Fundamental Analysis on the Novel 3-D Probing Technique for Micro-parts Using the Optical Fiber Trapping

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A novel three-dimensional probing technique for microparts with high aspect ratios is proposed. In this technique, a particle trapped optically at the optical fiber tip is used as a probe for position detection. In order to confirm the feasibility of this method, this paper demonstrates numerical computations about the optical force exerted on the probe sphere and the behavior of position detection signal using finite-difference time-domain method and Maxwell stress tensor. It is found that the optical force induced at the tapered fiber tip can trap the probe sphere three-dimensionally, and it has the performance as the position detection probe.

Key words: CMM, high aspect ratio, fiber trapping, finite-difference time-domain method

1. Introduction

With the recent development of micro electro mechanical systems (MEMS), mechanical parts have been smaller in the size of micrometer order. And using a variety of micro fabrication methods such as the photolithography, the LIGA process, etc., we can fabricate micron-sized three-dimensional (3-D) shapes. To guarantee the accuracy of microparts, it is indispensable to measure 3-D profiles like sizes and positions. At present, however, it is impossible to evaluate the geometrical quantities three-dimensionally. The 3-D coordinate measuring machine (CMM) for microparts with the measuring range of micrometers and the accuracy of nanometers is required. We reported the possibility of the probing technique using the laser trapping technique [1-3]. However, this technique can't be applied to micro objects with high aspect ratios such as micro deep holes and grooves because of the shadow effect. In truth, the measuring system that enables to measure the micro shapes with high aspect ratios has not been realized yet.

This paper proposes a novel 3-D probing technique for measuring microparts with high aspect ratio. This technique uses the optical force exerted on a dielectric particle in the intensity gradient field of light [2]. A particle with a diameter of 5 ~ 10 μm trapped optically at the tip of an optical fiber plays the roll of a probe for position detection, and the fiber with a diameter of smaller than that of the particle works as a stylus shaft.

The proposed probing scheme requires to trap a particle with 5 ~ 10 μm diameter against the gravity in the air using the light emitted from an optical fiber tip. There are many studies on the trapping technique using optical fibers and a nanometric aperture. These optical trapping techniques were derived from the work of Ashkin and co-workers on the optical trapping technique [2,3]. There have been various interesting studies on the fiber trapping technique, however, these used "two or more optical fibers in water" [4-6]. Okamoto and Kawata theoretically analyzed that an evanescent field near a nanometric aperture of metallic layer could trap subwavelength particles "in water" [7]. Choi et al. demonstrated similar calculations for nanometric particles [8]. Novotny et al. and Chaumet et al showed theoretically the trapping potential for nanoparticles in the field scattered by "a metal tip" [9.10]. The configurations of these studies are unavailable for our probing technique. Therefore, we have to confirm the possibility of the fiber trapping technique as used in our proposed method.

In this report, to validate our proposed method, we analyze numerically the optical force exerted on the probe sphere illuminated by the beam emitted from the fiber tip using finite-difference time-domain (FDTD) method and Maxwell stress tensor.

2. Principle of position detection

Fig. 1 shows the principle of the fiber trapping probing technique. A dielectric particle with a diameter of 5 ~ 10 μm is trapped by the optical force induced by the illumination light from the fiber tip. The particle serves as a positional detection probe and the optical fiber works as a stylus shaft. The optical fiber consists of the main body part, which is a single mode optical fiber, and the micro optical fiber part, whose core is exposed to the air. At the micro optical fiber part, the air serves as its cladding. The micro optical fiber part is thinner than the diameter of the probe sphere and longer than the depth of shapes like deep holes and grooves. This enables the probe to make an approach to the steep angle surface of the workpiece with high aspect ratios. The incident beam propagates through the fiber and is emitted from the fiber tip. The light traps the probe sphere optically, and is scattered by the spherical probe surface. Then, the scattering light returns into the fiber tip again and guided to the other fiber end, and its intensity is

