Parameter optimization for photonic nanojet of dielectric microsphere*

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The characteristics of photonic nanojets are analyzed by changing the parameters, such as the wavelength, refractive index of the surroundings, diameter and refractive index of the microsphere, in this paper. Quadratic functions are used to describe the relation between the above parameters and photonic nanojets' characteristics. Several techniques are proposed to control the photonic nanojets.

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The photonic nanojet becomes a significant aspect in the researches of nano-photonics[1-3]. Because of the property of sub-wavelength dimensional confinement, it has a great potential value in nanopatterning and laser cleaning, fluorescence correlation spectroscopy[4], tissue engineering[5], optical data storage[6], and the super resolution with white light[7,8].

The potential value of photonic nanojet is the enhancement of back scattering[3,9,10]. It can provide powerful force for the super resolution and high sensitive detection because of the interaction between the jet beams and particles placed in the jet field. Besides, more efforts have been done on the influence of various incident light beams[11-14]. These efforts include controlling the jet length, beam width, and jet field volume. Another technology using microspheres with multiple layers and gradual layers extends the jet length up to 10λ[15,16], which has potential value in optical data storage and the nanopatterning. In this paper, we analyze the characteristics of photonic nanojet via finite difference time domain (FDTD) method by changing the parameters, such as the wavelength, refractive index of the surroundings, diameter and refractive index of the microsphere. The results are of remarkable significance for applications of the photonic nanojet.

The Lorentz-Mie theory is generally used to find the electromagnetic field around a dielectric sphere, where calculations of far-field scattering properties of spheres are more routinely performed. And the FDTD method becomes a major means for simulation about the microsphere jet. To make the research more convenient, some parameters have been defined. Fig.1 is the schematic diagram of the photonic nanojet based on microsphere. As can be seen from it, incident beams are linearly polarized with wavelength of λ, and a $2R$-diameter microsphere with refractive index of N_d is placed in medium with refractive index of N_s. And a focused light field which has a jet length of Z_r and beam waist of W_d emerges from the rear side of it. I_{max} is defined as the focus intensity, and f is the focal length which is from the rear side to the focus. The jet length Z_r is the distance that the intensity decreases to I_{max}/e^2 along Z axis, and W_d is the one along the X axis. The characteristics of photonic nanojets have a close relationship with these parameters.

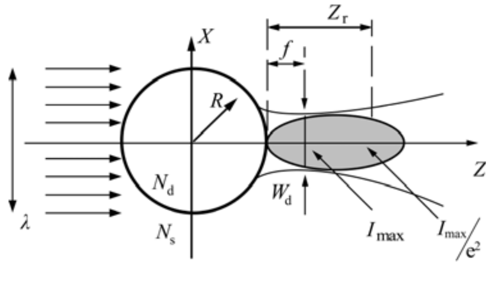

Fig.1 Schematic diagram of the photonic nanojet based on microsphere

The simulations of photonic nanojets are based on FDTD method, and the resolution is set as 20 nm. Characteristics of the photonic nanojets by changing the parameters including the wavelength, refractive index of the surroundings, diameter and refractive index of the

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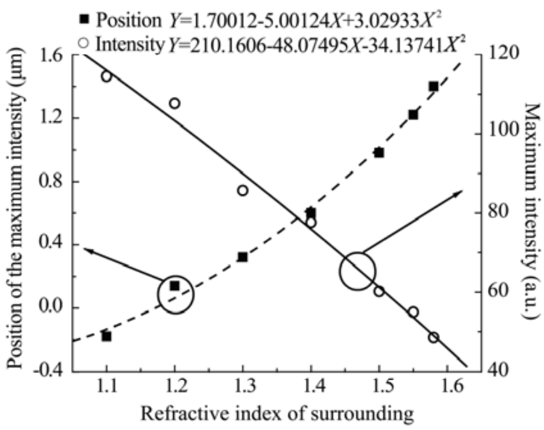
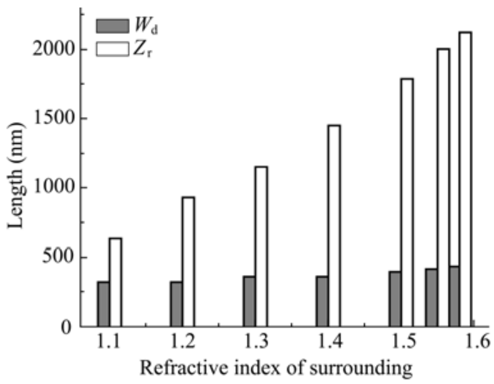
microsphere are thoroughly discussed.

