Evaluation of Measurement Properties Depending on Optical Coupling of Whispering Gallery Mode (WGM) Resonance – Based Diameter Measurement

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KEYWORDS: Micro-CMM, Microsphere, WGM resonance, Mode number, Near-field light, SNOM probe

For the insurance of the measurement accuracy of micro-Coordinate Measurement Machine (CMM), it's necessary to know the micro-CMM's probe diameter accurately. For the measurement of microsphere diameter, we proposed a method using Whispering Gallery Mode (WGM) resonance. By measuring the WGM resonant wavelength and estimating the mode number, we can derive the microsphere diameter accurately through WGM dispersion equation. Up to now we can measure the WGM resonant wavelength accurately and have proposed an estimation method for WGM mode number, but we haven't verified the estimation accuracy of WGM mode number. Therefore, we are attempting to measure WGM mode number directly by using a Scanning Near-field Optical Microscopy (SNOM) probe to measure the spatial period of the WGM electric field on microsphere surface. Through this study, we can verify the correctness of the proposed WGM mode number estimation method by identifying the mode generated within the microsphere, thereby providing experimental evidence for its general applicability. The purpose of this study is to experimentally determine the mode number of WGM resonance, and thus we conducted the two-dimensional scan on microsphere surface with a SNOM probe and analyzed whether the WGM electric field distribution was appropriately measured to ensure the accuracy of the mode number determination.

1. Introduction

The micro-Coordinate Measuring Machine (CMM) is a common tool used for dimensional measurement of micro-parts [1, 2], and its measurement accuracy relies on the probe. The diameter of micro-CMM's probe sphere about 10 to several 100 μm is crucial for the measurement accuracy and it needs to be known accurately. For ensuring the measurement accuracy of micro-CMM below 50 nm, the probe sphere needs to be measured below the accuracy of 10 nm [3]. Various methods for measuring microsphere diameter are being developed, and these typically involve contact measurement using micro-CMM [4, 5], Scanning Probe Microscopy (SPM) [6], or other universal measurement tools, which often requires calibration with standards with known dimensions. In our previous study, we have proposed a method for measuring microsphere diameter using Whispering Gallery Mode (WGM) resonance [7, 9]. This method involves coupling a laser into the microsphere using a tapered optical fiber, measuring the WGM resonant wavelength, estimating the WGM mode number, and subsequently deriving the microsphere diameter by searching the solutions of the WGM dispersion equation. For measuring microsphere diameter with high accuracy by this method, the accuracy of the two parameters of resonant wavelength and mode number are crucial. Thus, we have developed an accurate measurement method for resonance wavelength and proposed a mode number estimation method [7] based on phase match []. However, we haven't confirmed the accuracy of the estimated mode number due to the lack of information about the actual mode propagating inside the microsphere. To verify the correctness of estimated mode number, directly measuring the mode number experimentally is considered a reliable method. Therefore, we proposed the mode number measurement method by visualizing the WGM electric field using a Scanning Near-field Optical Microscopy (SNOM) probe [9]. By scanning on the microsphere surface with the SNOM probe, the WGM electric field distribution can be acquired and thus the mode can be analyzed from the electric field's spatial period. Based on our previous numerical simulations, for 100 μm microsphere, to achieve a mode number measurement accuracy of within 1, the SNOM probe needs to scan an angle of at least 30 degrees along the microsphere's surface around its center. This is necessary to obtain a sufficient number of spatial periods of the WGM electric field distribution, which helps reduce the measurement error of the mode number. However, this is actually a quite challenging experiment due to factors such as the stability of the SNOM probe's rotation and positional errors. Therefore, before conducting a large-range rotational scan of SNOM probe, we first performed a fine two-dimensional scan in a small area near microsphere's surface to ensure that WGM electric field signals can be properly measured by SNOM probe, and to evaluate whether WGM electric field signals were correctly measured.

2. Principle of Microsphere Diameter Measurement

2.1 WGM Resonance

WGM resonance is a phenomenon in which light propagates along the inner surface of a microsphere through repeated total internal reflections. If the optical path length of microsphere's circumference is an integer multiple of the wavelength, after the light propagating one round trip along the circumference, it returns to its starting point with the same phase and interfere with itself, resulting in strong optical resonance. Tapered fiber is a suitable optical coupler for efficiently exciting WGM resonance. The wavelength of the incident light at which WGM resonance occurs is called the resonant wavelength. As shown in Fig. 1 (a), the incident light is introduced into a tapered fiber, leaks out from the fiber surface in the form of near-field light, and after being scattered it propagates into microsphere. When WGM resonance is excited, a portion of the incident light's energy is transferred into microsphere, causing a sharp drop in the transmitted light intensity.