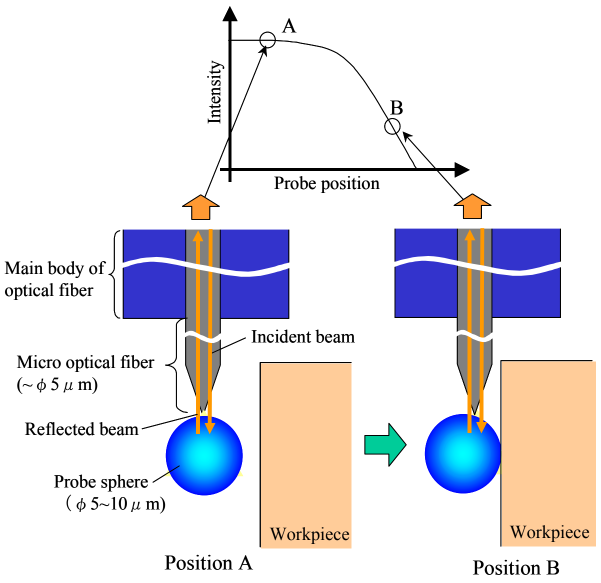

Fig. 1 Principle of position detection

monitored at the fiber extremity. In the measurement, if the probe sphere moves by touching the measured surface, the scattered light changes with the displacement of the probe sphere. In this way, the shift of the particle can be detected by monitoring its intensity at the other fiber extremity.

3. Theory and numerical modeling

In this report, we analyze numerically the optical force exerted on the particle illuminated by the laser light from the fiber. Optical forces are the result of the transfer of momentum from the illumination light to the particle in the process of light scattering. This transfer of momentum can be obtained by solving the electromagnetic scattering problem. Thus, it is essential to calculate the electromagnetic field that is scattered by the optical fiber tip and the particle. Solving an electromagnetic scattering problem requires the solution of the Maxwell equations. We employ the 3-D FDTD method to obtain the solution of the Maxwell equations [12]. In the FDTD method, the analyzed region is divided into discrete grids of points, and the finite-difference representation of Maxwell's curl equations using a central-difference formulation and the Yee-cell notation is applied to each grid. This computational method is widely and effectively used to solve electromagnetic problems with complicated configurations.

Once the scattering electromagnetic field is determined, we can obtain the optical force from the electromagnetic field by the Maxwell stress tensor [8-11]. Optical force is a kind of electromagnetic force. According to the conservation of momentum, providing momentum to an object generates the force acting on the object. In the case that the object receives the electromagnetic momentum from the light, optical force is exerted on the object. The electromagnetic momentum is expressed as Maxwell stress tensor given by

$$\mathbf{T} = \varepsilon_0\varepsilon\mathbf{EE} + \mu_0\mu\mathbf{HH} - \frac{1}{2}\mathbf{I}(\varepsilon_0\varepsilon\mathbf{E}\cdot\mathbf{E} + \mu_0\mu\mathbf{H}\cdot\mathbf{H}) \tag{1}$$

where ε_0 and μ_0 are the electric permittivity and the magnetic permeability of vacuum, and ε and μ stand for the dielectric constant and magnetic permeability of surrounding medium, respectively. By integrating this Maxwell stress tensor on the surface surrounding the object, the change of the momentum inside of the surface can be found. Since the momentum changes on the boundary of the object, the extinction amount of the momentum becomes the force acting on the object. The electromagnetic force **F** in a steady state is given by,

$$\mathbf{F} = \iint_S \langle \mathbf{T}\cdot\mathbf{n}\rangle dS \tag{2}$$

where $\langle \ldots \rangle$ represents the time average, and **n** is the outwardly directed normal unit vector.

