fiber optical probe composed of single-mode fiber, non-core fiber and GRIN fiber lens as shown in Fig. 2 [16,17]. In the model of ultra-small GRIN fiber probe shown in Fig. 2, as a special fiber with uniform index of refraction, the non-core fiber can overcome the problem of small mode field diameter of single-mode fiber through expanding light beams, thus improving the focusing performance of the probe. Due to the flat surface, GRIN fiber lens, which boast the self-focusing performance for the constantly changing index of refraction, can be integrated with other optical element with a flat surface easily by means of fusion welding. This is beneficial to improve the mechanical strength and stability of the probe. Boasting the advantages such as ultra-small size, superior focusing performance and weldability with other components, the ultra-small GRIN fiber probe can be integrated into a traditional fiber-optic interferometer, so as to realize miniaturization and integration of measuring head of the fiber-optic interferometer.

According to the model of all-fiber integrated Michelson interferometer based on the ultra-small GRIN fiber probe shown in Fig. 1, its working principle is: the light beam emitted from laser injects into the optical fiber, passes through the fiber-optic isolator, 3 dB coupler and then is divided into two beams, of which one passes through signal arm and then focuses on the target object by the ultra-small GRIN fiber probe, and the other one passes through the reference arm and is collimated on the reference mirror by the fiber-optic collimator. The two beams reflected back by the target object and the reference mirror respectively pass through the ultra-small GRIN fiber probe and fiber optical collimator again, inject into the signal arm and reference arm respectively. The two reflected beams are combined again at the 3 dB coupler and interfere with each other. The interferometric signal outputted from the output terminal of the 3 dB coupler is received by the photoelectric detector and converted into electrical signal. Finally, the electrical signal is transmitted into the signal collecting and processing unit, and the captured data will be transmitted into the PC to demodulate and analyze the physical quantities to be measured.

According to the model of integrated fiber-optic interferometer shown in Fig. 1, the theoretical basis in micro-displacement measurement will be analyzed in the following part. According to Fig. 1, the light emitted from laser source injects into optical fiber, in which the light field of incident light can be expressed as:

$$E = E_0 e^{i(\omega t - k_0 n l)} \tag{1}$$

where E_0 is the amplitude of light waves, ω the frequency of light waves, k_0 the wave number when light waves propagate in vacuum, n the refractive index of fiber core, l the optical path through the propagation process of light wave. Suppose I_0 is the light intensity injected into the optical fiber, and I is the interferometric light intensity received by the photodetector, the following (Eqs. (2) and 3) can be obtained according to the literature [18]:

$$I_0 = E_0^2 \tag{2}$$

$$I = I_0 \alpha R_f \left[\xi^2 + (1-\xi)^2 + 2\xi(1-\xi)\cos\ \Delta\varphi \right] \tag{3}$$

where ξ is the coupling ratio of the coupler (coupling coefficient), α the same optical attenuation coefficient of the sensing arm and reference arm of the interferometer, and R_f the reflectance product of reference mirror and target object.

Suppose the refractive index of air is 1, the target object and reference mirror are both placed in the air, the distance from the target object to the output end of the fiber probe is l_1, that from the reference mirror to the output end of the fiber-optic collimator is l_2, the length of the signal arm is l_s, and that of the reference arm is l_r, then the phase difference $\Delta\varphi$ can be expressed as:

$$\Delta\varphi = 2k_0 n l_s + 2k_0 l_1 - 2k_0 n l_r - 2k_0 l_2 \tag{4}$$

If the coupling coefficient ξ of the 3 dB coupler is 0.5, then Eq. (3) can be transformed into:

$$I = \frac{I_0 \alpha R_f}{2}(1 + \cos\ \Delta\varphi) \tag{5}$$

Substituting Eq. (4) into Eq. (5), we can get the following form:

$$I = \frac{I_0 \alpha R_f}{2}\{1 + \cos\ [2k_0(l_1 + n l_s - n l_r - l_2)]\} \tag{6}$$

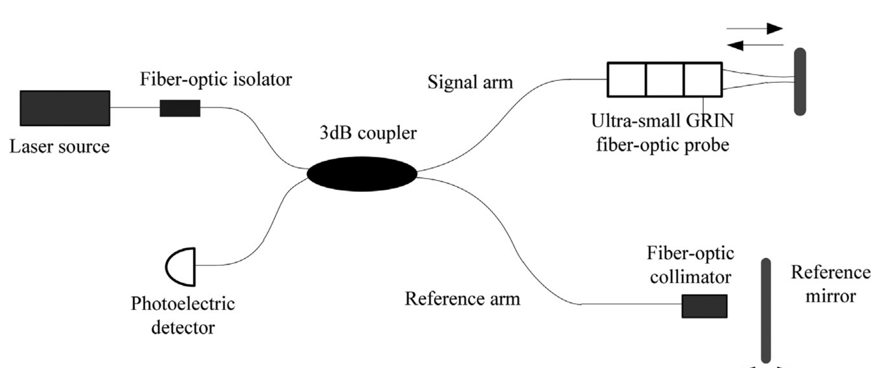

Fig. 1. Model of integrated fiber-optic interferometer.