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Real-space observation of photonic nanojet in dielectric microspheres

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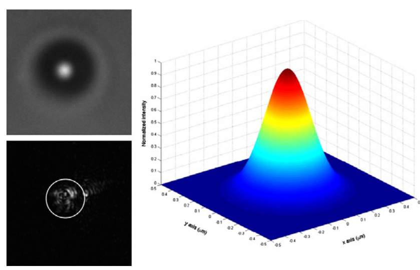
HIGHLIGHTS

- We present the real-space observation of photonic nanojet in microspheres.
- The photonic nanojets are measured by using a scanning optical microscope.
- The results provide a new tool to detect nano-objects in a far-field optical system.

GRAPHICAL ABSTRACT

We present the real-space observation of photonic nanojet in dielectric microspheres.



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ABSTRACT

The three-dimensional real-space observation of photonic nanojet in different microspheres illuminated by a laser is reported. The finite-difference time-domain technique is used to perform the three-dimensional numerical simulation for the dielectric microspheres. The key parameters of photonic nanojet are measured by using a scanning optical microscope system. We reconstruct the three-dimensional real-space photonic nanojets from the collected stack of scanning images for polystyrene microspheres of 3 μm, 5 μm, and 8 μm diameters deposited on a glass substrate. Experimental results are compared to calculations and are found in good agreement with simulation results. The full width at half-maximum of the nanojet is 331 nm for a 3 μm microsphere at an incident wavelength of 633 nm. Our investigations show that photonic nanojets can be efficiently imaged by a microsphere and straightforwardly extended to rapidly distinguish the nano-objects in the far-field optical system.

1. Introduction

The existence of diffraction limit is recognized by Ernst Abbe about 150 years ago using a conventional optical microscope [1,2]. The diffraction in the far field system results from the loss of evanescent waves that carry high spatial subwavelength information of an object. Moreover, when lightwave is focused by a traditional lens, the spot size cannot be infinitely sharpened due to diffraction. The dimension of light spot is usually calculated by the classic Rayleigh equation. In the recent years, several optical applications have been developed based on the research of dielectric microcylinders and microspheres. The phenomenon of photonic nanojets has been revealed by many scientific literatures [3–9]. The photonic nanojets appear as narrow and elongated spots with a high intensity of electromagnetic fields, if dielectric spherical micro-objects are well illuminated. Under theoretical and experimental investigations, these studies predict the appearance of a subwavelength-waist beam that emerges from the surface of the microsphere with low divergence. The excellent properties of photonic nanojets recommend nanojets as a useful implementation for high resolution nano-target detection [3,4], fluorescence microscopy improvements [10] and nano-patterning [11]. The more understanding of photonic nanojet is nevertheless needed to fully exploit the potential of microspheres as optical super-lens.

The experimental demonstration of photonic nanojet is very important for nano-scale applications. An experimental observation of photonic nanojets created by single microsphere has been

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performed using a fast scanning confocal microscope [12]. Detection of lightwave is achieved by an avalanche photodiode. The photonic nanojets in different diameters of microspheres with diameter ranging from 1 μm to 5 μm have been studied. It can be seen that photonic nanojets are efficiently imaged by a conventional optical microscopy system. Furthermore, Kim et al. have reported systematically how a modified and more complex illumination influences the properties of photonic nanojets [13]. The wavelength, the amplitude distribution, and the polarization of the illumination affect the localization and the shape of the photonic nanojets. Then, a novel approach is introduced to capture the optical virtual imaging at lateral resolution of 50 nm using microspheres and a white-light source [14,15]. The imaging mechanism in this optical system is related to photonic nanojets. However, the detailed imaging information of photonic nanojets should be studied further. In a simple optical microscope, an intensity enhancement has been obtained by focusing the incident lightwave with a silica microsphere for the green upconversion emission of a doped fluoroindate glass [16]. The experimental results offer an original method to enhance the upconversion emission intensity in biological specimens with rare earth doped particles that can be employed as nano-sensors.

In this paper, we theoretically and experimentally demonstrate the three-dimensional (3-D) real-space observation of photonic nanojet in different microspheres illuminated by a laser at a wavelength of 633 nm. The finite-difference time-domain (FDTD) technique is used to perform the numerical simulation for the dielectric microspheres. The key parameters of photonic nanojet are measured by using a scanning optical microscope system. The three-dimensional real-space photonic nanojets are reproduced from the collected stack of scanning images for polystyrene microspheres of 3 μm, 5 μm, and 8 μm diameters deposited on a glass substrate. The 3-D numerical simulations of photonic nanojets are presented in Section 2. The experimental setup and measurement results are shown in Section 3. Finally, we summarize the remarks and discuss the potential applications of this study in Section 4.

