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The measurement of the diameter change of a piezoelectric transducer cylinder with the white-light interferometry

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ABSTRACT

The measurement of the diameter change of a piezoelectric transducer (PZT) cylinder with the white-light interferometry is proposed and experimentally demonstrated. One arm of a Mach–Zehnder interferometer (MZI) is wrapped on the PZT cylinder, and the phase change of the interferogram of the MZI is used to determine the diameter change when a DC voltage is applied on the PZT cylinder. The Fourier transform white-light interferometry is used for recovering the phase change of the interferometer. The experimental results show that the diameter change resolution of 0.8 nm for the PZT cylinder with diameter of 40 mm is achieved.

1. Introduction

Piezoelectric materials have a natural property which is the ability of interaction between the electrical and mechanical states. They have attracted much attention due to their wide applications in sensing and actuating systems. Diverse styles of piezoelectric transducers have been developed with different structures such plate type, rod type, ring type, and cylinder type.

Piezoelectric cylinders are simple in construction than flat types and can easily deflect in all directions. They offer flexibility to operate under harsh condition such as high vacuum and high temperature. They are used in a wide range of applications such as atomic force microscopy (AFM) [1,2], scanning tunneling microscopes (STM) [3,4], optical fiber switch [5,6], optical fiber modulators [7], voltage sensors [8], Gyroscope [9], ultrasonic applications [10] and in ink jet printers [11].

Different methods are available for measuring piezoelectric transducer (PZT) coefficients: direct measurements of stress-induced charge [12], laser interferometers [13], laser scanning vibrometers [14], and piezoelectric force microscopes, etc. [15]. Laser interferometry methods are based on measuring the displacement deflection of the sample after an applied voltage. They have been established as popular and reliable technique for the measurement of piezoelectric coefficients d_{31} and d_{33} [16]. The displacement can be measured by a single-beam laser interferometer [17], where a Michelson interferometer is used .The reference arm length of the interferometer will change due to the piezoelectric deflection. This configuration has difficulty in separating the movement of the substrate from the dilatation of the sample. Double-beam interferometer was used to suppress the influence of the substrate movement [18,19]. To improve the measurement reliability and accuracy, other methods were proposed, such as scanning-modulated interferometer [20], and a Mach–Zehnder type heterodyne interferometer [21]. The crucial condition in these methods is the high resolution of an interferometer, which should be in the range of nanometer units [22]. Since the expansion of the PZT is small, the measurement is very sensitive to any small vibrations. Hence these techniques usually require a very quiet operation environment [23].

The white-light interferometry (WLI) is an attractive technique that is used for absolute measurements [24] and the measurement of the shape of objects [25], it allows the increase in the system operating range to overcome the fundamental problem that arises in conventional laser interferometry [26], and high resolution and dynamic range may be achieved [27].

In this paper, we present a technique for the PZT cylinder measurement by using the WLI. A PZT cylinder is wrapped by an arm of a MZI. We obtain the white-light interferogram when a DC voltage is applied between the faces of a PZT. The Fourier transform WLI is used for recovering the optical path difference (OPD) of the MZI [28]. Experimental measurements for diameter changes of a PZT cylinder at different driving voltages have been carried out, and experimental results show that the technique possesses high accuracy and high reliability.

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2. Operation principle

The experimental setup for measuring the diameter change of the PZT cylinder is shown in Fig. 1. The light source is an amplified spontaneous emission (ASE) source with the wavelengths covering 1525–1565 nm, and the output power of 20 mW. Two fiber optic 3 dB couplers are used for splitting and recombining the light. The broad-band ASE light is divided into two equal power signals through the first coupler, one goes to the reference arm, and another one goes to the sensing arm. The reference light and the sensing light recombine at the second coupler.

The sensing arm is circled on a PZT cylinder P-81 (from Heng Sheng Acoustics Electron Apparatus Company) with the size of $\phi 40 \times \phi 35 \times 30$ mm for outside diameter, inner diameter and height, respectively. A photograph of the PZT is shown in Fig. 2. A regulated DC source (NY1303A) is used with a voltage range of 0–30 V and a voltage resolution of 1% to drive the PZT cylinder.

The output of the MZI is interrogated by using a CCD based optical spectrum analyzer (OSA) (BaySpec FBGA-F-1525-1565) with the resolution of 0.1 nm. The OPD of the MZI must be smaller than the coherence length determined by the resolution of the OSA, otherwise we cannot detect the interferogram. The resolution of 0.1 nm respects to a coherence length of 24 mm at the wavelength of 1.55 μm. Thus the length different of the MZI between two arms must be shorter than 16.4 mm.

In the experiment, a DC voltage is applied between the faces of a PZT cylinder. By using the Fourier transform white light interferometry [28], the OPD of the MZI can be calculated. The recovery of the OPD starts from the measurement of the phase angle ϕ. ϕ is given by [29]

$$\phi = \frac{2\pi}{\lambda} \cdot OPD = \frac{2\pi}{\lambda} \cdot n \cdot L \tag{1}$$

where n is the refractive index of the fiber, and L is the difference in path length between the two beams of the interferometer.

