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Non-perturbative measurement of evanescent fields☆

Yoshimasa Kawata [a], Taihei Okamoto [b], Wataru Inami [b,*]

[a] Research Institute of Electronics, Shizuoka University, Johoku, Naka, Hamamatsu, 432-8011, Japan
[b] Faculty of Engineering, Shizuoka University, Johoku, Naka, Hamamatsu, 432-8561, Japan

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ABSTRACT

Evanescent electromagnetic fields that decay exponentially with distance from a substrate surface are challenging to measure accurately because the experimental procedure usually perturbs the distribution. We propose a non-perturbative method of characterizing an evanescent field by scanning a particle that is illuminated by a second wavefront that creates a controlled interference pattern. Because it can always be located in a dark region of the interference fringes, the particle does not scatter light and distort the evanescent field. We demonstrate the measurement principle with Finite-difference time-domain numerical simulations.

1. Introduction

Evanescent fields [1] are localized at the interface between media of high and low refractive indices and are created when light from the higher refractive index medium is incident at the surface under conditions of total internal reflection. Evanescent fields are also excited on the surface of fine structures and may carry information concerning the structures. They are the basis for near-field optical microscopy, which overcomes the diffraction limit [2] of conventional optical microscopy. An evanescent field is a non-propagating wave that is localized on the surface of structures. In order to detect the field distribution, a small-aperture probe is inserted within the penetration region and converts the evanescent field into a propagating wave. The apexes of apertureless probes are also used for scattering the evanescent field [3–6]. Theoretically, the amplitude of an evanescent field decays exponentially with distance from the surface [7,8]. However, it is difficult to accurately measure the field distribution because probes inserted in the field significantly disturb the distribution [9–13] by multiple scattering between the probe and the surface. Fig. 1 shows the theoretical amplitude distribution and scattering intensity from a particle in an evanescent field as a function of distance between the surface and the particle. We calculated the scattering intensity of the evanescent field at a far field by two-dimensional FDTD method. An evanescent wave is formed at a prism surface by total internal reflection of the incident wave in the prism. A gold particle, which is 50 nm in diameter is located at a distance from the surface and is scanned normal to the surface. The gold particle scatters the evanescent field and the intensity (vertical axis) is integrated intensity distribution at a line that is parallel to the prism surface, is 25 μm length and is 4 μm from the prism surface. The refractive indices of the prism and the surrounding medium are 1.5 and 1.0, respectively. As predicted, the intensity of scattering by the particle decreases exponentially for distances greater than 200 nm. However, the scattering intensity deviates considerably from theory for distances less than 200 nm because of multiple scattering between the particle and the surface. Therefore, a non-perturbing technique is required to accurately map the amplitude distribution of the evanescent field. We discuss non-perturbative detection of the evanescent field that is localized via total internal reflection at the flat interface between two media with different refractive indices. The field is detected by scanning a particle that highly scatters light.

2. Principle of non-perturbative detection of the evanescent field

Fig. 2 illustrates the principle of non-perturbative detection. The particle is located at the position (x_0, y_0, z_0). The electric field $\boldsymbol{A}(x_0, y_0, z_0)$ at this position has unknown amplitude, phase, and polarization, and is strongly distorted by the particle. We assume that another plane wave with independently controllable amplitude, phase, and polarization irradiates the particle from a different direction. The waves $\boldsymbol{A}$ and $\boldsymbol{B}$ interfere at the position of the particle. Thus, the total scattered intensity from the particle is determined by the unknown wave $\boldsymbol{A}$ and the controllable wave $\boldsymbol{B}$. The principle of the technique is verified below with finite-domain time differential (FDTD) simulations [14,15].

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* Corresponding author.
E-mail address: inami.wataru@shizuoka.ac.jp (W. Inami).

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We can minimize scattered light from the particle by controlling the polarization, amplitude, and phase of the wave ***B***. If the particle is small relative to the interference fringe spacing at position (x_0, y_0, z_0), and the particle is located in the dark region of the fringe, the scattered light is almost zero. In this case, the amplitudes of waves ***A*** and ***B*** are the same and the phase differs by π. Thus the relation $\boldsymbol{A} = -\boldsymbol{B}$ must be valid at position (x_0, y_0, z_0). Because it is located in the dark region of the fringe, light is not irradiated from the particle. This means that the ***A*** wavefront is not distorted by the particle [16]. We can detect its amplitude distribution by scanning the particle in three dimensions as the polarization, amplitude and phase of wave ***B*** is controlled to minimize the scattering. It is thus possible to determine the amplitude distribution of the unknown wave ***A*** without perturbation because the wave ***B*** is controlled such that the particle is always located in the dark region of the fringe. The method is also applicable to near-field light. Near-field light can interfere with the controlled light and dark fringes are produced. Structured illumination microscopy also uses interference fringes to improve the spatial resolution [17]. The fluorescent molecules on the bright regions of the interference fringe emit fluorescence light, but the fluorescent molecules on the dark regions do not absorb the excitation light and do not emit fluorescence light. The emission pattern carries information beyond the diffraction limit of light.

