Sensors and Actuators A 189 (2013) 86–92

Contents lists available at SciVerse ScienceDirect

Sensors and Actuators A: Physical

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

Common-path laser encoder

Chyan-Chyi Wu*, Jhih-Sheng Yang, Chun-Yao Cheng, Yan-Zou Chen

Advanced Photonics Laboratory, Department of Mechanical and Electro-mechanical Engineering, Tamkang University, Taiwan, ROC

ARTICLE INFO

Article history:
Received 21 June 2012
Received in revised form 24 August 2012
Accepted 25 August 2012
Available online 5 September 2012

Keywords:
Common-path
Grating
Displacement
Long-range
Nanometer

ABSTRACT

This study proposes a novel common-path laser encoder (CPLE) capable of effectively minimizing environmental disturbance. The proposed CPLE uses a two-aperture phase-shifting technique to form quadrature signals. Experimental results match well with HP5529A results for long-range measurements. Results also show that the estimated measurement resolution is 0.1 ± 0.046 nm. Therefore, the proposed design has great potential for nanometer resolution and long-range applications.

1. Introduction

Displacement measurements play an important role in the precise positioning systems and equipment of semiconductor and liquid crystal display (LCD) manufacturing. With the rapid advance of nanotechnology, 32 nm node on a 450 mm wafer should be feasible in 2012 [1]. Subnanometer resolution and superior immunity to environmental disturbance are required to facilitate displacement measurements over such a long range. Researchers have developed many displacement measurement techniques over the past few years. Optical interferometry is the most important of the various displacement measurement techniques. Optical interferometers are widely used for the precise measurement of displacement and other physical parameters because they have the capability of a long range and high resolution [2]. However, variations in temperature, pressure, humidity and vibration caused by environmental disturbance reduce measurement accuracy. Consequently, environmental conditions must be strictly controlled to achieve high measurement accuracy. The wavelength of the laser source also affects measurement accuracy [3–5].

Unlike optical interferometers, grating interferometers or laser encoders are not subject to environmental disturbances. These devices have better immunity to the environmental disturbances than optical interferometers because they transfer the measurement scale from the laser wavelength into the grating pitch. Teimel [6] introduced several laser encoders for submicron applications, reaching a measurement resolution of 5 nm. Dobosz [7] demonstrated a laser encoder with a resolution of 10 nm. He also proposed a method to slash the optics nonlinearity of laser encoders. Nevière et al. [8] used two gratings to detect linear displacement, and the laser encoder had a measurement resolution of 80 nm. Lee et al. [9] developed an optical heterodyne laser encoder with a transmissive grating. This laser encoder is robust to environmental disturbances. Wu et al. [10] adopted a laser encoder with a perpendicular optical configuration. This laser encoder has high head-to-scale tolerance and an accuracy of 37.3 nm. Kao et al. [11] presented a laser encoder with Littrow configuration grating. This encoder achieves a maximum measurement error of 53 nm and repeatability within ±20 nm for a 100 μm measurement range. Although these laser encoders achieve nanometric resolution, their optical configurations remain in a non-common path. Lee et al. [12,13] presented a quasi-common optical path laser encoder with a heterodyne laser source. They adopted the configuration of polarization interferometry, and used a half-waveplate to extract the p-polarization light from the s-polarization light before modulating the measured quantity into the laser source. In this design, the p- and s-polarization light traverse side by side, but not along the same path. This device achieves a positioning resolution of 2.3 nm over a 20 mm range. However, no researcher has yet developed a common-path laser encoder. Lee's work would be state of the art for a laser encoder because its configuration is closest to the common-path interferometer. The main problem with a common-path configuration for Lee's laser encoder is how to perform phase shifting in the same optical path, especially after the reference and test beams interfere.

This study presents a CPLE with a simple optical configuration. Because the CPLE is common-path, it possesses high measurement resolution and immunity to environmental disturbances. The CPLE

* Corresponding author at: Department of Mechanical and Electromechanical Engineering, Tamkang University, Tamsui Dist., New Taipei City 25137, Taiwan, ROC.
E-mail addresses: chyanchyi@gmail.com, ccwu@mail.tku.edu.tw (C.-C. Wu).

0924-4247/$ – see front matter © 2012 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.sna.2012.08.034

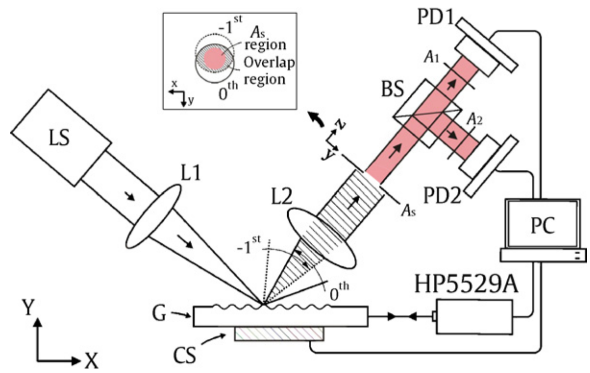

Fig. 1. Optical configuration of the CPLE and experimental setup.

adopts a two-aperture phase-shifting technique to achieve phase shifting after the reference beam interferes with the test beam in the same optical path. This study also presents a detailed description of the CPLE operating principle. Experimental results show that the CPLE has a resolution of 0.1 ± 0.046 nm. These results demonstrate that the CPLE can measure short and long displacement with nanometric resolution.