The OPD can be calculated when the phase is obtained by using Fourier transform WLI. However, when we scan the wavelength from λ_1 to λ_2, we obtain a phase change. So the OPD is obtained from the following equation:

$$OPD = \frac{(\lambda_1 \cdot \lambda_2)}{2\pi \cdot (\lambda_2 - \lambda_1)} \cdot \Delta\phi \tag{2}$$

Thus, the diameter change of the PZT can be calculated from the following equation:

$$\Delta D = \frac{\Delta OPD}{\pi \cdot k} \tag{3}$$

where ΔOPD is the change of the OPD due to an applied voltage, k is the number of fiber turns wrapped the PZT.

Therefore, the strain coefficient d_{31} can be estimated by the following equation [30]:

$$d_{31} = \frac{\Delta D \cdot t}{ID \cdot V} \tag{4}$$

where ΔD is the diameter change of the PZT, ID is the internal cylinder diameter, V is the applied voltage, and t is the wall thickness.

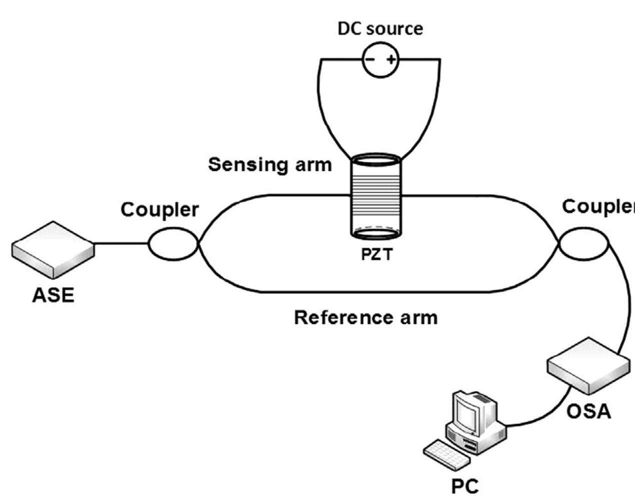

Fig. 1. Schematic diagram of the experimental setup.

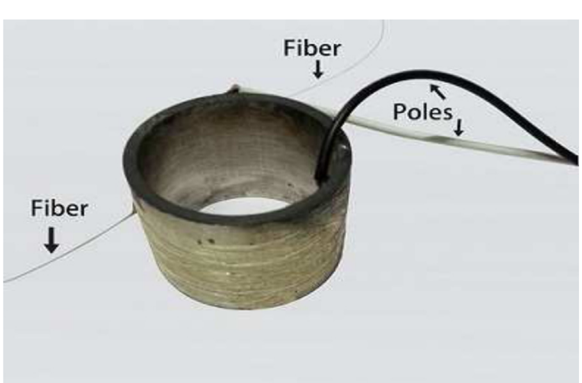

Fig. 2. Photograph of the piezoelectric transducer cylinder.

3. Experiment

In this experiment, the core and cladding diameters of the fiber are 9 μm and 125 μm respectively, and a fiber length of 9 m was used as one arm of the MZI. The PZT cylinder (P-81) with strain coefficient $d_{31} = 98$ pm/V and an external diameter of 40 mm was wrapped by 5 m of fiber and the number of fiber turns is 40 turns. In order to protect the measured sample against vibrations, a quiet operational environment is needed.

When the wavelength is scanned from 1525 nm to 1560 nm, the interference spectrum can be observed at the OSA by adjusting the OPD to be smaller than the coherence length determined by the resolution of the OSA. The optical spectrum of the MZI with an applied voltage of 0 V is shown in Fig. 3.

When the voltage is applied on the PZT cylinder, the interference fringes suffer a phase shift. It can be seen that the optical spectrum is red-shifted to a higher wavelength region, as shown in Fig. 4.

The OPD can be calculated by using Fourier transform WLI. Firstly the optical spectrum is Fourier transformed. The main frequency component is filtered and inverse Fourier transformed. Then we calculate a complex logarithm of the product. The phase

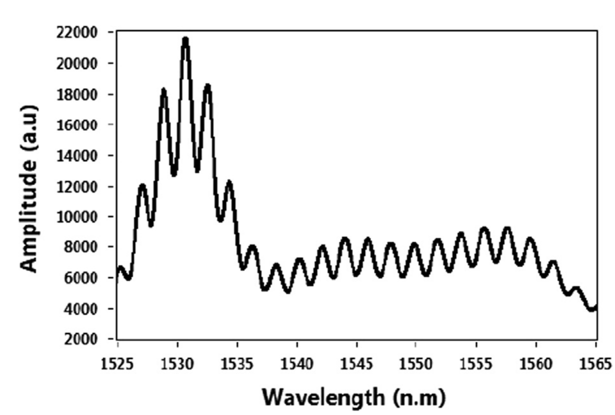

Fig. 3. The optical spectrum at 0 V.