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Research on the Characteristics of Photonic Nano-jets Based on Dielectric Microspheres with Different Refractive Indices

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Abstract

Photonic Nano-jets (PNJs) are narrow and high-intensity electromagnetic waves propagating in the medium behind the shaded surface when a plane wave irradiates a lossless dielectric micropillar or microsphere. PNJs were potentially applicable in the fields of nanoscale object detection, nano-manipulation, ultra-diffraction-resolution lithography, low-loss waveguide construction, and ultra-high-density optical storage technology. The study used the finite-difference time-domain (FDTD) method and COMSOL Multiphysics software for numerical simulations, which optimized the simulation process and accurately controlled the physical parameters of the dielectric microspheres, and provided new perspectives for an in-depth understanding of the formation mechanism and propagation properties of PNJs. The simulation results shown that with the increase of the refractive index of dielectric microspheres, the full width at half maximum of PNJs decreases and the electric field strength increases, indicating that the refractive index plays an important role in regulating the properties of PNJs. In addition, the study investigates the effect of microsphere radius on the properties of PNJs and finds that the focal length of PNJs becomes longer as the microsphere radius increases and the focal position is close to the edge of the microsphere. The study looks forward to the application of PNJs in biomedical imaging, photocatalysis and optoelectronics, and points out the future research directions in new material science, numerical simulation optimization, experimental validation and technology development.

Keywords

Photonic Nano-jets (PNJs), Refractive index, Finite-difference time-domain (FDTD) method, Nanoscale applications.

1. INTRODUCTION

Since the discovery of Photonic Nano-jets (PNJs)[1] in 2004, this phenomenon has attracted much attention in the field of optics. PNJs are narrow, high-intensity electromagnetic waves propagating behind the shadow plane into the background medium when irradiated by a plane wave into a lossless medium micropillar or microsphere[2]. They have non-sudden propagation properties and are capable of maintaining subwavelength transverse beamwidths in paths extending beyond the dielectric column or sphere. These properties, including their minimal FWHM beamwidth that breaks through the classical diffraction limit, high optical intensity, and significant perturbation of far-field scattering power, provide potential applications in areas such as detecting and manipulating objects on the nanometer scale, realizing nanopattern shaping and lithography with ultra-diffractive resolution, constructing low-loss waveguides, and developing ultra-high-density optical storage technologies. Although studies have been conducted to explore the generation mechanism of PNJs, the systematic study of the effects of microspheres with different refractive indices of media is still insufficient.

This study is dedicated to filling the gap in the current research field by using advanced numerical simulations to precisely control the physical parameters of dielectric microspheres and to deeply investigate the formation and propagation properties of photonic nano-jets (PNJs). Our goal is to use these simulations to understand the formation mechanism of photonic nano-jets and to reveal their propagation properties, thus providing new theoretical and experimental bases for the regulation and application of photonic nano-jets.

2. RESULTS AND DISCUSSION

2.1. Simulation theory

Photonic nano-jets was originally identified as a unique type of electromagnetic wave by Chen [3] and others, who coined the term “photonic nano-jets”to describe it. Using a high-resolution finite-difference time-domain (FDTD) algorithm to solve Maxwell's system of equations [4], it was shown that when a plane wave irradiates a micrometer-scale dielectric cylinder, it produces a narrow, high-intensity beam with a beamwidth below the diffraction limit propagating from the shadow side of the cylinder towards the background medium, which fulfills the Lorentz-Meter scattering theory and is given by J. P. Barton et al. A specific formula for the scattered field distribution after scattering from a geometry with a regular structure was given by J. P. Barton et al [5], which allows for a specific and comprehensive discussion of the spatial field distribution, the characterization of the optical forces and the physical mechanisms.

The numerical simulations in this paper are based on exact separated-variable eigenfunction solutions of Maxwell's equations in strictly spherical coordinates. The incident plane wave with unit amplitude in the spherical simple harmonic wave is expanded as:

$$E_{inc}(r)=\sum_{n=1}^{\infty} i^n\left\{\frac{2n+1}{[n(n+1)]}\right\}\left[M_{oln}^{(1)}(r)-iN_{eln}^{(1)}(r)\right] \tag{1}$$

M and N are vector spherical simple harmonic waves. where the expansion of the scattered field applies to all points outside the sphere and is given by Eq. [6] as:

$$E_{scat}(r)=\sum_{n=1}^{\infty} i^n\left\{\frac{2n+1}{[n(n+1)]}\right\}\left\{ia_nN_{eln}^{(3)}(r)-b_nM_{oln}^{(3)}(r)\right] \tag{2}$$

where a_n and b_n are the scattering coefficients, which together with M and N and the superscript denote the spherical Bessel functions.

