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New Non-contact Measurement of Small Inside-diameter Using Tandem Low-coherence Interferometer and Optical Fiber Devices

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Abstract. Recently, manufacturing techniques of small-scale products have been improved. As a result, precise measurement is required of small inside diameters, for example, of engine nozzles. However, an in situ measurement and measurement system for small-sized products has yet to be fully established. In this research, a contactless technique to measure small inside diameters is proposed. This new method uses tandem low-coherence interferometry and an optical fiber cut at an angle of 45°. This optical fiber is up to 30 µm in diameter and is used as a probe. Our objective is to measure holes as small as 50-µm inside diameter with an accuracy of 100 nm. In the present paper, we report on the measurement principle, calculate the measurement uncertainty and show that experimental measurements can be obtained of small-size holes up to 300-µm inside diameter with an accuracy of 100 nm.

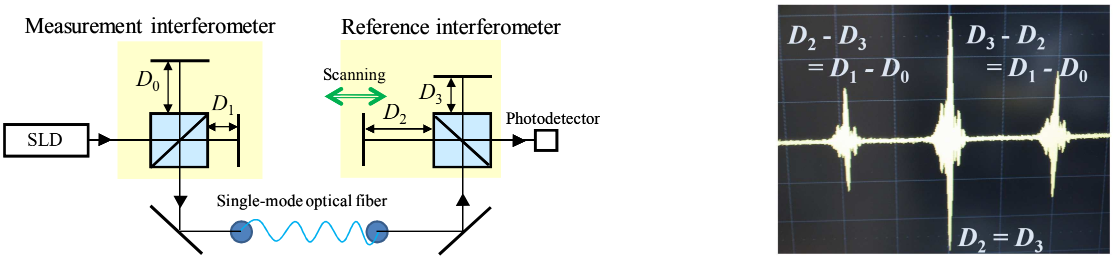
1. Introduction

Recent improvement of manufacturing techniques of small-scale products has meant that precise accessories with small inside diameters can now be manufactured, for example, engine nozzles and needles. However, an in situ measurement system for small-sized products has yet to be fully established. A touch sensor is able to provide accurate measurements, but has the problem that it may damage the measurement object [1]. The majority of other precise measurement systems have resolution problems. Therefore, those systems cannot be taken into factories because measurements may be influenced by environmental conditions, such as wind or vibration [2].

As a result, we propose a new method that uses tandem low-coherence interferometry and an optical fiber cut at an angle of 45°. Tandem low-coherence interferometry with a single-mode optical fiber is useful for remote measurement of length [3]. Moreover, by using a 45°-cut optical fiber as an interferometer, non-contact measurement is possible.

2. Measurement Principle

2.1 Principle of Tandem Low-coherence Interferometry



(a) Tandem interferometers (b) Three interference fringes

Figure 1. Principle of tandem low-coherence interferometer

As shown in Fig. 1(a), tandem low-coherence interferometry employs a measurement interferometer and a reference interferometer connected by single-mode optical fiber. An interference fringe is generated only when the optical path lengths are the same. Hence, if D_2 changes during scanning, interference fringes are generated when $(D_2 - D_3 = D_1 - D_0)$, $(D_3 - D_2 = D_1 - D_0)$ and $(D_2 = D_3)$, as shown in Fig. 1(b). A super luminescent diode (SLD) is useful as a light source for tandem low-coherence interferometry [4].

2.2 45°-Cut Optical Fiber

We connect one tip of a single-mode optical fiber to a fiber-optic connector/physical contact (FC/PC) connector and cut the other tip at an angle of 45°. Upon reaching the cut tip, the light is totally reflected in the radial direction normal to the tip length (Fig. 2). We propose to use this fiber as a measurement interferometer.