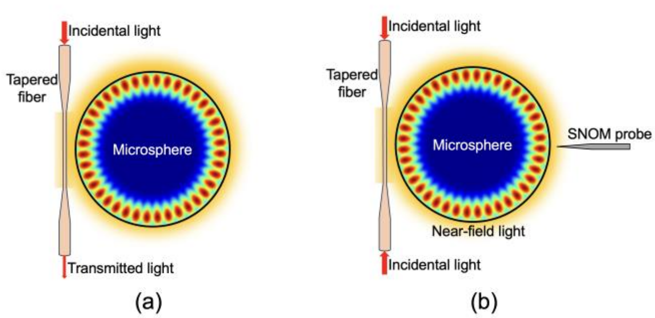


Fig. 1 WGM resonance excitation and mode number measurement

2.2 Mode Number Measurement

The mode number is an important parameter of WGM resonance, reflecting the number of resonant wavelength cycles that fit within the microsphere circumference. To measure mode number, the standing wave WGM is excited with incident light from both sides of the tapered fiber, and the WGM electric field distribution is shown in Fig. 1 (b). Unlike Fabry–Pérot resonance, which is a standing wave type, WGM resonance is a propagating type of resonance. Therefore, as shown in Fig. 1 (a), with light incident from one direction from the tapered fiber, the light propagates along the inner surface of microsphere. In this case, the time-averaged near-field light intensity on microsphere surface is uniform, and no periodic distribution can be obtained. Therefore, as shown in Fig. 1 (b), by introducing light from both sides of the tapered fiber, a standing wave WGM is formed, making it possible to measure the mode number based on the standing wave pitch. For mode number measurement, the SNOM probe is aligned close to microsphere surface, and the near-field light is captured by probe tip. By scanning probe tip along microsphere surface, the distribution of WGM electric field can be measured and from its spatial period mode number can be acquired.

Once the resonant wavelength and mode number are obtained, the microsphere diameter can be accurately calculated using the WGM dispersion equation [7].

3. WGM Electric Field Measurement

3.1 Experimental Setup

The experimental setup shown in Fig. 2 is used for measuring WGM electric field distribution. WGM resonance is excited using a tapered fiber, and the WGM electric field distribution on microsphere surface is measured by two-dimensional scan with a SNOM probe. The tapered fiber's narrowest part has a diameter of 500 nm, maintains horizontal polarization, and excites Transverse Magnetic (TM) WGM resonance. The microsphere is fabricated by thinning a 125 µm diameter optical fiber with a glass etchant and then irradiating its tip with a CO_2 laser to create a microsphere with a diameter of about 94 µm. SNOM probe is fabricated by etching an optical fiber and its tip is less than 100 nm in diameter. The position of tapered fiber, microsphere and SNOM probe is observed by a CMOS camera as shown in Fig. 3.