At the same time by K. S. Yee proposed the concept of finite time domain difference [7], through the method of central difference in Maxwell's system of equations in the form of partial differentials into the form of differentials and discretization in the time and space domains are also optimized for the numerical simulation of the photonic nano-jet computational process, the use of this method of simulation is also necessary for the mesh partitioning, each mesh is a Yee tuple. The FDTD simulation method is applied to solve Maxwell's spinodal equations in non-magnetic materials as [8]:

$$\frac{\partial D}{\partial t} = \nabla * H \tag{3}$$

$$D(\omega) = \varepsilon_0 \varepsilon_1^*(\omega) E(\omega) \tag{4}$$

$$\frac{\partial H}{\partial t} = -\frac{1}{\mu_0} \nabla * E \tag{5}$$

where D is the displacement field, $\varepsilon_1^* = n^2$is the complex relative permittivity, and n is the refractive index.

When using the FDTD method for numerical, the modeling process can be divided into the following four steps, firstly, set the simulation area (simulation), then add the research object (such as sphere, circle, etc.), then import the light source (such as plane wave, Gaussian beam, customized circularly symmetric Airy beam, etc.), and add a monitor, and get the electromagnetic field distribution of the research area through numerical simulation. The electromagnetic field distribution in the study area is obtained through numerical simulation, and the whole modeling system is continuously optimized during the computation process to optimize the mesh division and the setting of boundary conditions to obtain appropriate and accurate numerical simulation results.

2.2. Simulation study of photonic nano-jet properties

COMSOL Multiphysics is based on the finite element method to simulate real physical phenomena by solving partial differential equations (single field) or systems of partial differential equations (multi-field), which uses mathematical calculations to solve a variety of complex physical phenomena. The RF module in fluctuating optics is selected for simulation modeling in COMSOL Multiphysics. This module includes electromagnetic fields and waves in two and three dimensions. All simulation formulations are based on solving Maxwell's system of equations. Through a predefined physical field interface, the Fluctuating Optics interface, the user is able to build and solve electromagnetic field models and solve for time-harmonic electromagnetic field distributions. The Fluctuating Optics Interface includes EMF and wave simulations in the frequency domain, time domain, eigenfrequency and mode analysis, a “frequency domain” study type for source-driven simulations at a single frequency or a range of frequencies, and an “eigenfrequency” study type for finding resonant frequencies and their associated eigenmodes in resonant cavities. The “eigenfrequency” study type is used to find the resonant frequency and its associated eigenmodes in a resonant cavity. The simulation process is divided into the following steps: definition of the geometry, selection of the material, selection of the appropriate fluctuating optical interface, definition of the boundary and initial conditions, definition of the finite-cell mesh, selection of the solver and visualization of the results.

COMSOL Multiphysics was used to simulate the irradiation of a dielectric microsphere by perpendicular parallel light from above, and to analyze the field intensity distribution inside the microsphere as well as in the near-field, with an emphasis on the near-field region immediately below the microsphere on the lower surface. The radius of the dielectric microsphere is 2,500 nm, the material is silicon dioxide, so its refractive index is 1.4607 in real part; the background medium is a vacuum and the refractive index is set to 1. The wavelength of the light is set to 200 nm, and the Perfect Match Layer (PML) needs to be added at the boundary of the model, which is equivalent to supporting the passage of the electromagnetic wave through the boundary without reflection. The addition of a PML at the boundary of the computational domain is equivalent to supporting the passage of electromagnetic waves through the boundary in a non-reflective manner, which acts as a nearly ideal absorber or radiator domain. The perfectly matched layer at the edges is set as an ideal conductor, and all spaces are set as frequency domains where light can propagate. A port is set up at the upper boundary of the model with an energy of 1W, an electric field input of 1V/m in the z-direction only, 0 in both the x- and y-directions, a propagation constant of $K = 2\pi/\lambda$, and a mode phase of 0. Then a mesh is set up, using a free-triangle mesh, with a maximal cell not exceeding 1/7th of the wavelength and a minimal cell not less than 1/9 of the wavelength of light. The maximum cell is not more than 1/7 of the wavelength of the light and the minimum cell is not less than 1/8 of the wavelength. This grid size can get better simulation results without too much computation.