Fig. 2 shows the geometry of the model for the numerical analysis. The analysis region of 12 μm × 7.4 μm× 14 μm, which is the foremost part including the fiber tip and the spherical probe in the air, is considered. The origin of the coordinate system (x, y, z) is located at the fiber tip, and the top of the probe sphere ***P*** represents its position. The probe is a silica sphere (n=1.44) with diameter 5 μm. The micro optical fiber surrounded by the air cladding (n = 1.0) has 4 μm core (n = 1.47) diameter. Nd:YAG laser (λ = 1064 nm) is guided by the fiber, and emittid from its tip which is tapered with tip radius r = 500 nm and tip angle α = 45˚. In practice, this micro fiber with air cladding is a multimode optical fiber at λ = 1064 nm, and many modes propagate in it. However, the HE_{11} mode in the main body part couples the HE_{11} mode in the micro fiber part with 69% coupling efficiency at the boundary between the main body part and the micro fiber part, and the other light

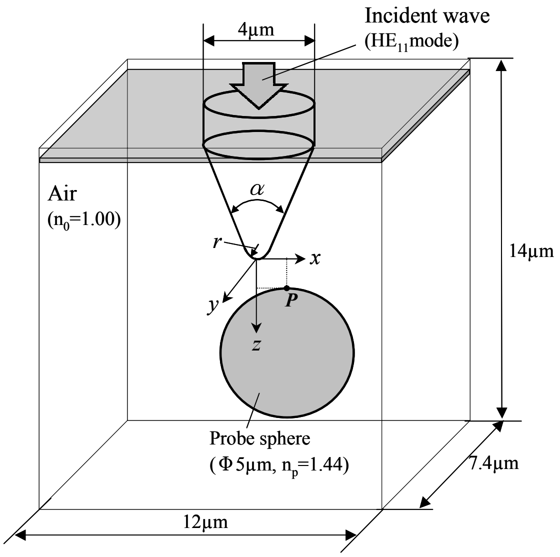

Fig.2 The geometry of the model. The fiber has a tip radius r = 500 nm and a tip angle α = 45˚.

leaks at the boundary or couples other modes. Since most light power is provided to the HE_{11} mode in the micro fiber, we assume that only HE_{11} mode is guided to the fiber tip and employ the HE_{11} mode as the incident wave.

We compute the electromagnetic field of this model using FDTD method, and calculate the trapping force exerted on the spherical probe by applying Eq. (1) and (2) to the cubic surface surrounding the probe. We take the time average of the force over the period of the electromagnetic field and continue these successive calculations until the force values no longer change significantly. In order to find the relation of the position of the probe and the force, the probe position was changed near the tip and the successive calculations are performed for each position.

4. Optical force exerted on probe sphere

Fig. 3 shows the electromagnetic field distribution near the fiber tip in the x-z plane. The spherical probe is absent in Fig.3 (a), and is placed under the fiber tip in Fig.3 (b). As shown in Fig. 3(a), the tapered structure of the fiber focuses the light to the tip and generates an evanescent field in the vicinity of the tip as the illumination mode fiber of NSOM. In Fig. 3(b), it is shown that the probe scatters the evanescent wave. This change of the electromagnetic field on the probe surface gives rise to the optical force acting on the probe sphere.

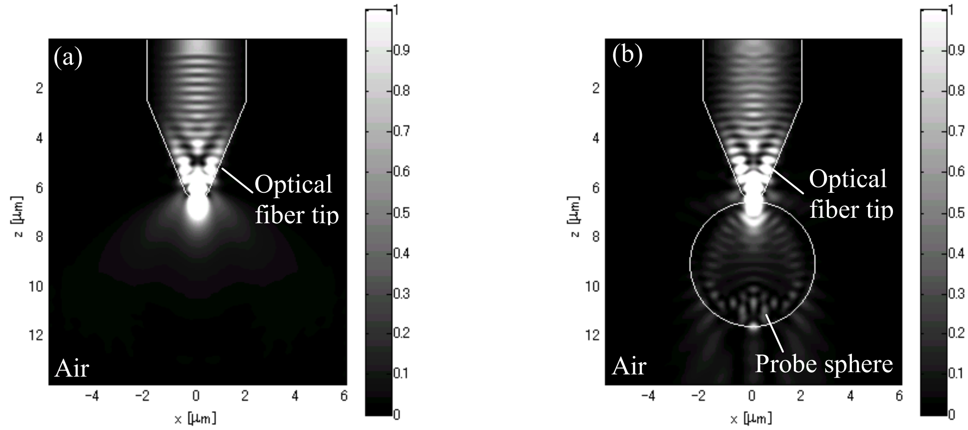

Fig.3 The distribution of the electromagnetic field in the vicinity of optical fiber tip (a) without the probe sphere, (b) with the probe sphere