Refractive index is a key point in photonic nanojets, which includes the N_d, N_s and the ratio of them. Fig.2(a) and (b) visualize the quadratic functions for a homogeneous 3 μm-diameter microsphere (N_d=1.8) illuminated by linearly polarized beams at λ=532 nm, and the N_s is 1.10−1.58. It can be seen from Fig.2(a) that the position of focus changes from -0.18 μm to 1.40 μm with the increase of N_s, and I_{max} decreases from 114.7 to 48.5. Consequently, focusing capability of the microsphere weakens as the N_s increases. Fig.2(b) shows that beam waist and jet length both have rising tendency, in which the jet length Z_r has a more remarkable one from 640 nm to 2140 nm. On the contrary, if the N_s is set as 1, N_d changes from 1.3 to 3.4, and the results will be reversed, as can be seen in Fig.2(c) and (d). All the properties of photonic nanojets have an opposite tendency with those shown in Fig.2(a) and (b). However, the position of focus will enter the microsphere when N_d > 1.6, which results in a slower change of intensity along Z axis. Thus, the jet length and beam width increase abnormally as shown in Fig.2(d). Most importantly, intensity and position of the focus change according to the form of quadratic functions if the refractive index is modified singly. The formulas are depicted in figures, in which the multinomial coefficient is determined by parameters mentioned above. In conclusion, larger jet length is at a cost of smaller intensity. The bigger the (N_d-N_s) is, the shorter f will be got. At the same time, a sub-wavelength three dimensional light field with higher intensity and shorter jet length could be achieved.

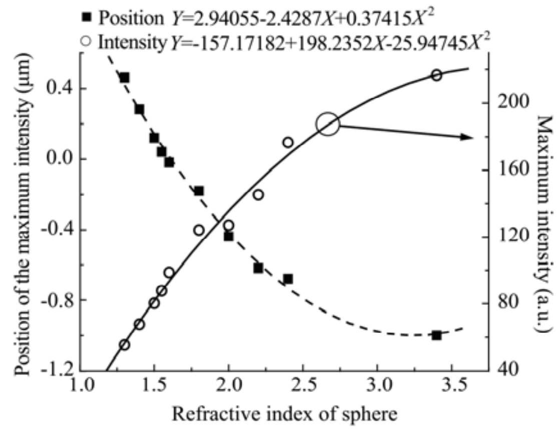
If the ratio of refractive index is fixed, things will be different. Fig.2(e) and (f) visualize the model for a homogeneous 5 μm-diameter microsphere illuminated by linearly polarized beams at λ=600 nm, N_d/N_s=1.5 and N_s varies from 1 to 1.3. It is shown that focus length changes around 0.3 μm and the jet length is almost around 2.5λ. While the refractive index is increasing, intensity of the focus has the same tendency at a cost of beam width decreasing. This stable characteristic has a significant potential value in applications.



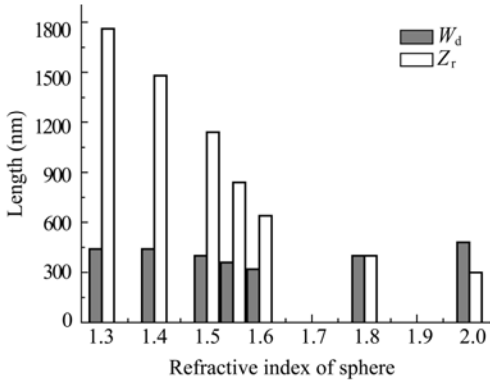
(a) Maximum intensity and its position of focus for 3 μm-diameter microsphere with λ=532 nm and N_d=1.8



