Nonlinearity in a fiber-optic coupled heterodyne interferometer

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Abstract

A high-accuracy (nonlinearity < 2nm) fiber-optic coupled displacement heterodyne measuring Michelson interferometer is developed. The primary limitation of accuracy encountered with this fiber-optic coupled heterodyne interferometer is the optical mixing arising from the imperfection of fiber-optic coupling system. The optical mixing results in the nonlinearity (first order and second order errors) in the displacement measurement of the interferometer. A theoretical model using Jones calculus is developed; the corresponding experiments are implemented. The theoretical results are consistent with the experimental results.

Keywords: Fiber-optic coupled interferometer; Distance measuring interferometer; Polarization-maintaining fiber; Nonlinearity;

1. Introduction

A lightweight and electrically passive interferometer is demanded by a number of applications for precision metrology such as machine tool metrology and on-machine feedback [1]. To satisfy these requirements, a fiber-optic coupled heterodyne displacement measuring Michelson interferometer [2] shown in Fig.1 is developed. In this interferometer, the laser light is coupled into the interferometer with a polarization-maintaining (PM) fiber to separate the application environment of the interferometer from the laser head.

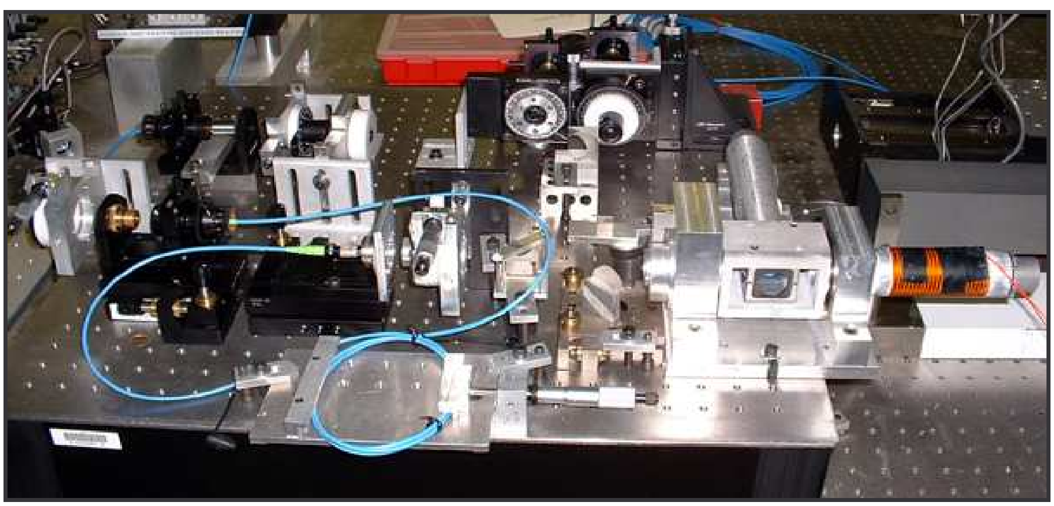

Figure 1 Fiber-Optic Coupled Displacement measuring Interferometer

2. Theory

Jones calculus [3] is used to build the theoretical model of the fiber-optic coupled interferometer. An optical fiber has a number of birefringent properties simultaneously. As the matrices do not commute, the Jones matrix representing birefringences of the fiber is not the simple product of individual birefringence matrices. To solve this problem, the differential matrices (N matrices) [4] can be used for the optical fibers. Typically, the PM fiber is subjected to bending, twisting, or combination of these two external behaviors. The bending produces a linear birefringence in the fiber, and the twisting induces a rotary birefringence. These birefringent properties reduce the polarization-maintaining ability of the fiber.