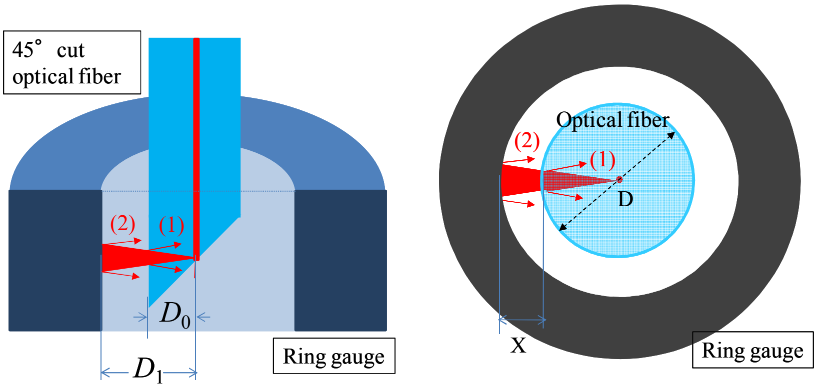


Figure 2. 45°-cut optical fiber for measurement interferometer

When the 45°-cut tip is inserted into a ring gauge, the totally reflected light is divided into two optical paths, (1) and (2). (1) is the optical path due to light being reflected from the inside wall of the fiber. (2) is the optical path due to light being reflected from the inside wall of the ring gauge. An optical path difference of $2(D_1 - D_0)$ is generated here.

2.3 Measurement System

Figure 3 shows a schematic of the measurement system.

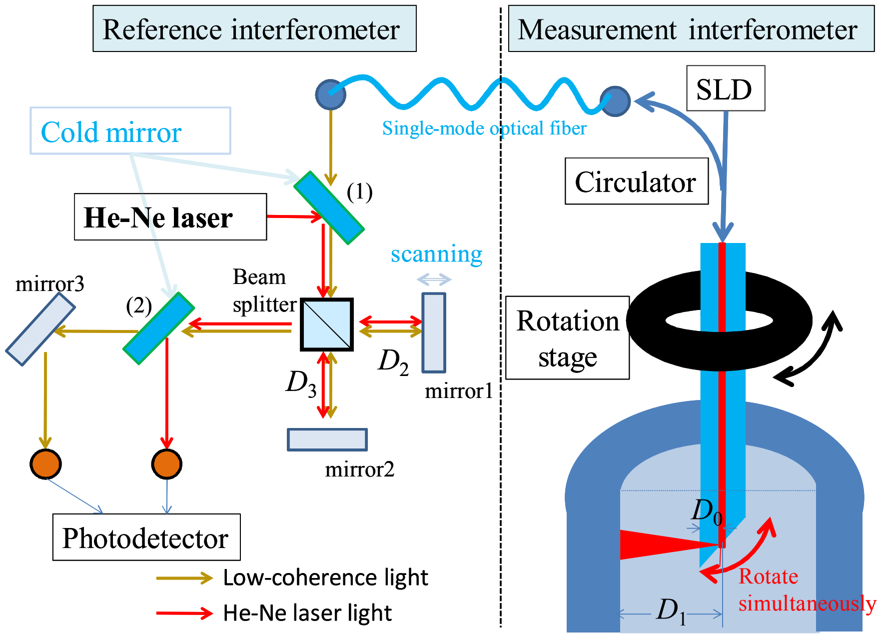


Figure 3. Schematic of measurement system

First, light from the SLD light source is transmitted along the optical fiber of the measurement interferometer to the 45°-cut tip, and an optical path difference of $2(D_1 - D_0)$ is generated. Maintaining this phase shift, the light is transmitted to the reference interferometer through the circulator and single-mode optical fiber. The low-coherence light passes through a cold mirror, is divided by a beam splitter and sent toward mirror1 and mirror2. The reflected beams are then combined and induce an interference fringe when the lengths of the optical paths are equal.

The red line in Fig. 3 shows the path of a helium-neon (He-Ne) laser beam. The He-Ne laser beam follows part of the same optical path as the SLD light so that the standard of length is realized. Figure 4 shows an example of this mechanism in practice.

