Key Engineering Materials Vol. 516 (2012) pp 533-538
Online available since 2012/Jun/14 at www.scientific.net

doi:10.4028/www.scientific.net/KEM.516.533

Remote Internal Diameter Measurement of Ring Gauge based on a Low-coherence Tandem Scheme

Dong Wei[1,a], Nan Wu[2,b], Kiyoshi Takamasu[3,c] and Hirokazu Matsumoto[3,d]

[1] Global COE Program “Mechanical Systems Innovation”, School of Engineering,
The University of Tokyo, 7-3-1 Hongo, Bunkyo, Tokyo 113-8656, Japan

[2] State Key Laboratory of Precision Measurement Technology and Instruments,
Department of Precision Instruments, Tsinghua University, Beijing 100084, China

[3] Department of Precision Engineering, The University of Tokyo,
7-3-1 Hongo, Bunkyo, Tokyo 113-8656, Japan

[a]weidong@nanolab.t.u-tokyo.ac.jp, [b]wun04@mails.tsinghua.edu.cn,
[c]takamasu@pe.t.u-tokyo.ac.jp, [d]hi.matsumoto@nanolab.t.u-tokyo.ac.jp

Keywords: length measurement, interference, ring gauge, low-coherence, tandem, remote calibration

Abstract. A novel internal diameter measurement method based on a low-coherence tandem scheme is firstly demonstrated. From operational analysis, it is understood that a low-coherence tandem scheme can be served for internal diameter evaluation by using a combination of a transmission grating and a ring gauge instead of a classical Michelson interferometer to store and transmit the internal diameter information. As a result of the experiment, in the present experimental environment, diameter measurement of several millimetres with a relative standard uncertainty of several micrometres was performed. Taken together, these results suggest that the present measurement method is expected to be used as a powerful remote internal diameter calibration tool for next-generation calibration network systems.

Introduction

Length measurements and their traceability are indispensable infrastructure for not only scientific purposes but also industrial requirements. Currently, the traceability of length for end users uses the gauge blocks on the production site in Japan. The traceability of the gauge blocks is conducted using either of the following two methods. The first method is that the gauge blocks are sent to the standards metrology centre for calibration. As for the second method, the car with the calibration function comes to the factory, and the gauge blocks are calibrated in the car. Each method cannot meet the demand of the industrial world, in which arbitrary length needs to be calibrated at low cost, anytime and anywhere. To satisfy these demands, recently, a calibration method of the gauge blocks [1-4] via the optical fibre was investigated and it succeeded in remote calibration with a standard deviation of tens of nanometres for a 50 millimetre (mm) length [1]. As a result, the remote calibration technology via the existing optical fibre network allows end users to directly access a traceable length in a national standard centre at low cost, anytime and anywhere. And the role of the remote calibration technology via the existing optical fibre network is expected to become more and more important for next-generation remote calibration network systems.

For science and industry, not only the measurements of external size but also the calibrations of the internal diameter are important. A complete review of the literature suggests that several experiments have been performed for the outside size remote measurements.

The following are some studies which focused on the characteristics of a tandem scheme to challenge various remote measurement problems. As far as the remote distant measurement based on two connected Michelson interferometers (namely, tandem interrferometric scheme) is concerned, Flournoy [5] et al. seem to have been the first, in the 1970s, to measure variations in moving transparent films. After that, various experiments were proposed using a white-light tandem scheme between two separated points – a transducer point and a receiver point – for measurement of the displacement [6-8], high-sensitivity detection of low surface-reflectivity [9], precision group refractive-index metrology [10-12] and remote calibration of length standards [1-3]. More recently, Volkov et al. applied a tandem interferometry for monitoring of metalorganic vapour-phase epitaxy processes [13], Kao et al. presented a scanning white-light tandem interrferometric method for determining the cell gap of liquid crystal displays [14] and Wei et al. proposed and experimentally demonstrated a more general tandem technique, called a femtosecond optical frequency comb-based tandem interferometer, which takes advantages of both the temporal coherence characteristics of a femtosecond optical frequency comb light source and the transmission characteristics of acquired length information based on a tandem interferometer [15].

However, in all of these previous works [1-15], the measurement is restricted to only outside size, and few technologies of determining the internal size were given.