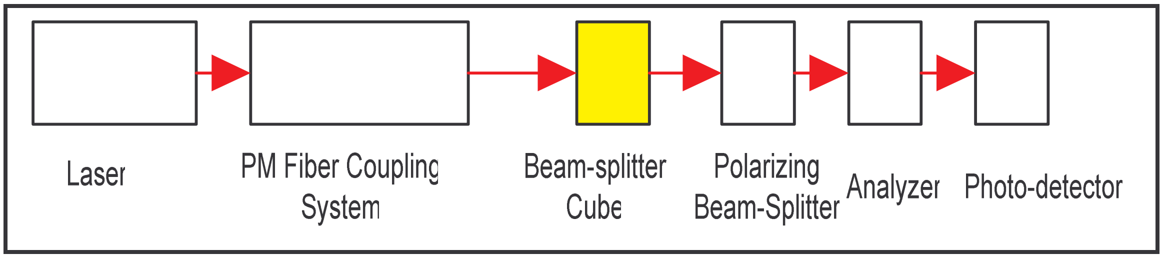

Figure 2 Block Diagram of Fiber-Optic Coupled Interferometer

The configuration of interferometer system is shown in Fig.2. The laser light transmits through the fiber-optic coupling system, a non-polarizing beam-splitter, a polarizing beam-splitter, and an analyzer in turn. The primary source of the optical mixing is fiber-optic coupling system. The fiber-optic coupling system can be represented by the following matrix [5]

$$M_{fiber-optic} = \begin{bmatrix} p & q \\ -\overline{q} & \overline{p} \end{bmatrix} \quad (1)$$

where p, q are in general complex.

The Jones matrix M_{system} of the fiber-optic coupled interferometer can be calculated from the following equation

$$M_{system} = M_{analyzer} M_{BS} M_{mirror} \left[\left(M_{PBS\parallel} M_{flip} M_{\phi_1} M_{PBS\parallel} + M_{PBS\perp} M_{flip} M_{\phi_2} M_{PBS\perp} \right) M_{fiber-optic} \right] \quad (2)$$

where $M_{analyzer}$ is the matrix of the analyzer, and M_{BS} is the matrix of non-polarizing beam-splitter, and M_{mirror} is the matrix of the turning mirror, and $M_{PBS\parallel}$ is the matrix of the polarizing beam-splitter for transmitted beam, and $M_{PBS\perp}$ is the matrix of the polarizing beam-splitter for reflected beam, and M_{flip} is transformation between the coordinate systems of the incident beam and the reflected beam, and M_{ϕ_1} is the matrix of the phase change of the light in the measurement arm, and M_{ϕ_2} is the matrix of the phase change of the light in the reference arm. According to equation (2), the first order error Γ_1 and the second order error Γ_2 can be expressed as follows

$$\Gamma_1 = \frac{K_1}{K_0} = \left(\alpha_{12}^2 + \overline{\alpha_{21}}^2 \right) - \frac{r}{\overline{r}} z^2 \left(\overline{\alpha_{12}}^2 + \alpha_{21}^2 \right) - \frac{z}{\overline{r}} \cdot c\tan(2\theta) \left(1 + |r|^2 \right) - \frac{z}{\overline{r}} \frac{1 - |r|^2}{\sin(2\theta)} \quad (3)$$

$$\Gamma_2 = \frac{K_2}{K_0} = \alpha_{12}^2 \overline{\alpha_{21}}^2 - \frac{r}{\overline{r}} z + \frac{z}{\overline{r}\sin(2\theta)} \left[\left(\alpha_{12}^2 - \overline{\alpha_{21}}^2 |r|^2 \right) - \cos(2\theta) \left(\alpha_{12}^2 + \overline{\alpha_{21}}^2 |r|^2 \right) \right]^2 \quad (4)$$

where the optical mixing term $z = \overline{q} / p$. $\alpha_{12}^2, \alpha_{21}^2$ are the leakage of the polarizing beam-splitter, and θ is the analyzer angle, and r is the transmission ratio of the non-polarizing beam-splitter. The equation (3) and (4) clearly show the nonlinearity is a function of the optical mixing z, the polarizing beam-splitter's leakage and the analyzer angle θ. The optical mixing z primarily arises from the misalignment of the half-wave plates, the bending of the PM fiber in the fiber-optic coupling system.