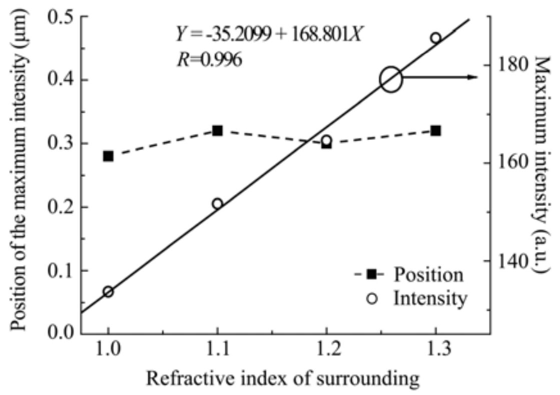
(b) Jet length for 3 μm-diameter microsphere with λ=532 nm and N_d=1.8



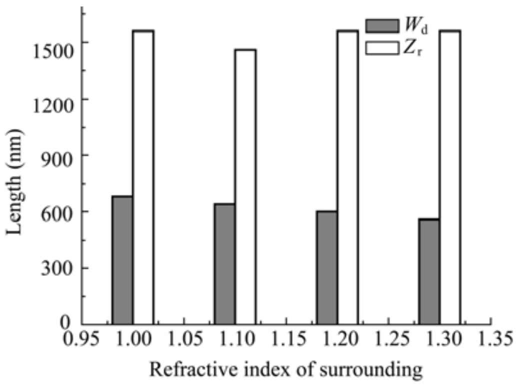
(c) Maximum intensity and its position of focus for 3 μm-diameter microsphere with λ=532 nm and N_s=1



(d) Jet length for 3 μm-diameter microsphere with λ=532 nm and N_s=1



(e) Maximum intensity and its position of focus for 5 μm-diameter microsphere with λ=600 nm and N_d/N_s=1.5

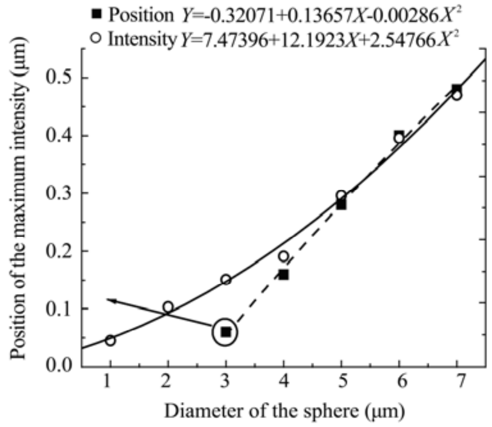


(f) Jet length for 5 μm-diameter microsphere with λ=600 nm and N_d/N_s=1.5

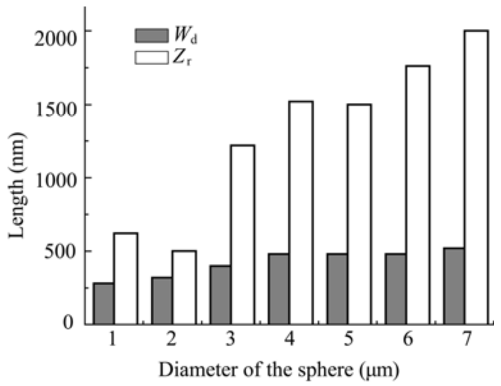
Fig.2 Characteristics of the photonic nanojet influenced by the refractive index

Diameter of microsphere and wavelength of the incident beam are another two key points to the photonic nanojets. Fig.3(a) and (b) depict the quadratic functions for a homogeneous microsphere (N_d=1.8) in the solution with N_s=1.2 illuminated by linearly polarized beams at λ=700 nm, and the diameter changes from 1 μm to 7 μm. As the diameter increases, the intensity of focus has surged 10-fold and the focal length increases from -0.02 μm to 0.48 μm. The larger R makes the sphere have larger area to accept energy at a cost of smaller radius of curvature. And then, if we fix the diameter at 3 μm, the wavelength of incident beams varies from 0.4 μm to 0.8 μm, and quadratic functions will have reverse tendencies. As shown in Fig.3(c) and (d), formulas are depicted clearly.