The work presented here is a tandem interrferometric scheme aiming at determining the ring gauges' internal size based on a combination of a transmission grating and a ring gauge instead of a classical Michelson interferometer to store and transmit the internal diameter information. As shown below, this method maintains the simplicity of the equipment. This is, to the best of our knowledge, the first demonstration of application of a tandem interrferometric scheme to internal size evaluation. Our results show that this grating-based tandem interrferometric method can be used as an internal size measurement tool. As an example, this method is applied to measure internal sizes of 1 mm and 5 mm.

Principles

Note that the tandem interrferometric scheme is essential for the mentioned method. In the following, let us first consider the principle of the tandem interferometer as shown in Fig. 1. For more details about a tandem interferometer, we recommend references [8, 12].

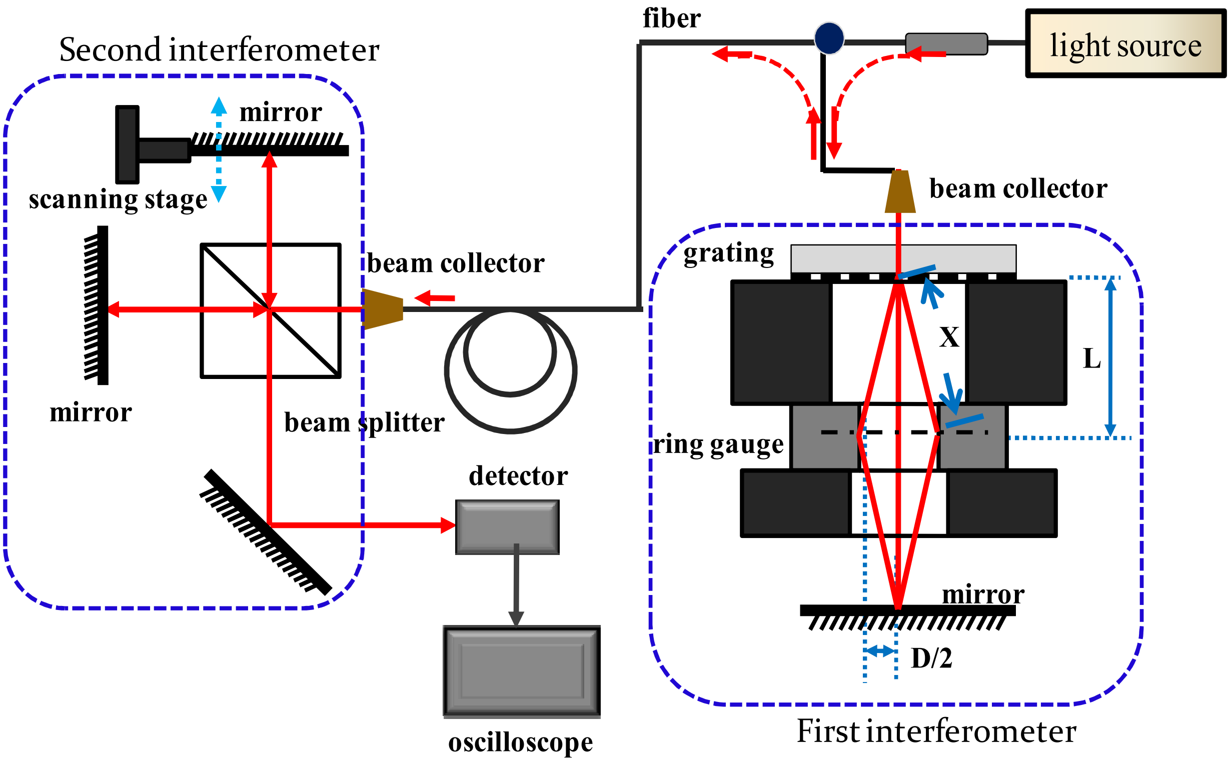


Fig. 1 Optical layout

Figure 1 shows an overview of the developed system. The optical scheme is carried out with a system consisting of a white light source, a tandem interferometer and system controls.

