NON-CONTACT REMOTE MEASUREMENTS OF RING GAUGE USING A LOW-COHERENCE INTERFEROMETER

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Abstract:
In order to measure important ring gauges without contact, we have developed a new measurement system of low-coherence tandem interferometer. The measuring system consists of a measurement interferometer and a reference interferometer. The two interferometers are installed at separated locations and are connected by a single-mode optical fiber. Low-coherent super luminescent diode (SLD) is a common light source of the system.

A ring gauge settled in the measurement interferometer is aligned perpendicularly to the beam of the SLD. The beam splitter is settled at the center of the ring gauge. One beam is transmitted the beam splitter, the other beam is reflected by the beam splitter, then reflected by the inner surfaces of the ring gauge, reflected by the beam splitter again, and combined with the transmitted beam. The combined SLD-beam from the measurement interferometer is induced to the reference interferometer through the single-mode optical fiber while keeping the optical path difference corresponding to the diameter of the ring gauge. In the reference interferometer, a corner reflector is mounted on a high-precision linear slide stage. Scanning the corner reflector generates the interference fringes corresponding to the diameter of ring gauge. A length-measuring He-Ne laser interferometer, which has common optical paths with the low-coherence Michelson interferometer, measures the position of the corner reflector. The experimental results show the reproducibility of 0.05 µm for 20 mm, 0.13 µm for 50 mm, 0.15 µm for 63 mm and 0.06 µm for 100 mm.

Keywords: Ring gauge, Non-contact measurement, Low-coherence interferometer, Remote calibration, Optical fiber

1. INTRODUTION

Measuring uncertainty on calibration of a ring gauge with conventional contact probes includes effects of several factors such as bending of the probe with contact force, geometrical error of stylus tip and "Abbe" errors. An optical interferometeric measurement system without contact technique and following "Abbe" principle can eliminate those errors. In order to measure important ring gauges without contact, we have developed a new measurement system of low-coherence tandem interferometer that has a single-mode optical fiber useful for remote calibration of length.

Remote measurement of light of gauge block from 47 km away was demonstrated [1] with low-coherence tandem interferometer, and the foresight that can be measured with the uncertainty of 50 nm was obtained [2].

2. LOW-COHERENCE TANDEM INTERFEROMETER FOR RING GAUGE

2.1 Principle of Low-coherence Interferometer

Figure 1 shows the principle of low-coherence interferometer. Low-coherent beam from the light source is incident to a beam splitter, then one beam is transmitted to a scanning mirror, the other beam is reflected by the beam splitter to a fixed mirror. These beams are reflected at the mirrors respectively, combined, and incident on a photo detector. Scanning the mirror generates the interference fringes only when D_1 equals to the distance D_0. This principle, which has been well known already, is applied to the new non-contact remote measurements system of ring gauge.

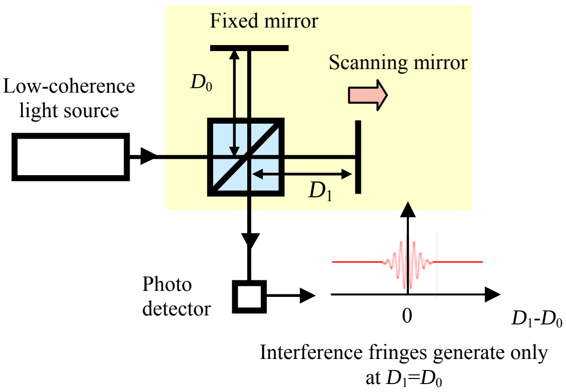
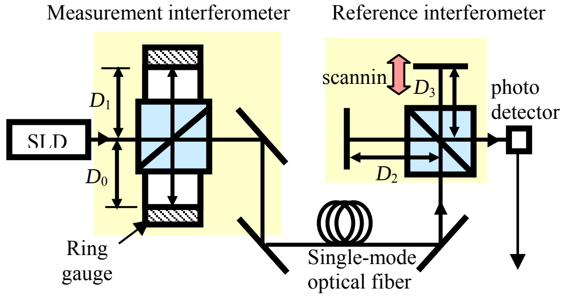


