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Laser focal profiler based on forward scattering of a nanoparticle

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ABSTRACT

A laser focal intensity profiling method based on the forward scattering from a nanoparticle is demonstrated for in situ measurements using a laser focusing system with six microscope objective lenses with different numerical apertures ranging from 0.15 to 1.4. The measured profiles showed Airy disc patterns although their rings showed some imperfections due to aberrations and misalignment of the test system. The dipole radiation model revealed that the artefact of this method was much smaller than the influence of the deterioration in the experimental system; a condition where no artefact appears was predicted based on proper selection of measurement angles.

1. Introduction

The intensity distribution near the laser focal spot is a key performance indicator of many laser micro-/nanotechnologies. It determines the spatial resolution of laser microscopes [1–6], the efficiency of laser beam machining [7], the record density of optical data storage [8–10], the spring constant of force measurement systems with optical trapping [11–13], among others. To achieve higher performances, methods for modifying the focal intensity distribution have been extensively investigated using a variety of techniques, including nonlinear optics [1,3–6] and pupil function engineering [14–16]. Adaptive optics have also been developed to retrieve the original focal intensity distribution from the deteriorated one due to the aberrations in the optical system [17] and the refractive index mismatch between the specimen and the objective immersion medium [13,18,19]. The vector wave theory of electromagnetic fields [20–22] has been successfully used to describe the polarisation effect observed in the focus of linear polarised light with high numerical aperture (NA) resulting in an ellipse-shaped Airy disc. In addition, this theory can describe the intensity distributions resulting from pupil function engineering and the effects of refractive index mismatch between the specimen and the surroundings [23]. However, methods for directly measuring the intensity distribution near the laser focal spot with a high NA objective lens are still under development.

An in situ technique for intensity profiling of the laser focus using a CCD/CMOS camera is commercially available and records the intensity profile directly using a two-dimensional detector array [24]. A disadvantage of this profiler is the limited spatial resolution and sampling frequency due to a large pixel size, which is more than a micron at minimum. To apply this profiler to a focal spot smaller than the pixel size, the focal spot needs to be magnified with optics and imaged onto the detector. However, this magnification method may induce unwanted aberrations; it is difficult to align and requires that the magnification optics have a higher NA than those used for focusing the laser beam.

The knife-edge method [25] is another in situ technique that has been developed to measure the one-dimensional profile and determine the diameter of the waist of the Gaussian beam, which is symmetric with respect to the propagating axis. This technique has been demonstrated for small focal spots equivalent to the range of wavelengths of the incidence light [26,27]. With growing interest in analysing two-dimensional distributions, the knife-edge method has been modified for two-dimensional profiling where the one-dimensional profiling is repeated at different angles to obtain a series of data that are used to reconstruct a 2D distribution using Radon back-transformation [28–30]. It has been reported that the interaction between the metal knife-edge and incident light introduces an artefact in the profile [31] and a correction protocol has been suggested [32].

The point scanning method has also been used to investigate the laser focal spot of microscopes and the point spread function of optical systems. A fluorescent bead [33], gold particle [34,35] or a cantilever tip of a near-field scanning optical microscope [36,37] are illuminated in the laser spot focused by a microscope objective lens. Then, the backward fluorescence or Rayleigh backscattering are passed through the same objective lens and detected by a single detector; this measurement is repeated with scanning to obtain 2D or 3D distributions of the intensity. This epi-detection method is difficult to apply commercially available instruments which are not designed in advance to mount the laser focal measurement system. It has also been pointed out [28] that detection of the limited solid angle may induce an artefact as scattering from the particle has an angular pattern [38]. In this study, a point scanning

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method with forward scattering detection has been developed as a laser focal profiler (LFP) and is demonstrated for in situ measurements.

2. Forward scattering detection optics

The optical arrangement of the detection system in the LFP system is shown in Fig. 1(a). A nanoparticle is fixed at the centre of the face of a glass hemisphere (HS). When a focusing laser beam with the focusing angle θ_i converges to the centre of the hemisphere face and illuminates the particle, some fraction of incident light is scattered omnidirectionally by the particle while another fraction is refracted without any interaction with the particle, as shown in Fig. 1(b). The refraction angle of the marginal ray is denoted as θ_r. Both the forward scattered light, which scattered towards the centre of the hemisphere, and the refracted light diverging from the centre of the hemisphere, propagate along the normal direction to the hemisphere surface and penetrate the surface without refraction. The refracted light propagating through the hemisphere surface is blocked by a beam stopper (BS) comprising a metal disc located between the hemisphere and the collimator lens (L_1). The diameter of the BS is chosen to ensure that the maximum blocking angle (θ_1) is larger than θ_r. On the contrary, light scattered at angles between θ_1 and the maximum collection angle (θ_2) of L_1 is collected by L_1, while that scattered at an angle smaller than θ_1 is blocked by the BS. The collected light is collimated with L_1 according to the optical configuration where the centre of the hemisphere face is located at the focus of L_1 and is then focused onto a photodetector (PD) with a focusing lens (L_2). Hence, only forward scattered light over the range of angles between θ_1 and θ_2 reaches the photodetector. Here, the relation between these angles is expressed as

$$0 < \theta_r < \theta_1 < \theta_2 < \frac{\pi}{2}. \tag{1}$$

An electrical circuit board (ECB) converts the PD signal into a voltage signal that can be analysed using a personal computer. The distribution of the laser intensity, that is converted into a voltage signal, near the laser focal spot can be obtained by scanning the entire detection system of the LFP.