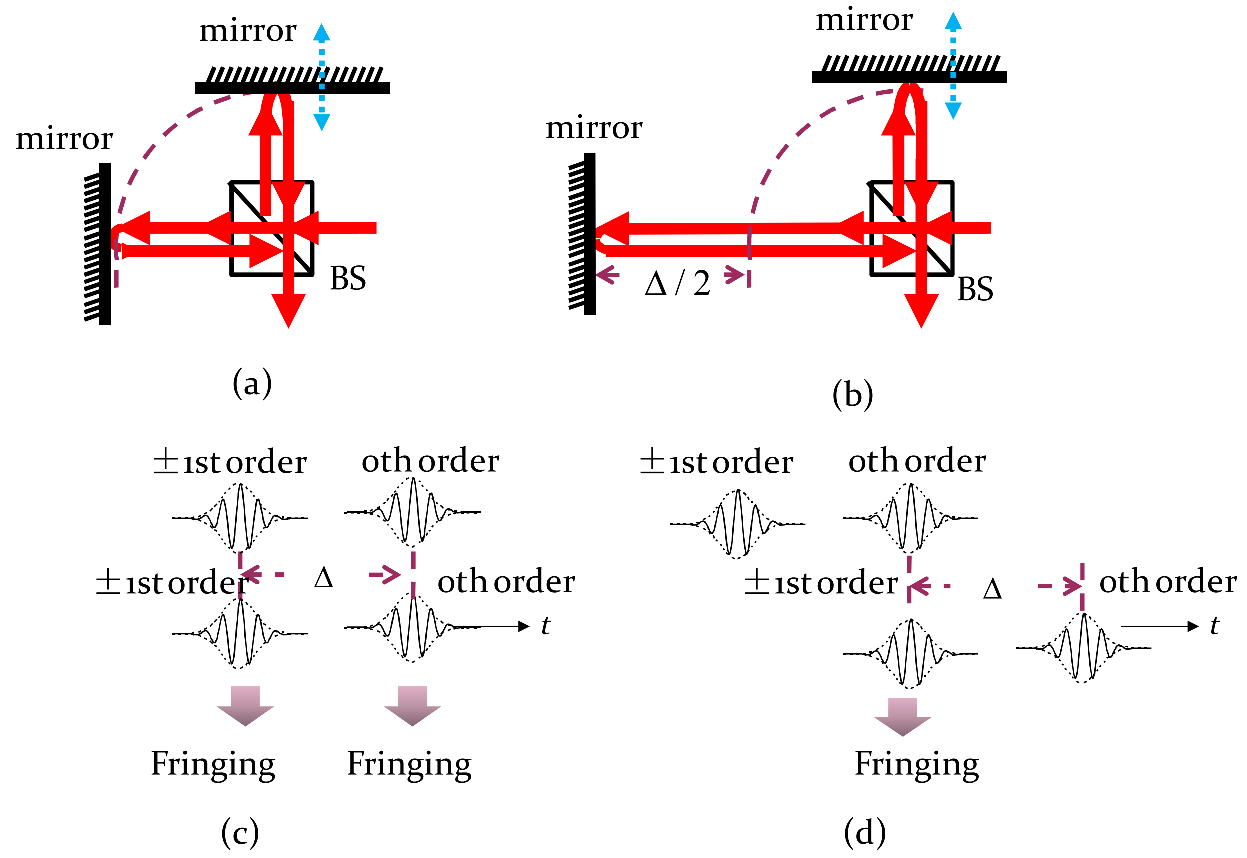
The tandem interferometer has a tandem configuration of two unbalanced optical-path Michelson interferometers. The first interferometer is composed of a grating, a fixed reference mirror and a ring gauge, as shown in Fig. 1. The light beam from the white light source is introduced into the first interferometer and split into three parts at the diffraction grating, and then the direct transmission (zero order) beam is reflected by the fixed reference mirror and the first positive and minus order beams are reflected by internal surfaces of the ring gauge and the fixed reference mirror is delayed relative to the direct transmission beam with $\Delta = 4(X - L)$, and they are finally recombined at the diffraction grating.

The relation between the internal diameter of the ring gauge D and the relative optical-path difference distance Δ is expressed as Eq. (1).

$$D = (X - L)\cdot(1/\sin\theta - 1/\tan\theta)^{-1}. \qquad (1)$$

where $\cos\theta = L/X$.

Eq. (1) means that the internal diameter of the ring gauge is stored by the first interferometer and transmitted to the second interferometer.



(a) (b) (c) (d)

Fig. 2 Interference fringes are formed with different relative delays.

Interference fringes are formed with different relative delays between two beams formed by the second interferometer. With relative optical-path delay as 0 (a), and Δ (b), the relatively delayed beams will overlap as (c), and (d), respectively, and the expected interference fringes can be observed.