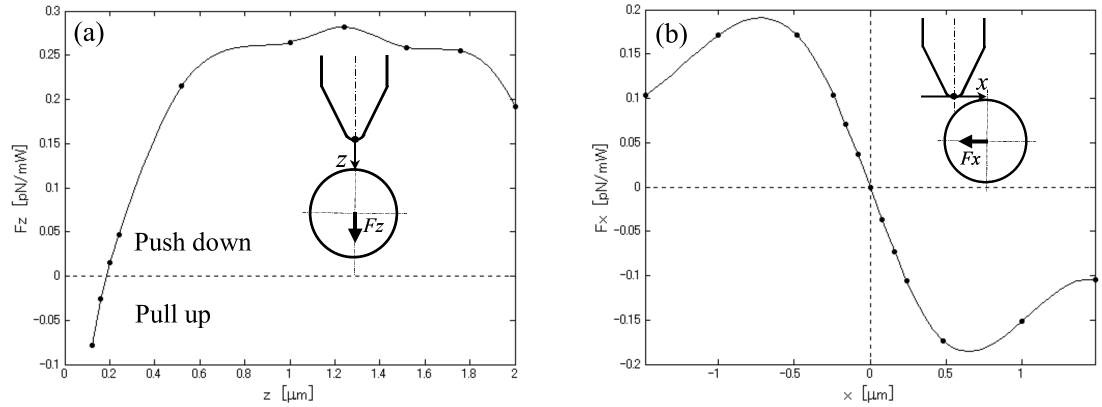

Fig.4 (a) Longitudinal optical force and (b) transverse optical force, in pN per milliwatt of total power transmitted in the optical fiber.

The calculated optical force for each probe position is shown in Fig. 4. Fig. 4(a) shows the longitudinal optical force acting on the probe sphere located along the fiber axis. A positive force acts to push the probe down, and a negative force acts to pull it up. We note that the pushing force acts on the probe in the region of $z > 0.2$ μm, and pulling force acts on it in the region of $z < 0.2$ μm. Fig. 4(b) shows the evolution of the transverse force acting on the probe as the probe moves laterally. The result indicates that when the probe shifts its position, the optical force acts to attract the probe to the fiber axis. In both the direction along the z and x axes, the probe is attracted toward the strong intensity field. This phenomenon is similar to the conventional optical gradient trap in which a particle is trapped near a spot focused by an objective lens. The weight of the silica particle as probe (density 2.0 g/cm^3) is 0.13

pg. Since, in the vicinity of the tip, the pulling up force of 0.078 pN/mW exerts on the probe sphere, we can trap the probe sphere at the tip the fiber tip against the gravitational force with 16.4 mW transmission light power. In the region of $-0.5 < x < 0.5$, there is a linear relation between the displacement and the transverse force. Therefore, the spring constant of this probe system can be found. In the case of 16.4 mW power, we obtain the lateral axial spring constant $k = 5.8 \times 10^{-6}$ N/m, which is much lower than the spring constant of the AFM (k= 0.1). Consequently, this probe can have quite a low measuring force and avoid the damage to delicate samples.