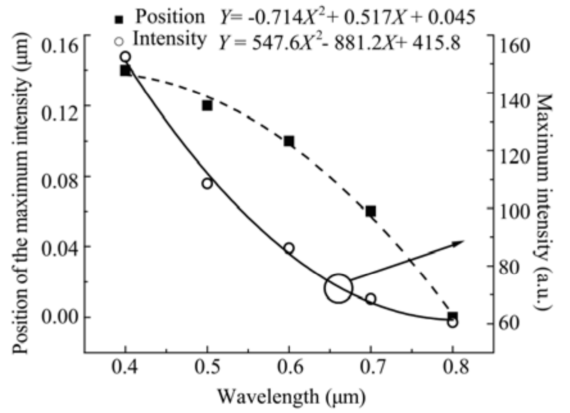
Under fixed $\lambda/2R$, a new stable situation appears. As Fig.3(e) and (f) illustrate, the model represents a microsphere (N_d=1.46) illuminated in air with the wavelength from 0.4 μm to 0.7 μm, in which $\lambda/2R$=0.2. Results show that characteristics of photonic nanojets, such as intensity of focus, jet length and beam width, change little as λ increases. This stable state has significant potential value in practical applications by optimization of parameters.



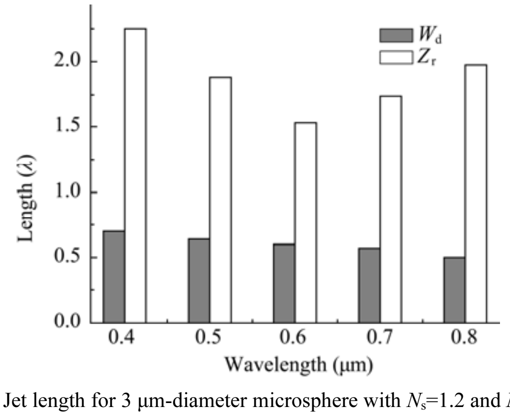
(a) Maximum intensity and its position of focus for the microsphere with λ=700 nm, N_s=1.2 and N_d=1.8



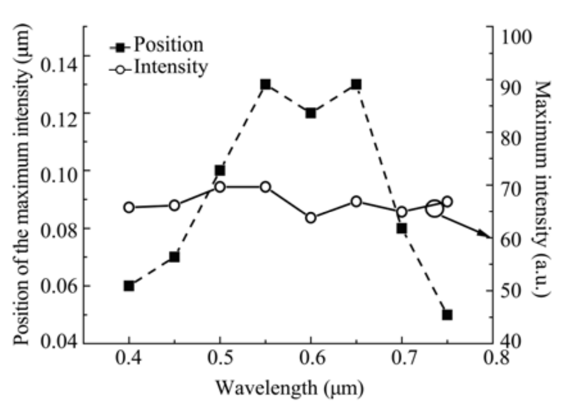
(b) Jet length for the microsphere with λ=700 nm, N_s=1.2 and N_d=1.8



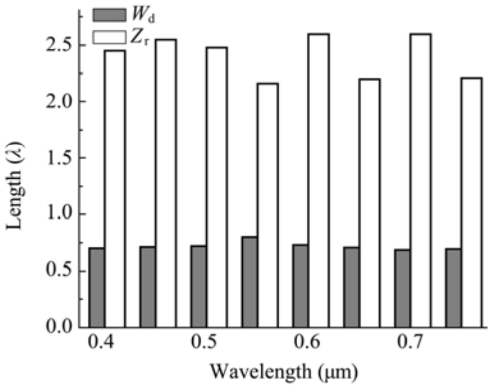
(c) Maximum intensity and its position of focus for 3 μm-diameter microsphere with N_s=1.2 and N_d=1.8



(d) Jet length for 3 μm-diameter microsphere with N_s=1.2 and N_d=1.8



(e) Maximum intensity and its position of focus for the microsphere with N_d=1.46, N_s=1 and λ/R=0.2



(f) Jet length for the microsphere with N_d=1.46, N_s=1 and λ/R=0.2

Fig.3 Characteristics of the photonic nanojet influenced by the diameter of the sphere and the wavelength

The photonic nanojets have attracted wide attention in the fields, such as nano-patterning, laser cleaning, optical data storage and the tissue engineering. This paper discusses many parameters which influence the characteristics of jet beams. Several conclusions are drawn: The position and intensity of focus vary in a quadratic function when only a single parameter is considered; The longer jet length is at a cost of lower intensity of focus when the refractive index is regarded singly; When the diameter and wavelength are considered separately, the intensity of focus and jet length have the same tendency with the varying parameter; If more parameters are taken into account simultaneously, a stable state can be achieved. When the ratio of two parameters is fixed, such as N_d/N_s and R/λ, it is of great significance in practice.

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