After travelling though the first interferometer and the optical fibre, the recombined beams are introduced into the second interferometer. The second interferometer of the tandem interferometer is composed of a beam splitter, a moving reference mirror, which is fixed on the top surface of a computer-controlled ultrasonic stepping motor, and a fixed object mirror. The recombined beams are split into two identical parts at the beam splitter, and then one beam is reflected by the moving reference mirror and the other beam is reflected by the fixed object mirror. The moving reference mirror is delayed relative to the fixed object mirror with different relative optical-path delays, as shown in Fig. 2, and they are finally recombined at the beam splitter. When relative optical-path delay is 0, the interference fringes can be observed as an ordinary Michelson interferometer. The zero order beam and the first positive and minus order beams result in interference fringes reappearing at delays equal to Δ and -Δ since the three parts were separated from the same original beam at the diffraction grating. In the second interferometer, when the two beams finally overlap at the beam splitter (see Figures (2) and 2(d)), the interference fringes will be observable.

The summary of the operational analysis is the relative optical-path delay Δ introduced by the first interferometer, which is related to the internal diameter of the ring gauge as indicated by Eq. (1), and which is stored and transferred by the characteristics of the tandem interferometer, can be presumed from the observed interference fringes' peaks by the second interferometer.

Experiment

Armed with the understanding of the principles, we now turn to the optical experiment. The experiment is carried out with an Amplified Spontaneous Emission (ASE) light source (1460~1490 nm). The beams from the ASE light source are expanded and collimated by a collimator and introduced into the tandem interferometer. In the first interferometer, a transmission grating is used with an 80 l/mm period, and the relative optical path difference Δ between the two beams is about 0.624 mm. During the measurement, by moving the reference mirror by means of a computer-controlled ultrasonic stepping motor, we could observe the interference fringes. After travelling different path lengths, these two beams overlap at the beam splitter. A lens makes an image of the interference fringes on a photo detector.

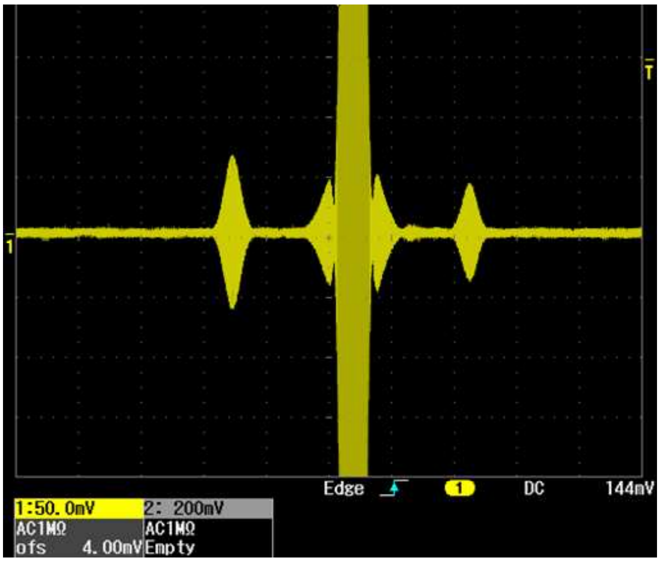


Fig. 3 Interference fringes with different relative delays between two beams

Figure 3 illustrates the acquired interference fringes. The three interference fringe signals exhibit a high contrast between the two beams by the relative optical displacements -Δ, 0 and Δ, respectively. To obtain the interference fringes' peaks from the obtained interference fringes and measure the related optical displacement, the following basic steps of the analytical process are used. First, the obtained interference fringe is Fourier transformed. Second, the unwanted noise is filtered out by a band pass filter, and the Fourier element of the interference fringe is inverse Fourier transformed into the time domain. Third, the envelope of the interference fringe can be obtained as the 2 times absolute value of the inverse Fourier transformed value. Finally, the displacement of related interference fringes' envelope peaks are found as performed in the conventional white light interference method.

Due to restricted equipment, only 1 mm and 5 mm internal diameter measurements of the ring gauges are conducted in this proof-of-the-principle experiment. As shown in Table 1, the 1 mm and 5 mm internal diameter of the ring gauges can be remotely calibrated with a standard deviation of 5 μm and 24 μm, respectively.

Table 1 Measured internal diameters and the related standard deviations

	5 mm	1 mm
Internal diameter [mm]	4.937	0.932
Related standard deviation [μm]	0.024	0.005

As a result, we achieved remote internal diameter measurement results of several micrometres to several millimetres. Compared to the target value for the practical remote internal diameter calibration (namely, 10^{-7} order), from the above optical experiment, the experimental results show that future effort is necessary to achieve stability of the optical experiment system. We are currently pursuing an approach to apply the proposal method with a high-accuracy optical component and an appropriate design of the experimental system.