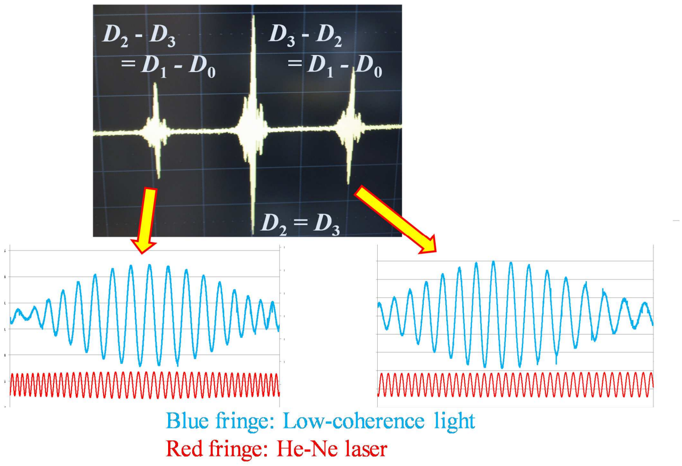
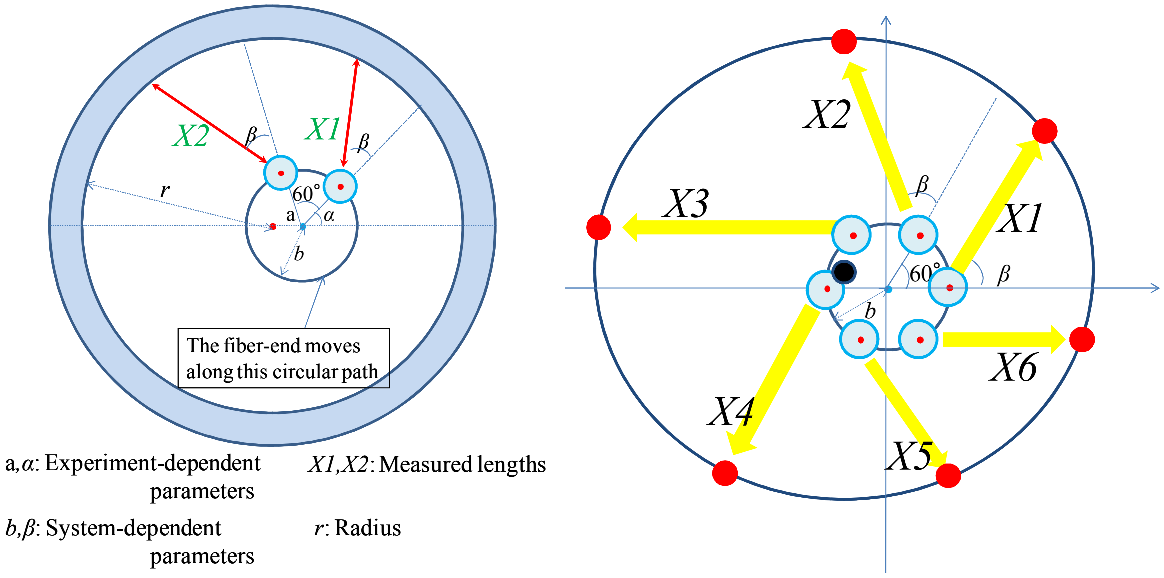


Figure 4. Interference fringes of low-coherence light and He-Ne laser light

First, we determine the non-central peaks of the low-coherence fringe by using an approximation curve. We do not utilize the central peak ($D_2 = D_3$) of the fringe, because this peak is easily influenced by noise. Second, the He-Ne laser interferometer measures and records the position of these non-central peaks. The wavelength of a He-Ne laser is highly stable at around 632.82 nm. Third, we calculate the distance ($D_1 - D_0$) from the recorded positions by using measurement software.

2.4 Optical Fiber Rotation

To measure distances in different directions, we do not adjust the centers of the optical fiber and measurement object, but instead rotate the optical fiber.