3. Verification results of non-perturbative detection method

Fig. 3 show a simple case of the non-perturbative detection. The electric field amplitude distributions are calculated by FDTD simulations. In this case, plane wave is illuminated the small particle and the transmitted wave and the scattering wave are reflected back with the plane mirror (Fig. 3(a)). The 100-nm gold nanoparticle is located at the position of the dark region of the interference pattern with the incident plane wave and the reflected plane wave. The plane wave (λ = 500 nm) is incident to the particle, the light is scattered and the wavefront is distorted (Fig. 3(b)). After the reflected light is reached to the particle (Fig. 3(c)), the scattering light decreases and distorted the wavefront is recovered gradually. The wavefront distortion is recovered and back to plane wave (Fig. 3(d)). Both of the illuminated wave and the reflected wave are recovered to plane waves. When the steady state is reached after a certain time, the interference fringes do not move. It means that the particle located dark region of the interference pattern does not disturb the electric field distribution. Video 1 (see Appendix A) also presents the process of the wavefront recover.

Fig. 4 plots the dependence of the scattering intensity on particle size, which is normalized by the fringe spacing. The scattering intensities are calculated by FDTD for the particle positioned in the bright and dark regions of the interference fringe. Relative to that in the bright region, the intensity in the dark region significantly decreases with particle size. For a particle with a size that is only 20% of the fringe spacing, the scattered intensity in the dark region is 0.2% of that in the bright region. This scattered intensity is 99.4% smaller than that in the absence of the interference fringe.

To verify the principle of this technique, light scattering of the evanescent field by the particle is evaluated with FDTD simulations. Fig. 5 illustrates the simulation model. A rectangular prism is used to generate, by total internal reflection, an evanescent wave at the top surface. The refractive indices of the prism and the surrounding medium are set to 1.5 and 1, respectively, so that a 45-degree incident wave totally reflects at the top surface of the prism. A plane wave with controllable amplitude, phase, and polarization illuminates the upper region normal to the top surface. A particle near the top surface is scanned in the normal direction. The 50-nm particle diameter is 14.6% of the interference fringe spacing between the evanescent and plane wave.

We show the gold nanoparticle located on the dark region of interference fringe does not scatter the field. Video 2 (see Appendix A) shows the calculation result of electric field distribution for the model in Fig. 5

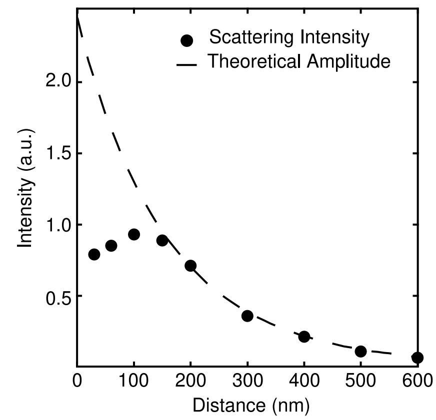

Fig. 1. Theoretical amplitude distribution and scattering intensity from a particle in the evanescent field. The amplitude distribution and scattering intensity depend on the distance between the surface and the particle.

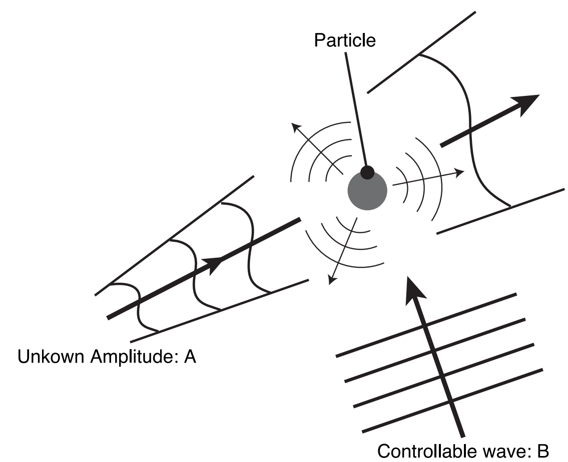

Fig. 2. Principle of non-perturbative field measurement with a highly scattering particle. The unknown electric field A wave is scattered by the particle. The polarization, amplitude, and phase of a second wave B are controlled to minimize the scattering.

when the particle is positioned on the dark region of interference fringe. At first only evanescent field is incident and the light is scattered on the gold nanoparticle on the surface, and the wavefront of the evanescent wave is much distorted. Then a plane wave is illuminated from the upper side. Since the gold nanoparticle is located at the dark region of the interference fringe, the scattering wave is gradually decreases in time and finally the scattering light is disappear and the wavefront of evanescent wave is recovered to the wavefront with no distortion. Video 3 (see Appendix A) shows the electric field distribution when the particle is positioned on the bright region of interference fringe. First, the evanescent field is formed on the prism surface due to total internal reflection and the particle scatters the evanescent field. After that, a plane wave entered from the upper side. The plane wave interfered with the evanescent field and the scattered light intensity by the particle enhanced. Video 4 (see Appendix A) shows the electric field distribution for the model without the particle. The electric field distribution is same as Video 1 after the recovering of wavefront. It indicated that the gold nanoparticle which located at the dark region of the interference fringe does not perturb the evanescent wave. The gold nanoparticle located on the dark region of interference fringe does not scatter the field.

Fig. 6 depicts the simulated electric field distributions when the particle is located in the dark (Fig. 6(a)) and bright (Fig. 6(b)) regions. For comparison, the intensity distribution in the absence of the particle is shown in Fig. 6(c). To visualize the intensity distortions due to