Different refractive index media microspheres (polystyrene, polymethyl Methacrylate (PMMA), silica, barium titanate) were used to study the effect of the refractive index of the microspheres on the photon nano-jet. The refractive indices studied were n_2=1.46， n_3=1.50， n_4=1.59， n_5=1.93. Light with wavelength = 500 nm propagates from top to bottom in the medium where the microspheres are located, and the peak electric field plots are obtained from Fig.1 (a) to Fig.1 (d). When the light of wavelength λ is incident from above and penetrates the dielectric column, Fig. 1 exhibits the electric field distribution in the vicinity of different microspheres. It can be clearly seen that the incident laser light is focused in a small area on the shadow side of the microsphere, and thus the laser intensity is significantly enhanced. The peak electric fields for n_2=1.46，n_3=1.50，n_4=1.59，n_5=1.93 are 4.66486 V/m, 4.83988 V/m, 4,93065 V/m, and 5.211496 V/m, respectively, which are obtained by numerical simulation. It can be seen that with the increase of refractive index, the focusing position of the photonic nano-jet is not only nearer to the edge of the microsphere region but also the intensity of the electric field is significantly enhanced. significantly enhanced. The intensity enhancement of the particles usually increases with the increase of the ratio of the refractive index of the particles to the medium (when the refractive index of the microspheres is higher than the refractive index of the medium). The study of the enhancement multiplier is of great significance in the field of optical sensing, imaging, etc., but in the field of micro and nanofabrication is not a direct response to the micromachining, because the absorption of different wavelengths of light by the substrate material, and the transmission of different wavelengths of light by the microsphere array structure, etc., affect the energy needed for the processing, and the energy density is a parameter that can be controlled for the laser, and even if the enhancement effect is relatively low, but it is necessary to enhance only the Even if the enhancement effect is relatively low, it is still possible to process the whole structure by simply enhancing the energy density. The real big influence on the processing resolution is the focal length of the photon nano-jet and the half-height width of the center peak position.

The electric field intensity distribution curves of the cylinders with refractive index n_2=1.46，n_3=1.50，n_4=1.59，n_5=1.93 radius d_μ = 5μm under the propagation of light with wavelength λ_1 = 500 nm are shown in Fig.2 (a) - (d), and the focal lengths of photon nano-jets corresponding to the different refractive indices of the dielectric microspheres are obtained by calculating the polar values of the electric field, where the focal lengths are 4.6468μm, 4.3727μm, 3.7374μm, 2.8705μm, respectively. It can be seen that as the refractive index of the refractive index medium microspheres increases, the focusing position is also gradually close to the lower edge of the microspheres. For barium titanate microspheres with high refractive index, the focus is almost close to the edge of the microsphere, which is not favorable for practical applications. In the lower refractive index microspheres, the focus position is obvious and far away from the edge of the microsphere, which is favorable for applications in other fields such as micro-nano processing.