Figure 1. Principle of low-coherence interferometer

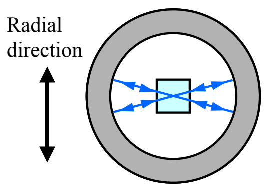
2.2 Low-coherence Tandem Interferometer for Ring Gauge Measurements

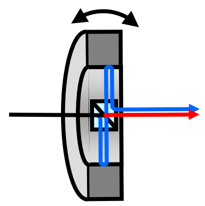
As shown in Fig.2(a), the low-coherence tandem interferometer consists of a measurement interferometer and a reference interferometer. The two interferometers are installed at separated locations and are connected by a single-mode optical fiber. Low-coherent super luminescent diode (SLD) is a common light source of the system.

The optical path difference $2(D_0+D_1)$ is generated between the transmitted and reflected beams in the measurement interferometer. The transmitted and reflected SLD light beams are combined and induced to the reference interferometer through the optical fiber while keeping the difference $2(D_0+D_1)$. The interference fringes are generated only when $2(D_0+D_1)$ equals to the distance $2|D_2-D_3|$ and $D_2-D_3=0$ as the same principle of Fig.1.

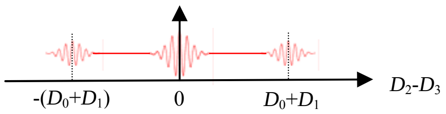


(a) Outline of tandem interferometer

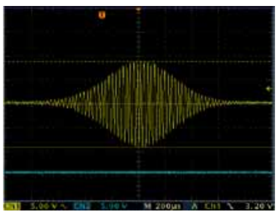




(b) Ring gauge top view (c) Ring gauge side profile view



(d) Relation of interference fringes generation to D_2-D_3



(e) Image of interference fringe

Figure 2. Low-coherence tandem interferometer

Figure 3 is a picture of measurement interferometer for ring gauge. The SLD light is collimated into a beam of 2.9 mm diameter.

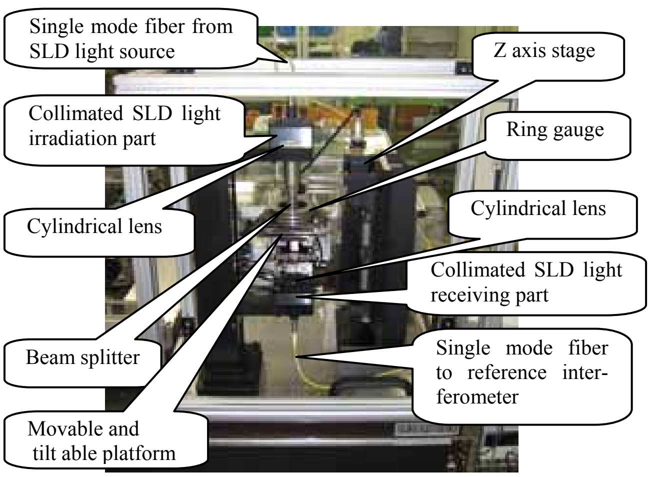


Figure 3. Measurement interferometer

As shown in Fig. 2 (b), the collimated low-coherence light is focused at the center of beam splitter in radial direction of ring gauge by the cylindrical lens while the height direction of the ring gauge is kept parallel 2.9 mm. The position in radius direction and the inclination of the ring gauge on the movable and tilt able platform is adjusted to find the maximum signal amplitude of interference fringes. The maximum signal amplitude position in radial direction is the center of ring gauge and the inclination is the perpendicular to the inner surfaces of the ring gauge. One beam is transmitted the beam splitter, the other beam is reflected by the beam splitter, then reflected by the inner surfaces of the ring gauge, reflected by the beam splitter again, and combined with the transmitted beam as shown in Fig.2 (c). The combined SLD-beam from measurement interferometer is induced to reference interferometer through the single-mode optical fiber while keeping the optical path difference corresponding to the diameter of the ring gauge.