The spatial resolution is defined by the size of the scatterer, while the maximum numerical aperture of the focusing laser beam (NA_{fl}) to be evaluated is determined by θ_1 and the refractive index of the hemisphere (n_{HS}). The NA of the focusing laser beam is defined as

$$NA_{fl} = n_i \sin\theta_i, \tag{2}$$

where the refractive index of the medium between the focusing lens and the hemisphere is denoted as n_i. Snell's law at the boundary of the hemisphere face is expressed as

$$n_i \sin\theta_i = n_{HS} \sin\theta_r. \tag{3}$$

Then, the relation between NA_{fl}, θ_1, θ_2 and n_{HS} can be derived using Eqs. (1)–(3) as follows:

$$NA_{fl} < n_{HS} \sin\theta_1 < n_{HS} \sin\theta_2. \tag{4}$$

In the experimental setup, the diameter of BS or $\sin\theta_1$ can be changed depending on NA_{fl}, while L_1 or $\sin\theta_2$ is fixed. Hereby, the NA of the LFP NA_{LFP} and of its cut-off NA_{cutoff} ,which means the maximum NA that can be analysed, are defined as

$$NA_{cutoff} = n_{HS} \sin\theta_1, \tag{5}$$

$$NA_{LFP} = n_{HS} \sin\theta_2. \tag{6}$$

Then, the relation between the NA of the focusing laser beam, LFP and its cut-off is

$$NA_{fl} < NA_{cutoff} < NA_{LFP}. \tag{7}$$

The LFP can evaluate the focal intensity distribution formed by the focusing lens with a NA smaller than the cut-off of the LFP.

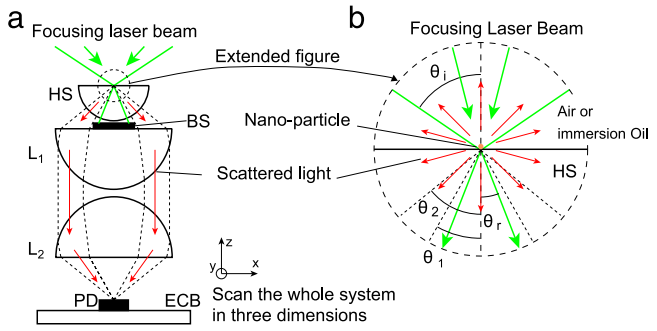

Fig. 1. (a) Schematic showing the arrangement of the optical components of the detection system in the laser focal profiler (LFP). HS: hemisphere; L_1: collimator lens; L_2: focusing lens; PD: photodetector and ECB: electrical circuit board. (b) Extended figure showing the scattering by a nanoparticle with the laser focus at the centre of the face of a glass hemisphere showing the focusing angle (θ_i), refraction angle (θ_r), maximum blocking angle (θ_1) and maximum collection angle (θ_2).

3. Experimental setup

The detector of the LFP was assembled using a hemisphere with a refractive index of 2.0 at a wavelength of 532 nm and an aspherical lens with an NA (= $\sin\theta_2$) of 0.83 for L_1. Therefore, the NA_{LFP} was determined as 1.66 from Eq. (6). The NA_{cutoff} value was set to 1.45 by adjusting the diameter of the BS disc or $\sin\theta_1$ in Eq. (5) for all measurements with six objectives with different NA values (0.15, 0.3, 0.45, 0.8, 0.9 and 1.4), while the optimum disc size depended on the NA_{fl} of each objective lens with respect to the amount of light detected. For L_2, the same lens as L_1 was adopted. The total size from the hemisphere face to the focal plane of L_2 was 28 mm, compact enough to be set with a xyz piezoscanner with a precision better than 10 nm on an upright microscope stage.

A gold particle with a diameter of 40 nm was used as a scatterer and prepared as follows. A 40 nm colloidal gold solution (EMGC40, BBI Solutions) was filtered using a membrane filter with a pore size of 200 nm and was dropped onto the centre of the hemisphere face using a 30 μL micropipette. This resulted in isolated single gold particles as well as aggregates of two or more particles being distributed around the centre of the hemisphere face after the solution dried.

The detector of the LFP with the piezoscanner was set on the stage of an upright microscope, as shown in Fig. 2. To generate a laser focal spot for testing, a laser beam with linear polarisation from a 532 nm diode laser (#84–929, Edmund Optics) was expanded with a beam expander of 10× magnification, resulting in a laser beam with a diameter of more than 20 mm. This beam was guided into the microscope and propagated through a polarising beam splitter (PBS) ensuring linear polarisation along the x-axis at the pupil of the objective and was projected on the pupil of the objective lens of the microscope. Then, the objective lens focused the laser beam onto the centre of the hemisphere face. The hemisphere face was observed with a CCD camera to confirm that the laser focus was located near the centre indicated by a circular marker of 300 μm diameter on the hemisphere face. The focal spots of six objectives with different NA (0.15, 0.3, 0.45, 0.8, 0.9 and 1.4) were measured. Because the objective lens of NA 1.4 is an oil immersion objective, the immersion oil was filled in the medium between the objective lens and the hemisphere for the use of this lens while the others are dry objectives and nothing but the air was filled in the medium for the use of the dry lenses.

4. Results

When the LFP detector was scanned over the square area of 100 μm on each side in the focal plane, a map of many Airy disc patterns was obtained. Many of them showed almost the same patterns because