(a) Four measurement parameters (b) Coordinate system for calculating inside diameter

Figure 5. Inside-diameter calculation

As shown in Fig. 5(a), fiber rotation measurements are dependent on four parameters. To perform measurements, firstly, we measure lengths *X1* to *X6* for a ring gauge of known (500 μm) inside diameter by axially rotating the optical fiber tip through 360° at 60° intervals. Secondly, from these measured lengths, we can estimate parameters b and β by using the exterior penalty function method. Thirdly, we measure new lengths *X1* to *X6* of the objective hole (Fig. 5(b)). Finally, as shown in Fig. 5(b), we calculate the coordinates of the six reflection points (red points) from the lengths and estimated parameters, and we can calculate the position of center of the hole (black point) and, thus, the inside diameter by the least-squares method.

Note that we calculate the inside diameter by this method on the assumption that the objective hole is a perfect circle.

3. Measurement Uncertainty

In performing measurements, errors can potentially arise from 11 origins (Table 1), such as errors in determining the peak positions of the low-coherence interferometer fringes, rotation angle errors, uncertainties in the beam diameter and calibration errors from measuring the 500-μm ring gauge. We estimated the magnitude of each of these errors theoretically and experimentally.

Table 1. Overall error

Origin of uncertainty/error	**Measurement uncertainty**
He-Ne laser wavelength	2.2 [nm]
Peak positions of interferometer fringes	17.3 [nm]
Scanning stage speed	0.5 [nm]
Alignment	0.04 [nm]
Environmental conditions	11.1 [nm]
Rotation angles	19.5 [nm]
Inclination of fiber device	1.3 [nm]
Beam diameter	18.4 [nm]
Calibration using 500 μm ring gauge	**28.9 [nm]**
Fiber diameter	2.5 [nm]
Simulation	0.002 [nm]
Combined standard measurement uncertainty	44.6 [nm]
Expanded measurement uncertainty ($k = 2$)	89.1 [nm]

Table 1 lists the origins of all uncertainties/errors, the values found for each of these, the combined standard measurement uncertainty and the expanded measurement uncertainty (with coverage factor $k = 2$). Calibration of the system using a 500-μm ring gauge as a reference standard is found to produce the largest error at around 29 nm (bold font in Table 1). The expanded measurement uncertainty ($k = 2$) was determined to be 89 nm and corresponded to simulation results.

4. Experiments

Figure 6 is a photograph of the reference and measurement interferometers. They are connected by a single-mode optical fiber.

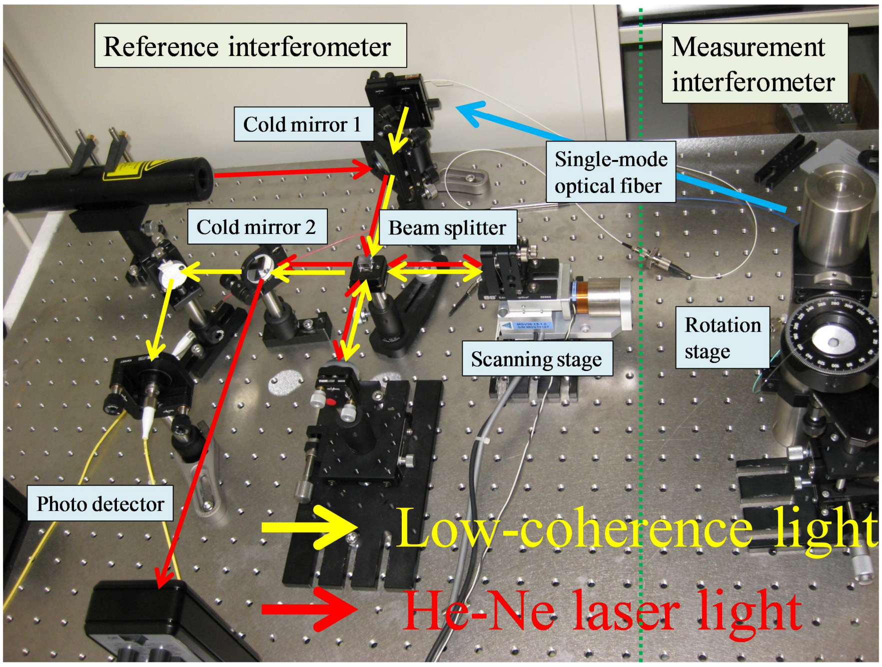


Figure 6. Measurement system

Table 2. Measured length *Xi* (*i* = 1,…, 6) in each direction

Xi	Measured length Xi
X1	234.939 [μm]
X2	173.472 [μm]
X3	167.879 [μm]
X4	234.330 [μm]
X5	323.136 [μm]
X6	316.713 [μm]