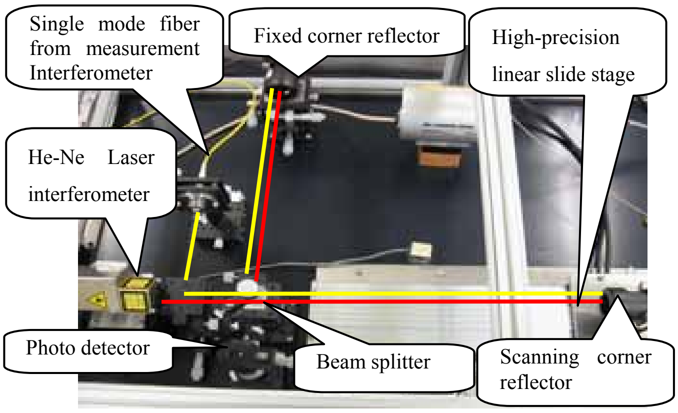


Figure 4. Reference interferometer (common optical paths)

Figure 4 is a picture of the reference interferometer to detect the fringe corresponding to the ring gauge diameter. Red line shows the He-Ne laser light path and yellow line shows the low-coherence light path.

The scanning corner reflector of reference interferometer is mounted on the high-precision linear slide stage. The interference fringes are generated as the image of Fig.2 (e) at $D_2-D_3=0$ and $|D_0+D_1| = |D_2-D_3|$ positions as shown in Fig.2 (d). A length-measuring He-Ne laser interferometer, which has common optical paths with those of the low-coherence Michelson interferometer, measures the position of the corner reflector.

A trigger pulse for the He-Ne interferometer is generated at the low-coherence interference fringe peak point by an electronic circuit as shown in Fig.5. Interference fringes are rectified by absolute circuit as Fig.5 (b) to make envelope line through low-pass filter as Fig.5 (c). The trigger pulse is generated at the intersection point with envelope signal and differentiated circuit signal as Fig.5 (d) and Fig.5 (e). He-Ne laser interferometer measures and memorizes the each position of $D_2-D_3=0$ and $|D_0+D_1| = |D_2-D_3|$ with the generated trigger pulse through the circuit. Ring gauge diameter is calculated with memorized positions by the measurement software in personal computer between $+(D_0+D_1)$ and $-(D_0+D_1)$ to eliminate the velocity ripple of the linear slide stage.

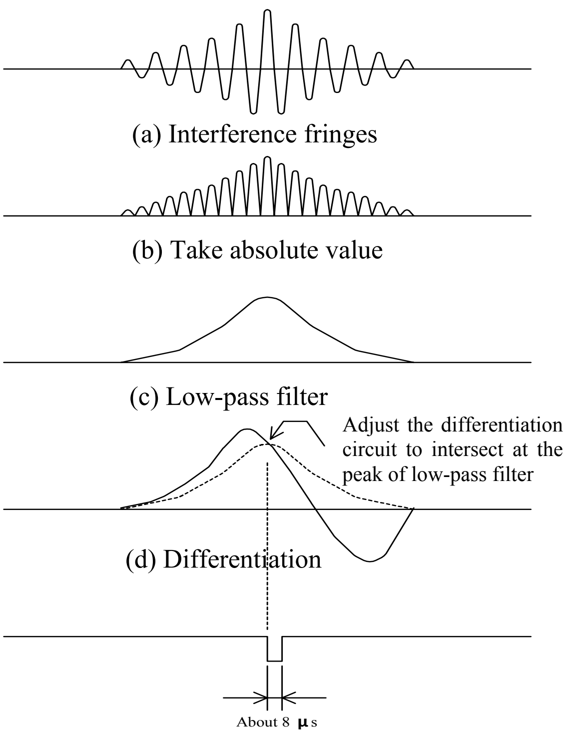


Figure 5. Trigger pulse generating circuit at the fringe peak point

3. MEASUREMENT RESULTS OF RING GAUGE

3.1 Repeatability of The Measurement

Repeatability of the low-coherence tandem interferometer of the ring gauge measurement for about 20 mm, 50 mm, 63 mm, and 100 mm are shown in Table 1. The repeatability is evaluated by 3 times of standard deviation from 25 times measurements without moving of the ring gauges. Measurement period is about 10 minutes for each diameter of ring gauge.

