Widefield Interferometric Detection and Size Determination of Dielectric Nanoparticles

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***Abstract*—We propose an interferometric technique to detect and size low-index nanoparticles with radius smaller than 100nm. The method offers sensitive detection and identification of pathogens such as viruses based on the size information.**

I. Introduction

High-throughput, cost-effective and fast characterization of nanoparticles plays crucial role in materials engineering, biomedical applications and homeland security. Optical techniques are in particular versatile for various applications due to their sensitive and compact nature. However very small biological and low-index dielectric particles are difficult to be detected optically due to the fact that they provide low contrast to the surrounding medium. Conventional elastic-scattering techniques suffer rapid decrease of detected signal as the scattered light intensity scales with sixth power of the radius of nanoparticle [1].Recently several methods based on discrete photonic devices which utilize enhanced light-matter interaction have been reported for single polystyrene nanoparticle and virus detection and sizing down to 30nm in radius [2]. However these methods are mostly proof of principle and yet to be practical for large-scale implementation as the detection is prone to environmental noise and low-throughput. In this study we theoretically demonstrate a widefield interferometric imaging technique which is capable of detecting thousands of nanoparticles in parallel with a few image acquisition. Our technique which utilizes a planarly layered reflecting surface platform, employs common-path interferometric detection of elastically scattered field and provides better dynamic range and sensitivity to small particles comparing to the conventional scattering techniques. We further determine the size of each nanoparticle by z-stepping the sample platform and recording the interferometric visibility which yields the size information for each nanoparticle.

The proposed optical setup is composed of a telescopic imaging platform with an LED source in Kohler Illumination configuration. The nanoparticles with various sizes are dispersed on a reflective substrate which is made of thin layer of silica on top of a silicon wafer. The interferometric signal which is mixing of elastically scattered field from nanoparticles and reflected incident field is collected by a high NA objective and imaged on a CCD detector.

II. Theory

Elastic scattering from nanoparticles can be modeled as scattering from a driven dipole in the electrostatic limit. The induced dipole moment on an isotropic and homogeneous spherical particle by an external field is given [3]:

$$\mathbf{p} = 4\pi\varepsilon_m R^3 \frac{\varepsilon_p - \varepsilon_m}{\varepsilon_p + 2\varepsilon_m}\mathbf{E_0}(\mathbf{r_0}) \tag{1}$$

where $E_0(r_0)$ is the driving electric field on particle center; ε_m and ε_p are the permittivity of the surrounding medium and particle respectively. Angular Spectrum Representation (ASR) can be employed to obtain the scattered field on a CCD detector through a telescopic imaging system. The detail of the ASR can be found elsewhere [4]. Assuming the driving field is $\mathbf{E_0}(\mathbf{r_0}) = E_{dr}\hat{\mathbf{x}}$ and particles are in perfect focus for simplicity, the Cartesian components of the scattered field on the detector can be found:

$$\mathbf{E_s^x}(\rho,\varphi) = A\frac{pfe^{ik(f-f')}}{8\pi f'}\begin{bmatrix} I_0(\rho) + I_2(\rho)\cos 2\varphi \\ I_2(\rho)\sin 2\varphi \\ -2iI_{12}(\rho)\cos\varphi \end{bmatrix} \tag{2}$$

where $A = i\frac{kw^2}{\varepsilon_0 c^2}$, f and f' are the focal length of the objective and tube lens respectively. The $I(\rho)$ expressions are the diffraction integrals. It should be noted that the contribution from reflected surface is included in the diffraction integrals as particles are located on a reflective surface. The explicit form of the diffraction integrals are not given here for the sake of brevity [4]. The reference light is the reflected field that is not scattered in the vicinity of a nanoparticle and the field expression can be obtained on the detector as well. The detected intensity on the detector is given as:

$$\begin{aligned} I_{CCD}(\rho,\varphi) &\propto \mid \mathbf{E_s} + \mathbf{E_{ref}} \mid^2 \\ &\propto \mid \mathbf{E_{ref}} \mid^2 + 2 \mid \mathbf{E_s} \mid\mid \mathbf{E_{ref}} \mid \cos\phi \end{aligned} \tag{3}$$

where the first term in equation above is the background due to reference intensity, the second term is the interferometric signal and the pure scattering intensity is ignored since it is small comparing other two terms for small particles. ϕ denotes the relative phase between reference and scattered fields. In order to estimate the size of the particles from the interferometric term, ϕ must either be known or decoupled from the

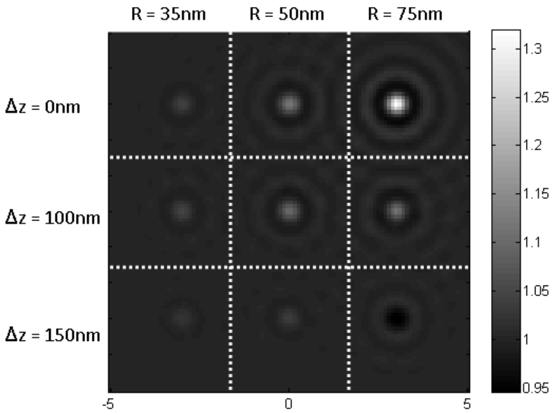

Figure 1. The simulated image of particles on a CCD detector. Colorbar indicates the contrast values.