5. Position detection signal

In order to characterize the behavior of position detection signal, we analyzed the reflection light signal returning into the fiber while the probe is approaching the measured surface. Fig. 5 shows the simulation result. The horizontal axis indicates the spatial relation x of the measured surface and the approaching point O on the probe at the equilibrium position. The positive x means the distance between the approaching point O and the measured surface, and the negative x means the displacement of the probe (see Fig. 5). The vertical axis indicates the intensity of the detection signal that is calculated by integrating the electromagnetic field intensity of the reflected wave inside of the fiber. We obtained the electromagnetic field of the reflected wave by subtracting that of the incident wave from the total electromagnetic field inside of the fiber. We note that when x is positive, there is no change of the detection signal. When the probe contacts the measured surface and the probe shift becomes more than 200 nm, the signal intensity increase with the shift amount. Then if the shift amount exceeds 300nm, the signal intensity decays substantially. We can detect the position of the measured surface by sensing this substantial change of the signal. However, it is a problem that the probe needs such a large shift of 200 ~ 300 nm until the position is detected. In the actual measurement, we have to calibrate this bias value. It is indispensable to improve the system for more sensitive probe.

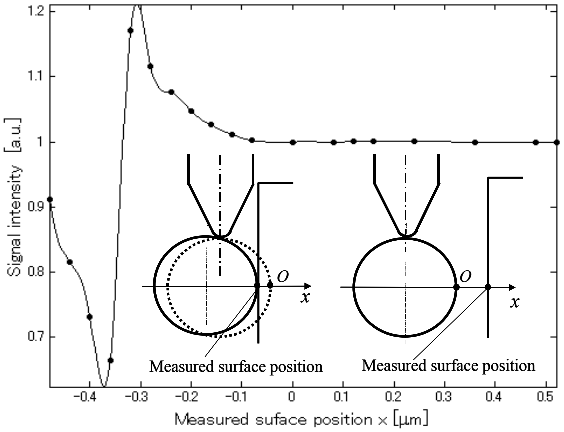

Fig.5 The intensity of position detection signal and displacement of the measured surface position x.

6. Conclusion

The fundamental analysis on the fiber trapping probe technique is demonstrated using FDTD method and Maxwell stress tensor. We confirmed that the probe sphere could be trapped three-dimensionally by optical force from a tapered fiber tip with a tip radius 500nm and a tip angle 45°. The lateral spring constant of the probe is 5.8×10^{-6} N/m, which is much lower than the spring constant of the AFM. Therefore, this probe can have quite a low measuring force and avoid the damage to delicate samples. In addition, we characterized the position detection signal. The probe shift beyond 200 ~ 300 nm gives rise to the substantial change of the signal intensity. It is possible to detect the position of the measured surface by sensing the signal change. However, it is necessary to improve the probing system for the more sensitive probe.

References

[1] Y. Takaya, S. Takahashi, T. Miyoshi: ASPE Proceedngs, 27, 367 (2002)
[2] A. Ashkin, J. M. Dziedzic, J. E. Bjorkholm, S. Chu: Opt. Lett. 11, 288 (1986)
[3] A. Ashkin: Phys. Rev. Lett. 24, 4, 156 (1970)
[4] A.Constable, J. Kim, F. Zarinetchi, M. Prentiss: Opt. Lett. 18, 1867 (1993)
[5] K. Taguchi, K. Atsuta, T. Nakata, M. Ikeda: Opt. Quant. Electron. 33, 99 (2001)
[6] S. D. Collins, R. J. Baskin, D. G. Howitt: Appl. Opt. 38, 28, 6068 (1999)
[7] K. Okamoto, S. Kawata: Phys. Rev. Lett. 83,22,4534 (1999)
[8] W. H. Choi, J. H. Jo, S. Chang: Jpn. J. Appl. Phys. 39, 3961 (2000)
[9] L. Novotny, R. X. Bian, X. S. Xie: Phys. Rev. Lett. 79, 645 (1997)
[10] P. C. Chaumet, A. Rahmani, M. Nieto- vesperinas: Phys. Rev. Lett. 79, 645 (1997)
[11] T. Uno: Finite Difference Time Domain Method for Electromagnetic Field and Antennas, CORONA PUBLISHING CO., Japan (1998)