The repeatability of low-coherence tandem interferometer of ring gauges is excellent as those of 0.08 μm for diameter 20 mm, 0.14 μm for 50 mm, 0.16 μm for 63 mm, and 0.18 μm for 100 mm. A difference between the values calibrated by contact type method (Calibrated) and those measured by the interferometer (Measured) of ring gauges is exists as shown in Fig.6 and is almost constant. The beam splitter (10 mm-cube and refractive index 1.51 of material BK7) existence in ring gauges at the measurement of interferometer is one of the causes of the constant difference.

Table 1: Repeatability of the ring gauge measurement

Nominal size (mm)	Calibrated (mm)	Measured (mm)	Measured-Calibrated (mm)	3σ (μm)
20	19.99946	25.176459	5.17700	0.08
50	50.00083	55.176076	5.17525	0.14
63	63.24567	68.421027	5.17536	0.16
100	99.99984	105.174890	5.17506	0.18
		Average	5.17566	

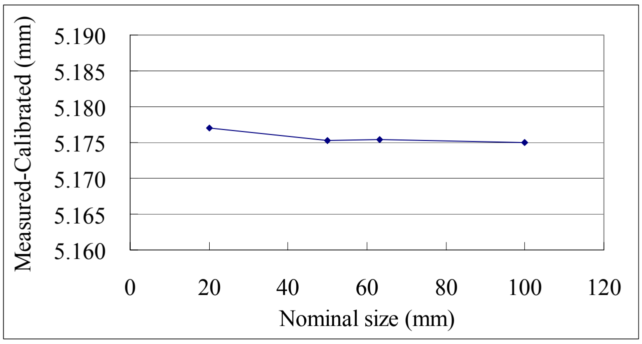


Figure 6. Diameter difference between calibrated and measured values

3.2 Reproducibility of The Measurement

Reproducibility of the measurement for 20 mm, 50 mm, 63 mm, and 100 mm ring gauges is shown in Table 2. The measurement reproducibility is evaluated by resetting the individual ring gauges ten times on the platform of measurement interferometer. Each time of the measurement, interference fringe signal amplitude is the maximum with the movable and tilt able platform adjustment of the position in radial direction and of the inclination. Each result is an average of 25 measurements. The reproducibility of low-coherence tandem interferometer of ring gauges is excellent as those of 0.05 μm for 20 mm, 0.13 μm for 50 mm, 0.15 μm for 63 mm, and 0.06 μm for 100 mm as shown in Table 2 and Fig.7.

Table 2: Reproducibility of the ring gauge measurement

Nominal size	20 (mm)	50 (mm)	63 (mm)	100 (mm)
1	25.17646	55.17605	68.42100	105.17529
2	25.17644	55.17595	68.42092	105.17534
3	25.17645	55.17602	68.42106	105.17529
4	25.17643	55.17599	68.42106	105.17530
5	25.17645	55.17602	68.42105	105.17529
6	25.17646	55.17592	68.42111	105.17529
7	25.17644	55.17602	68.42104	105.17527
8	25.17643	55.17605	68.42106	105.17530
9	25.17646	55.17605	68.42103	105.17530
10	25.17641	55.17602	68.42103	105.17528
Average	25.17644	55.17601	68.42103	105.17530
3σ (μm)	0.05	0.13	0.15	0.06

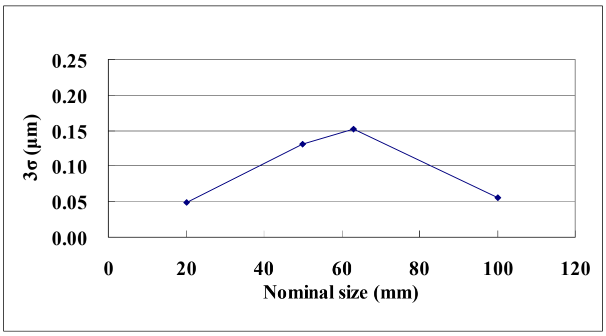


Figure 7. Reproducibility of ring gauge measurement

3.3 Posture Error of Ring Gauge Setting

To eliminate the setting error at a ring gauge measurement by the interferometer, the maximum interference fringes signal amplitude have to be found with the movable and tilt able platform in measurement interferometer by adjusting the position in radial direction and the inclination as mentioned above.