2. Principle

Fig. 1 shows the optical configuration of the CPLE. A laser source (LS) is focused by lens L1 onto the diffraction grating G and then split into 0th order and −1st order diffraction beams. These two diffracted beams diverge and overlap partly in the adjacent regions. These two divergent beams are collimated by lens L2 and then pass through the aperture stop A_s to extract the overlapping region of the 0th and −1st order diffracted beams (see the inset of Fig. 1). After A_s, these two collimated beams produce typical interference fringe. These two beams subsequently enter the beam splitter BS and pass through apertures A_1 and A_2, respectively. The apertures A_1 and A_2 can assign an additional phase shifting for the interference signals in the CPLE or interferometers with a common path. Finally, photodetectors PD1 and PD2 measure two-beam interference fringes. This section introduces the Doppler frequency shift, which is modulated into the diffracted beams when the diffraction grating G is moving. This section also presents the principle of phase shifting using two apertures and derives the relationship between the phase variation and the grating displacement.

2.1. Doppler frequency shift in focus/divergent beam

The displacement of diffraction grating G modulates a specific Doppler frequency shift $\Delta\omega_m$ into each diffracted beam. This relationship can be written as [10].

$$\Delta\omega_m = \vec{v}_G \cdot (\vec{k}_m - \vec{k}_i), \tag{1}$$

where m is the diffraction order, $\vec{v}_G$ is the velocity of diffraction grating G, $\vec{k}_m$ is the wavevector of the mth diffraction order beam, and $\vec{k}_i$ is the wavevector of the incident beam. In (1), the Doppler frequency shift depends only on the difference of the horizontal projections of the wavevectors between the incident and diffracted beams for a given velocity $\vec{v}_G$ of diffraction grating G. For convenience, consider the in-plane diffraction cases shown in Fig. 2. Because the incident beam focuses onto diffraction grating G, there are separate wavevectors for various parts of the incident beam. Similarly, there are also separate wavevectors for the various parts of the specific diffraction order (divergent) beam. Consider that the focus and divergent beams comprise many finite beams, as Fig. 2 shows. The grating equation must hold for every finite beam pair in the focus or divergent beams. The grating equation, in the momentum conservation form, can be written as follows:

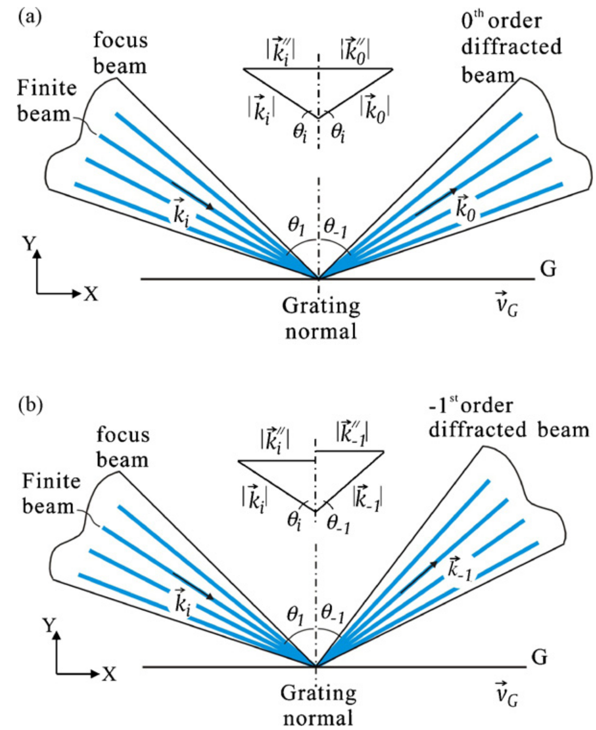

Fig. 2. Finite beam model and schematics of different horizontal projections of wave vectors.

$$\left|\vec{k}''_m\right| - \left|\vec{k}''_i\right| = \frac{2m\pi}{\rho}, \tag{2}$$

where ρ is the grating pitch. Eq. (2) shows that the difference between the horizontal projections of the incident wavevector and diffracted wavevector is equal to the corresponding grating momentum, $2m\pi/\rho$. Eq. (2) also holds for the linear grating diffraction in three dimensions. Combining (1) and (2), the Doppler frequency shift can be rewritten as follows:

$$\Delta\omega_m = \mathrm{sign}(\vec{v}_G)\frac{2m\pi}{\rho}|\vec{v}_G|, \tag{3}$$

where the sign function, $\mathrm{sign}(\vec{v}_G)$, is equal to +1 when $\vec{v}_G$ is along +X, and $\mathrm{sign}(\vec{v}_G)$ is equal to −1 when $\vec{v}_G$ is along −X. Eq. (3) shows that every finite beam pair has the same Doppler frequency shift for a specific diffraction order, irrespective of whether the beam is focused or divergent.

2.2. Interference condition for diffracted beams

The proposed CPLE uses the divergent 0th and −1st order diffracted beams to interfere with each other. However, a certain condition must be met to successfully obtain the interference fringe. Consider the schematic of the overlap region of the 0th and −1st diffracted beams (Fig. 3). The grating equation reads [14]

$$\sin\theta_d = \sin\theta_i + \frac{m\lambda}{\rho}, \tag{4}$$

where θ_d is the diffraction angle of the mth order diffracted beam, θ_i is the incident angle of the laser beam, m is the diffraction order, ρ is the grating pitch, and λ is the wavelength of the laser source. Eq. (4) identifies the key diffracted angle of each marginal ray of the focusing laser beam; that is, θ_ℓ^0 and θ_u^{-1}. Fig. 3 shows that θ_u^{-1} must be greater than θ_ℓ^0 to achieve a proper overlap region between the 0th