3. Theoretical Results and Experimental Results

The theoretical results of nonlinearity vs. fiber bending change using equation (3) and (4) are show in Fig.3. The bending change refers to the length change of the minor axis of the fiber coil. Both the first harmonic error and the second harmonic error oscillate with the bending change. The experimental results shown in Fig.4 are consistent with theoretical results.

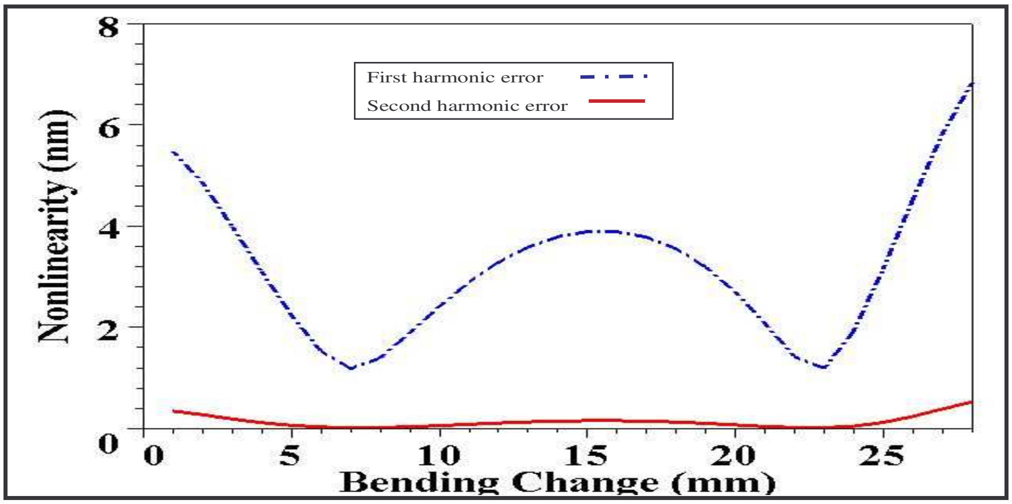

Figure 3 Theoretical Result of Nonlinearity vs. Fiber Bending Change

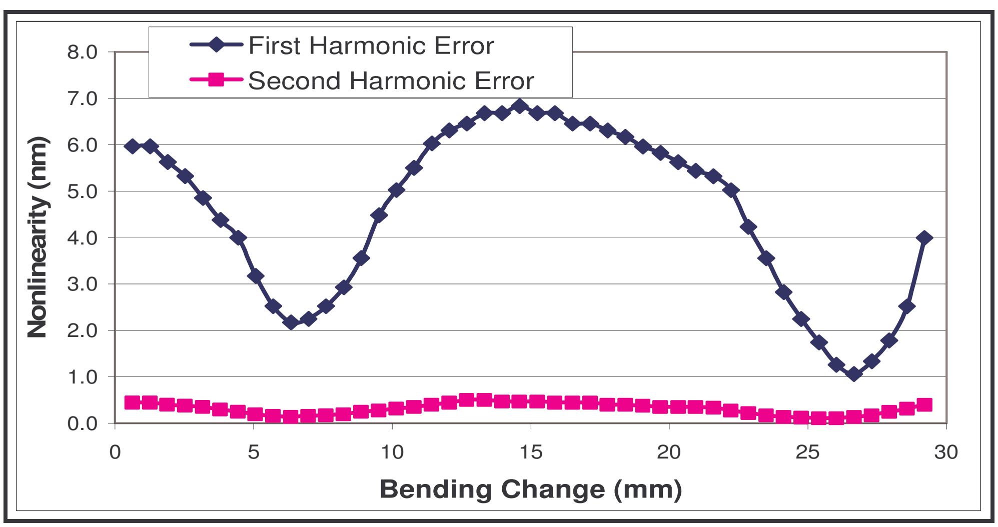

Figure 4 Experimental Results of Nonlinearity vs. Bending Change

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