The influence of the posture error of ring gauge setting is confirmed for the radius direction as shown in Fig.8 and for inclination as shown in Fig.9 for 50 mm ring gauge. It is not difficult to find the posture for the maximum interference fringes signal amplitude with developed system of low-coherence tandem interferometer as shown in these figures.

It is thought that the measured diameter grows with the posture error of inclination, but the diameter of the experiment result has become small oppositely. The focused low-coherence light in radial direction of ring gauge by the cylindrical lens at the center of beam splitter and the cubic shape with refractive index 1.51 of beam splitter in measurement interferometer are seem to be the cause of this reason which becomes opposite. It is necessary to investigate continuously.

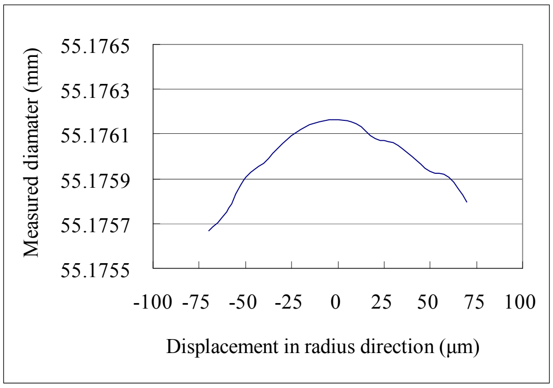


Figure 8. Posture error in radius direction

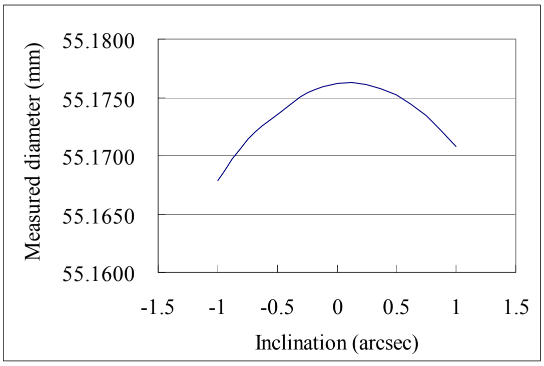


Figure 9. Posture error for inclination

3.4 Uncertainty of The Low-coherence Tandem Interferometer for Ring Gauge Measurements

Table 3 shows the uncertainty budget of the low-coherence tandem interferometer for ring gauge measurements calculated from the result of the above-mentioned repeatability and reproducibility. The He-Ne laser wave-length stability, material temperature error and alignment cosine error of the He-Ne laser light axis and low-coherence light one to slide stage axis are considered as an element of the uncertainty. The uncertainty of the calibrated by contact probe system are included to Table 3 for the reference.

Table 3: Uncertainty budget

Nominal size (mm)	20	50	63	100
Repeatability (μm)	0.076	0.139	0.163	0.178
Reproducibility (μm)	0.049	0.131	0.153	0.055
He-Ne laser wave-length stability (μm)	0.002	0.005	0.006	0.010
Material temperature at 20±0.5℃(μm)	0.001	0.002	0.003	0.004
Alignment cosine error (μm)	0.001	0.001	0.002	0.003
Combined standard measurement uncertainty (μm)	0.091	0.190	0.222	0.188
Expanded measurement uncertainty (κ=2) (μm)	0.182	0.381	0.443	0.376
Calibrated by contact probe system (κ=2) (μm)	0.210	0.220	0.700	0.900

4. SUMMARY

Newly developed measurement system of low-coherence tandem interferometer measured the diameter of 20 mm, 50 mm, 63 mm, and 100 mm and shows the excellent repeatability and reproducibility because the posture error can be easily avoided by detecting the maximum interference fringe signal amplitude with the platform in measurement interferometer. Expanded measurement uncertainty of each ring gage measurement is 0.19 μm for 20 mm, 0.38 μm for 50 mm, 0.44 μm for 63 mm, and 0.38 μm for 100 mm. The uncertainty is almost the same as that of contact type measurement for 20 mm and excellent for 63 mm and 100 mm but inferior for 50 mm. It is necessary to investigate continuously for 50 mm.

ACKNOWLEDGEMENTS

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