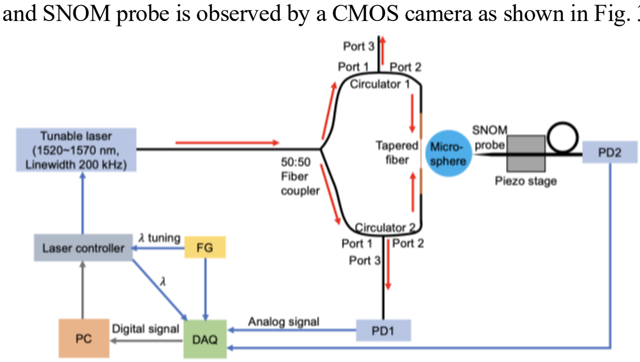


Fig. 2 Experiment setup for measuring WGM electric field distribution

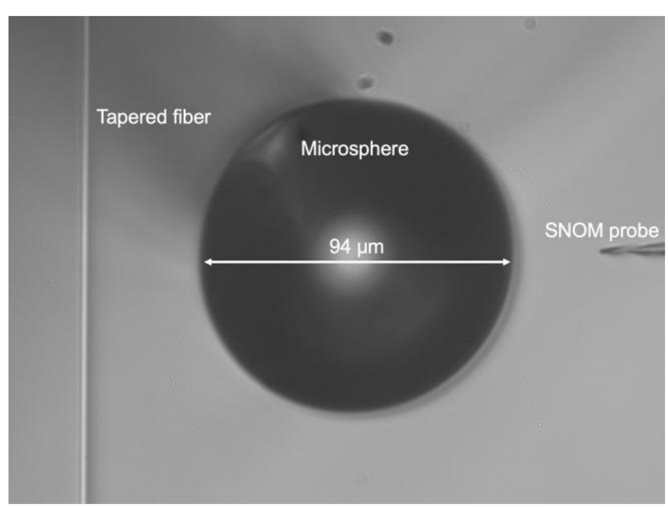


Fig. 3 Image of tapered fiber, microsphere and SNOM probe tip

3.2 Resonant Wavelength Measurement

To excite WGM resonance in microsphere, it is necessary to measure the resonant wavelength with an accuracy of less than 100 nm. A tunable laser with a wavelength range of 1520-1570 nm is used to scan the wavelength of incident light on tapered fiber, and resonant wavelength is identified by detecting the intensity of the transmitted light using a photon detector (PD). Based on the coarse-to-fine method, the wavelength is first roughly scanned to locate the approximate position of the resonant wavelength, and then finely tuned using a function generator (FG) to precisely determine resonant wavelength. All the signals are collected by a data acquisition (DAQ) device and then transferred to PC for data process. The measurement result of wavelength scan is shown in Fig. 4. In the range of 1520-1570 nm, there are 8 main periodic modes detected. These modes should have adjacent mode numbers. To confirm this and verify the adequacy of SNOM probe measurement, the wavelength was fixed at 1522.62, 1528.60, 1546.40, and 1566.07 nm, and SNOM probe is used to scan and measure the electric field distribution.

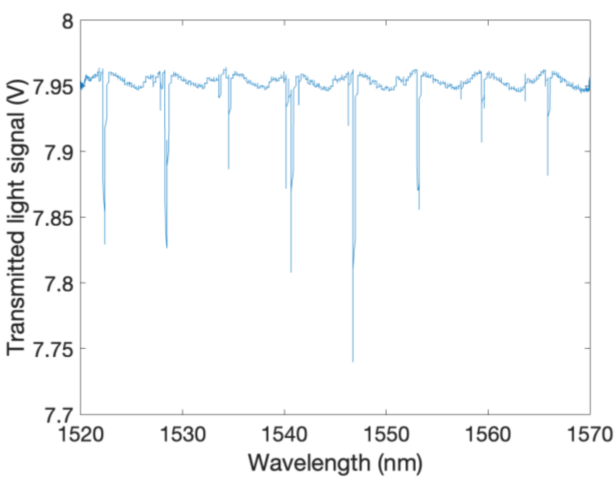


Fig. 4 WGM resonant wavelength measurement

3.3 WGM Electric Field Measurement

The 8 modes in Fig. 4 have the same free spectral range (FSR) of about 6 nm and should have the same radial and azimuthal mode numbers, with the difference of 1 in angular mode number. To verify if SNOM probe can detect this, as shown in Fig. 5, we first scan SNOM probe along the z-axis to measure azimuthal mode. Then, SNOM probe is scanned in two-dimensional of xy axes to measure the WGM electric field periodicity and confirm of the different angular modes.