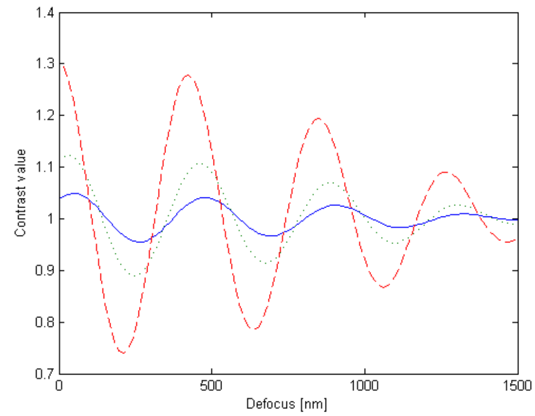

Figure 2. Peak contrast values of the nanoparticles with radius 35nm (solid), 50nm (dotted), 75nm (dashed) versus defocus distance from the silica surface

signal. When different size nanoparticles are dispersed on a flat reflective surface, all particles are not in focus inevitably. A term $\Psi = exp(-2ik\Delta z(\cos\theta - \cos\gamma))$ must be added into the kernel of the diffraction integrals in order to take the defocus into account for different size of particles. γ denotes the angle of the illumination plane-wave. As long as the focal plane position is accurately known, the contribution of Ψ into the relative phase between reference and scattered fields can be calculated. In real-life situations it is quite challenging to locate the exact position of the focal plane all over the field of view due to experimental noise and even small deviations can cause faulty results. Therefore we suggest z-stepping of focus and simultaneous recording the interferometric visibility $I_{vis} = (I_{max} - I_{min})/(I_{max} + I_{min})$ in the vicinity of the reflective surface. Fitting the parameter I_{vis} as a function of particle radius will provide an accurate metric to determine the size of the nanoparticles on a large field of view.

III. Results

In order to demonstrate the concept, we model an LED source in Kohler Illumination scheme as a collection of mutually incoherent point sources at the back aperture of the focusing objective. For each individual point sources the illumination can be assumed to be plane wave with a certain angle after refracted at the objective. If the back aperture is uniformly filled then the corresponding intensity profile is also uniform and coherent only at the extend of diffraction limit on the sample plane[5]. Therefore the signal from small nanoparticles which are separated by a distance larger than resolution limit will not interfere with each other thus it allows parallel processing in large field of view. Figure 1 shows simulated CCD image for 35nm, 50nm and 75nm polystyrene nanoparticles (n = 1.45) at different defocus distances. The focusing and collection objective NAs are 0.1 and 0.8 respectively, the thickness of the silica layer is chosen as 100nm and the wavelength of the LED is 525nm. Δz values show the upward defocus distance from the silica surface. Different size particles have distinct responses at different defocus values as expected. For $\Delta z = 0nm$ case, the individual responses seem to be correlated to size of the particles. However at $\Delta z = 100nm$ case, response of the particles are very close to each other. The conclusion that can be drawn from this observation is that the defocus distance must be known accurately in order to characterize the size of the particle by the interferometric signature. Figure 2 demonstrates the z-stepping concept for the same three size of particles. The peaks and dips for different size of particles do not coincide at a specific defocus value. A rapid z-stepping in the vicinity of the reflective surface can be done to record peak values on CCD for each particle. Thus the size information is decoupled from the unknown phase term introduced by the focal plane distance ambiguity.

IV. Conclusion

We theoretically investigated a new technique which is capable of detecting and sizing low-index nanoparticles much smaller than wavelength of the incident light. The technique combines the interferometric detection with widefield imaging capability thus it offers sensitive, fast and high-throughput characterization. Size information provides distinctive fingerprint for various pathogen species. Since the optical setup is cost-effective and compact, it is suitable to be used in field operations against epidemics caused by small pathogens such as H1N1. We have acquired experimental data (not presented here) which successfully provides verification for dielectric nanoparticle and virus detection and sizing concept as presented here.

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