(a)

Xi	Measured length Xi
X1	200.886 [μm]
X2	173.058 [μm]
X3	205.326 [μm]
X4	287.485 [μm]
X5	323.728 [μm]
X6	270.596 [μm]

(b)

Xi	Measured length Xi
X1	465.094 [μm]
X2	520.387 [μm]
X3	558.118 [μm]
X4	535.614 [μm]
X5	479.869 [μm]
X6	447.064 [μm]

(c)

Xi	Measured length Xi
X1	122.277 [μm]
X2	120.609 [μm]
X3	146.628 [μm]
X4	176.344 [μm]
X5	174.238 [μm]
X6	146.455 [μm]

(d)

To determine the values of b and β, we measured the 500-μm ring gauge twice (Tables 2(a) and (b)). By the exterior penalty function method, we determined that b = 71.82 μm and β = 129.79° for both calibrations.

Table 2(c) lists the measurement results of a nominal size 1-mm ring gauge with a calibrated size of 999.5 μm. We rotated the 45°-cut optical fiber in the ring gauge and measured the lengths *Xi* (*i* = 1,…, 6) in each direction. From these data and the estimated parameter values, we calculated an inside diameter of 999.423 μm. This result differs by only 77 nm from the calibrated size and corresponds to expanded measurement uncertainty (k = 2) in Table 1.

Table 2(d) lists the results of a hole with 307.4 μm (as measured by an electron microscope) inside diameter. Figure 7 shows a schematic of the proposed calculation method to find the inside diameter.

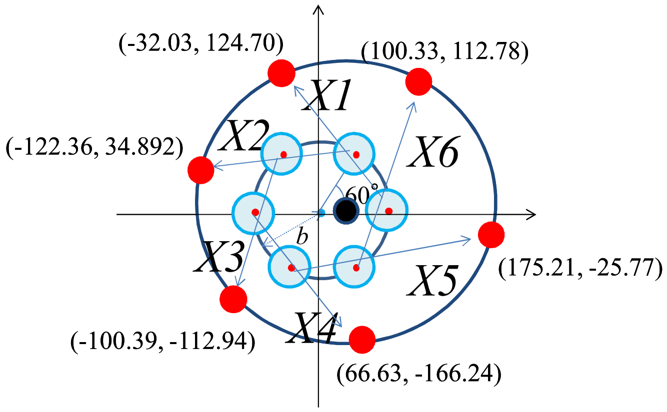


Figure 7. Calculation of 307.4 μm hole

When rotating the optical fiber, the 45°-cut tip traced a circle of radius 71.82 μm. From the measured data (*X1*,…, *X6*), the reflection positions were calculated as the six red points in Fig. 7. The inside diameter was thus estimated to be 307.48 μm by the least-squares method. This result differs by only 81 nm from the value determined with a microscope and once more corresponds to the expanded measurement uncertainty ($k = 2$) in Table 1.

5. Conclusion

5.1 Conclusion

We have developed a new technique of non-contact measurement of small inside diameters by using tandem low-coherence interferometry and a 45°-cut optical fiber. We theoretically estimated an expanded measurement uncertainty of within 89 nm. Furthermore, we have succeeded in experimentally measuring the inside diameter of a 300-μm hole with an error of less than 89 nm.

5.2 Future Work

Our objective is to measure holes as small as 50-μm with an accuracy of 100 nm. To fulfill this requirement, we will attempt to use the 30-μm diameter optical fiber more efficiently and to decrease the value of parameter *b* by improving the rotation stage.

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