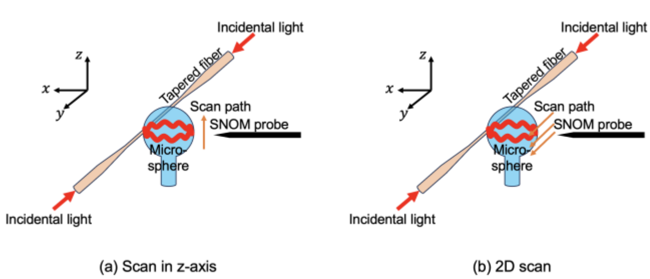


Fig. 5 SNOM probe scan for WGM electric field measurement

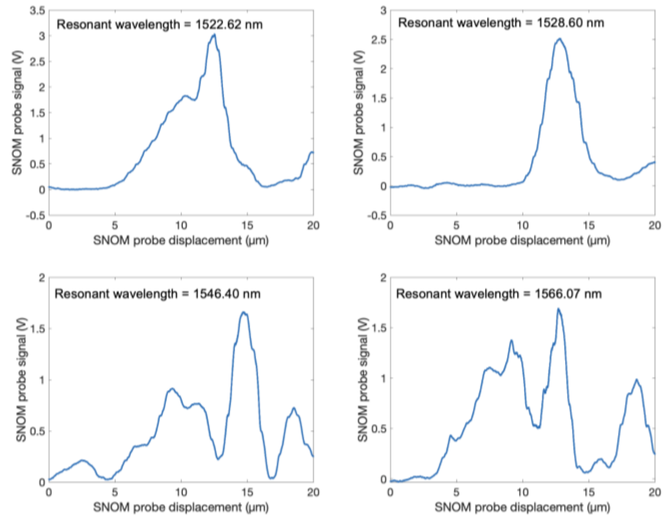
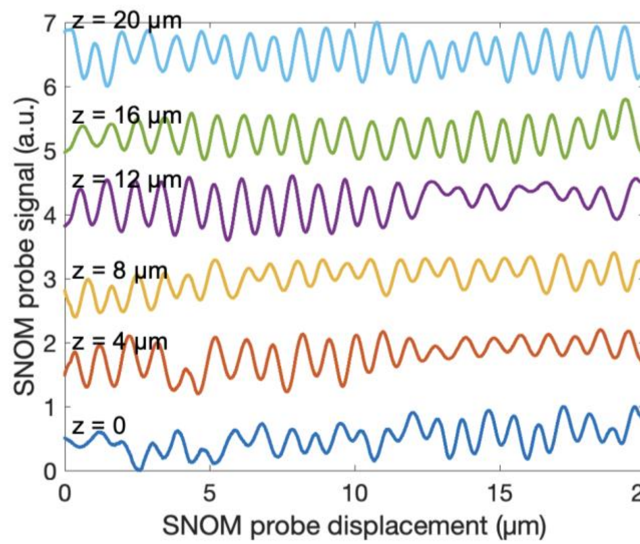
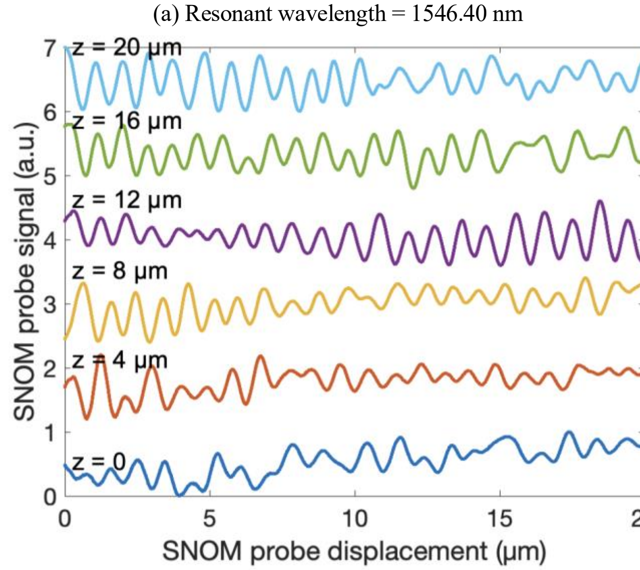


Fig. 6 WGM electric field distribution in z-axis



(a) Resonant wavelength = 1546.40 nm



(b) Resonant wavelength = 1566.07 nm

Fig. 7 WGM electric field distribution in y-axis

The measurement results of the WGM electric field in z-axis at 4 resonant wavelengths are shown in Fig. 6. For the 4 resonant modes, 3 peaks were detected in the z-axis at wavelengths of 1546.40 and 1566.07 nm, indicating that these 2 modes may have the same radial mode and are separated by about 3 times the FSR, so their angular mode numbers should differ by 3. However, the electric field distributions at 1522.62 and 1528.60 nm are different, possibly because they were fixed at the different radial mode.

Next, two-dimensional scan is performed with SNOM probe to verify if the differences of the resonant modes between 1546.40 and 1566.07 nm can be detected. SNOM probe is scanned 20 μm in the y-axis at 4 μm intervals over a 20 μm range in the z-axis. The results are shown in Fig. 7. Nearly periodic distributions are detected within the 20 μm range in the z-axis for the two modes, even when SNOM probe is offset from the peak positions shown in Fig. 6. Next, the probe signals' pitchs are calculated to evaluate whether the WGM electric field distribution and spatial period were properly measured. The SNOM probe signal was first compensated using an envelope to align the peaks, followed by Fourier transform to remove noise. Then the data was smoothed, and the pitches were calculated by fitting a sine wave. The results are shown in the Table 1.