Summary

In closing, this paper describes a tandem interferometric method for internal diameter measurement, and the proof-of-the-principle optical experiment system that was developed in order to validate the proposed method. A complete review of the literature suggests that this is the first report of the experiment of internal diameter measurement based on a tandem interrferometric scheme which stores and transmits the internal diameter information by a combination of a transmission grating and a ring gauge instead of a classical Michelson interferometer. As a special demonstration, measurements of the nominal internal diameter of 1 mm and 5 mm ring gauges with micrometre relative standard uncertainty were demonstrated. Note that the ring gauge, used as a standard of the measuring instrument, is indispensable for the calibration of a precise measuring instrument and product works on the production site. The results suggest that the presented measurement method will be used as a powerful remote internal diameter calibration tool for next-generation calibration network systems.

Acknowledgements

One of the authors (D.W.) was supported through the Global Center of Excellence Program on "Global Center of Excellence for Mechanical Systems Innovation" granted to the University of Tokyo, from the Japanese government. D.W. gratefully acknowledges the scholarships given by Takayama International Education Foundation, Heiwa Nakajima Foundation, and the Ministry of Education, Culture, Sports, Science and Technology of Japan (MEXT).

References

[1] H. Matsumoto, K. Sasaki, A. Hirai, 103-km-Long Remote Measurements of End Standards Using Low-Coherence Optical-Fiber Tandem Interferometer in Experimental Room, Jpn. J. Appl. Phys. 44 (2005) 6287-6288.

[2] H. Matsumoto, K. Sasaki, A. Hirai, Remote Calibration of Length Standards Using 47-km-Long Optical Fiber Network, Jpn. J. Appl. Phys. 44 (2005) L970-L972.

[3] H. Matsumoto, K. Sasaki, Remote measurements of practical length standards using optical fiber networks and low-coherence interferometers, Jpn. J. Appl. Phys. 47 (2008) 8590-8594.

[4] M. Hirokazu, H. Akiko, Remote Measurements of Lengths by Excess-Fraction Method Using Optical Fiber Networks and Tandem Interferometer, in Optical Fiber Communication Conference, OSA Technical Digest (CD) (Optical Society of America, 2009), OMG5

[5] P.A. Flournoy, R.W. McClure, G. Wyntjes, White-Light Interferometric Thickness Gauge, Appl. Opt. 11 (1972) 1907-1915.

[6] A. Koch. R. Ulrich, Fiber-optic displacement sensor with 0.02 [mu]m resolution by white-light interferometry, Sens. Actuator A 25 (1990) 201-207.

[7] Q. Wang, Y.N. Ning, K.T.V. Grattan, A.W. Palmer, A curve fitting signal processing scheme for a white-light interferometric system with a synthetic source, Opt. Laser Technol. 29 (1997) 371-376.

[8] H. Matsumoto, A. Hirai, Transmission of optical length information through single-mode fiber by a low-coherence tandem interferometer, Opt. Eng. 40 (2001) 2365-2366.

[9] H. Matsumoto, A. Hirai, A white-light interferometer using a lamp source and heterodyne detection with acousto-optic modulators, Opt. Comm. 170 (1999) 217-220.

[10] A. Hirai, H. Matsumoto, Low-coherence tandem interferometer for measurement of group refractive index without knowledge of the thickness of the test sample, Opt. Lett. 28 (2003) 2112-2114.

[11] A. Hirai, H. Matsumoto, Measurement of group refractive index wavelength dependence using a low-coherence tandem interferometer, Appl. Opt. 45 (2006) 5614-5620.

[12] H. Matsumoto, K. Sasaki, A. Hirai, Remote measurement of refractive index of air using tandem interferometer over long optical fiber, Jpn. J. Appl. Phys. 47 (2008) 7386-7389.

[13] P.V. Volkov, A.V. Goryunov, V.M. Daniltsev, A.Y. Luk'yanov, D.A. Pryakhin, A.D. Tertyshnik, O.I. Khrykin, V.I. Shashkin, Novel technique for monitoring of MOVPE processes, J. Cryst. Growth 310 (2008) 4724-4726.

[14] C.-F. Kao, S.-K. Tsai, S.-H. Lu, Measuring cell gap of liquid crystal displays by scanning white-light tandem interferometry, Jpn. J. Appl. Phys. 48 (2009) 106508-106508-4.

[15] D. Wei, S. Takahashi, K. Takamasu, H. Matsumoto, Femtosecond optical frequency comb-based tandem interferometer, J. Europ. Opt. Soc. Rap. Public. 4 (2009) 09043-1-09043-4.