2. Numerical approach

In order to procure precise numerical results for local electromagnetic field produced by the scattering of a homogeneous dielectric microsphere, the FDTD method has been selected to execute the 3-D calculations for photonic nanojets [17]. Recently, we have conducted two-dimensional and 3-D FDTD calculations with high resolution on photonic nanojets for microcylinders and microspheres [18–21]. The detailed enhancement analyses of localized elongated photonic nanojets generated by a core – shell microcylinder and a graded-index microellipsoid are reported. Therefore, we study the internal and near external electromagnetic field distributions of plane wave illuminated

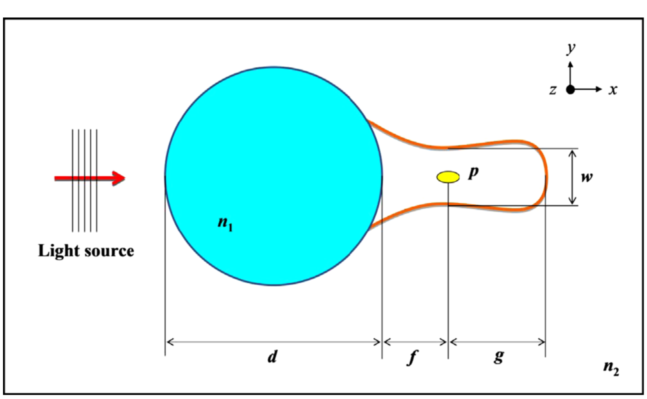

Fig. 1. Schematic diagram of a microsphere for photonic nanojet.

dielectric microspheres by using an FDTD algorithm under the perfectly matched layer boundary conditions. The computational domain is a cubic box in the 3-D simulations. The physical model consisted of four components: the light source, the dielectric microsphere, the surrounding medium (air), and the glass substrate. The centered finite difference expressions are used to the space and time derivatives that are estimated and second-order accurate in the space and time steps. The calculation step is 10 nm, which can ensure enough accuracy and high calculation speed. The propagation direction (x axis) of the illuminated light is normal to the surface of the glass substrate. For further details, refer to Ref. [17–21]. The calculation of FDTD approach is written in Matlab code. The personal computer used in the calculation has the central processing unit of Intel Core i7 and the random access memory of 24 GB.

Fig. 1 depicts the several key parameters of a 3-D photonic nanojet. The four key parameters are defined in order to characterize the photonic nanojets. The maximum amplitude of the electromagnetic field in the photonic nanojet is the peak amplitude (p). The radial distance of the point of peak amplitude from the surface of the microsphere is the focal length (f). The radial distance from the point of peak amplitude at which the electromagnetic field decays to 1/e of the peak amplitude is the decay length (g). The double distance in the y direction of the point of peak amplitude to the points where the electromagnetic field decays to 1/e of the peak value is the nanojet width (w). The peak amplitude is the measurement of the focusing energy. The focal length is analogous to the working distance of a conventional lens. The diameter and the refractive index of microspheres are d and $n_1 = 1.59$. The refractive index of surrounding medium is $n_2 = 1$. A lightwave illumination at a wavelength of 633 nm in the x direction is incident from the left and impinges on the microspheres.

Fig. 2 depicts the normalized power flow patterns of the photonic nanojets along the z axis for the microspheres at diameters $d = 3$ μm, $d = 5$ μm, and $d = 8$ μm. The dependence of intensity distributions has been explored by applying three different diameters. We observe that the nanojet size is directly proportional to the diameter of microsphere as it could be found in the focal spot of a conventional lens. Fig. 3 depicts normalized power flow patterns of the photonic nanojets along the x axis for the microspheres at diameters $d = 3$ μm, $d = 5$ μm, and $d = 8$ μm. This is easily intelligible as the photonic nanojet is a non-resonant phenomenon. The transverse full widths at half-maximum of nanojets are calculated to be 326 nm, 336 nm, and 346 nm for the diameters 3 μm, 5 μm, and 8 μm, respectively. Taking the ratio of nanojet size to diameter provides quantitatively comparable values.

3. Experimental measurement

In our experiments, we investigate the emerging electromagnetic fields comprising photonic nanojets with a high sensitivity optical microscope. The mean diameters of the polystyrene microspheres, obtained from Duke Standards, are specified as 3.002 μm ± 19 nm, 4.993 μm ± 40 nm, and 7.979 μm ± 75 nm. The refractive index of polystyrene microspheres is 1.59. The microspheres diluted in pure water and deposited on a cleaned microscope coverslip before air drying. The refractive index and thickness of borosilicate glass substrate are 1.51 and 150 μm, respectively. The concentration of microspheres is set to approach an average surface density of 1 bead per 50 × 50 μm^2. Thus light scattering between neighboring microspheres is completely avoided.

A high sensitivity optical microscope system to measure the characteristics of photonic nanojet from microspheres has recently been developed at the Tamkang University. Fig. 4 shows a schematic diagram of the experimental setup. A single mode stabilized Helium Neon laser (Melles Griot 25-STP-912-230, 633 nm) is used