Table 1 Pitches (nm) of SNOM probe signals at two resonant modes

z-axis (μm)	0	4	8	12	16	20
λ = 1546.40	844.0	868.9	865.3	863.3	856.1	837.8
λ = 1566.07	882.5	874.6	867.5	881.2	833.0	889.6

According to Table 1, the probe signal period at the resonant wavelength of 1566.07 nm is larger than that at 1546.40 nm, which shows the correct trend. The spatial period of the WGM standing wave inside the microsphere is about 540 nm ($= \lambda_0/2n$), and the period of the WGM standing wave on the microsphere surface increases with the radial mode number, so it is expected to be larger than 540 nm. However, since the measured period exceeds above 800 nm, further precise measurements and evaluation are needed to determine if the measurement result reasonable. Under the two resonance modes, different periods were measured at different positions. To determine whether this variation in the WGM electric field distribution is inherent or due to measurement errors, further precise measurements and validation are necessary.

4. Conclusions

To ensure the measurement accuracy of the microsphere diameter using WGM resonance, we proposed an experimental method for measuring the WGM mode number to validate the mode number estimation method proposed in our previous study. To assess whether the WGM electric field distribution can be properly measured, we used an SNOM probe to scan the surface of the sphere and evaluated the reasonableness of the measurement results.

By scanning the wavelength, 8 adjacent resonant modes with the FSR about 6 nm were detected within the 1520-1570 nm range. The wavelength was then locked at the resonant states, and by scanning the SNOM probe along the z-axis, the azimuthal distribution was confirmed for the two adjacent modes at 1546.40 nm and 1566.07 nm. WGM electric field distribution was measured through a two-dimensional scan at these two modes, and it was confirmed that electric field spatial period increases with the resonant wavelength. However, the accuracy of the spatial period measurement and whether the period varies at different positions along the z-axis require more accurate measurement and validation in the future. After ensuring the accuracy of small-area WGM electric field measurement, we will scan SNOM probe over a larger range to measure WGM mode number with high accuracy and verify the mode number estimation method.

ACKNOWLEDGEMENT

This work was financially supported by Japan Society for the Promotion of Science (No. 23H01313), Machine Tool Engineering Foundation (No. 44-B1/2023), World-Leading Innovative Graduate Study Program for Quantum Science and Technology Fellowship Program (WINGS-QSTEP), and the Mitutoyo Association for Science and Technology (MAST).

REFERENCES

1. Hansen, H. N., *et al.*, "Dimensional micro and nano metrology," *CIRP Ann.*, Vol. 55, No. 2, pp. 721-743, 2006.
2. Huang, Q., *et al.*, "A three-dimensional resonant triggering probe for micro-CMM," *Appl. Sci.*, Vol. 7, No. 4, 403, 2017.
3. Michihata, M., "Surface-sensing principle of microprobe system for micro-scale coordinate metrology: a review," *Metrology*, Vol. 2, No. 1, pp. 46-72, 2022.
4. Küng, A., Meli, F., and Thalmann, R., "Ultraprecision micro-CMM using a low force 3D touch probe," *Meas. Sci. Technol.*, Vol. 18, No. 2, pp. 319-327, 2007.
5. Kondo, Y., Hirai, A., and Youichi, B., "Two-point diameter calibration of a sphere using a micro-coordinate measuring machine at NMIJ," *Metrologia*, Vol. 59, No. 2, 024005, 2022.
6. Fang, C., *et al.*, "Measurement and uncertainty evaluation of the microsphere used for micro-CMM probe," *Meas. Sci. Technol.*, Vol. 31, No. 2, 025004, 2019.
7. Kobayashi, Y., *et al.*, "Radial mode number identification on whispering gallery mode resonances for diameter measurement of microsphere," *Meas. Sci. Technol.*, Vol. 30, No. 6, 065201, 2019.
8. Knight, J. C., *et al.*, "Phase-matched excitation of whispering-gallery-mode resonances by a fiber taper," *Opt. Lett.*, Vol. 22, No. 15, pp. 1129-1131, 1997.
9. Liu, Y., *et al.*, "Measurement properties of electric field intensity distribution of whispering gallery mode with near-field optical probe," *Meas. Sci. Technol.*, Vol. 33, No. 9, 095501, 2022.