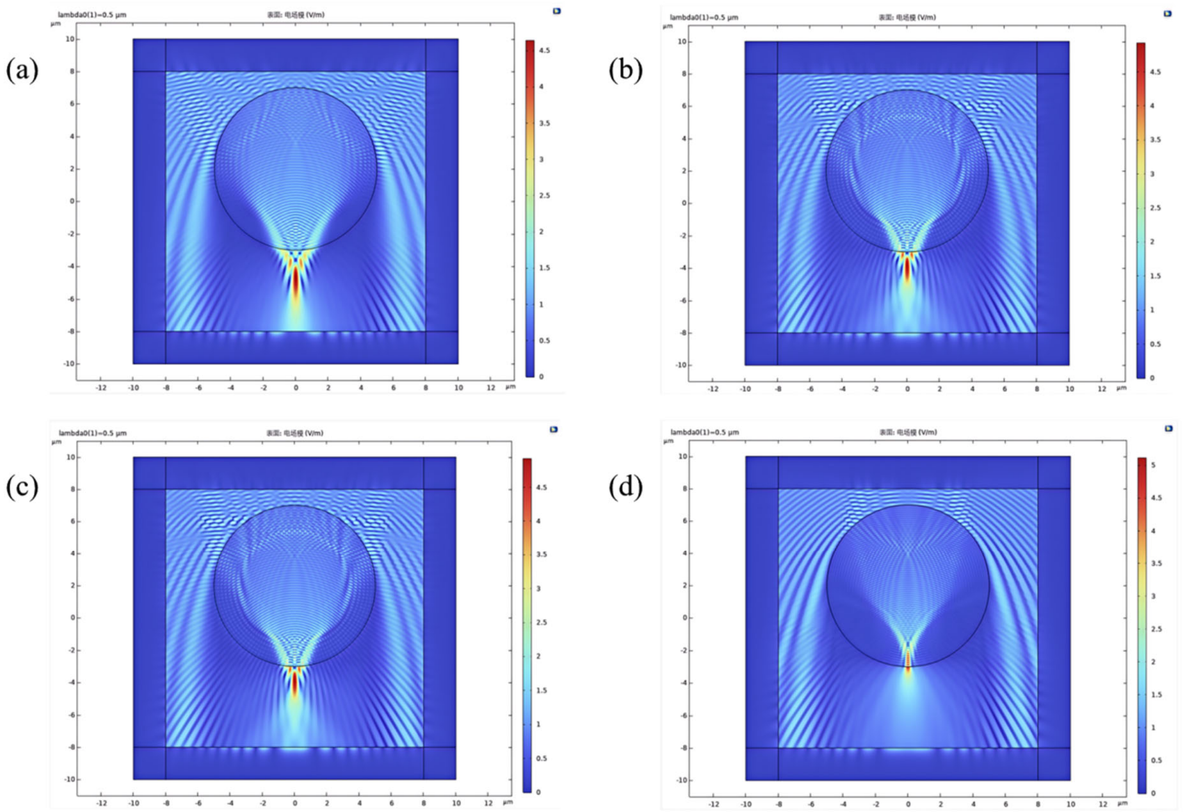

Figure 1. The PNJs properties of microspheres with different refractive indices (a)n=1.46, (b)n=1.50, (c)n=1.59, (d)n=1.93

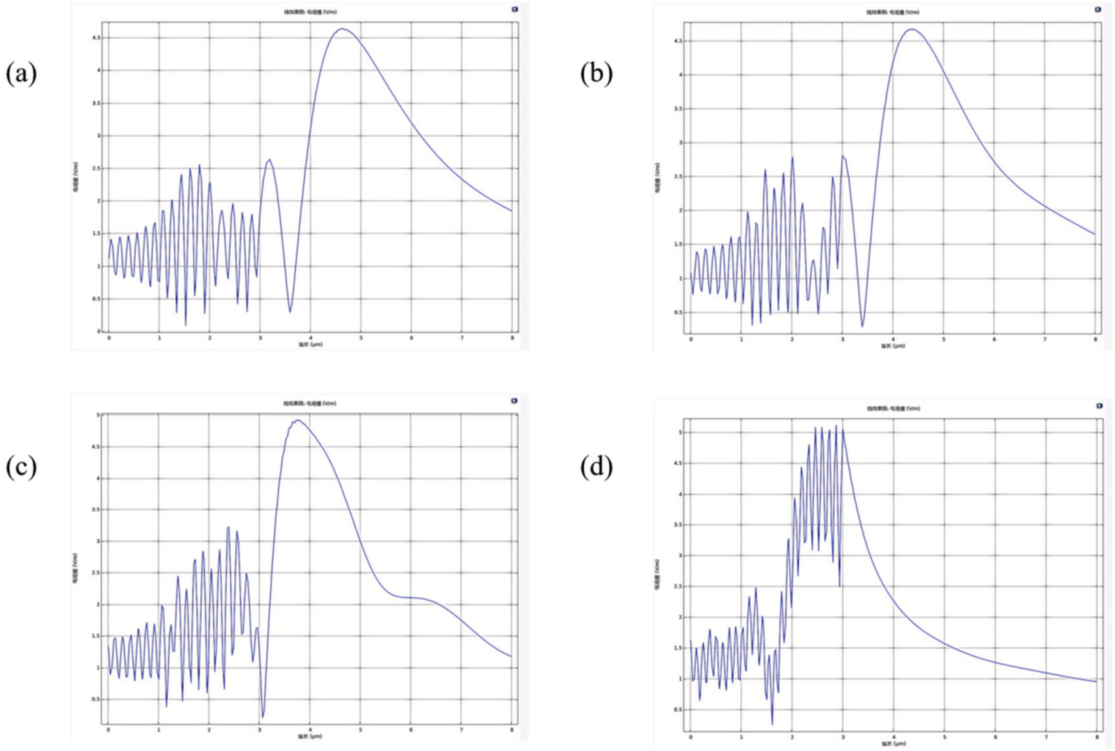

Figure 2. The variation of the focal length of photon nano-jets generated by microspheres with different refractive indices is demonstrated, where the refractive indices are respectively (a)n=1.46 (b)n=1.50, (c)n=1.59 and (d)n=1.93.

The trend of full width at half maximum (FWHM) with the irradiation laser wavelength and microsphere diameter size is shown in Fig.3 (a)-(d) , and the values of FWHM of the refractive index of the medium from small to large at the extreme value of the electric field are 0.6949 μm, 0.7760 μm, 1.2659 μm, 2.5213 μm, respectively. In the case where the diameter of the microsphere is larger than the wavelength of the irradiation laser, the refractive index will have an effect on the micromachining resolution, the smaller the refractive index the higher the resolution that can be processed, this is because the smaller the refractive index the smaller the diffraction limit corresponding to the photon nano-jet formed by the dielectric microspheres, and therefore the higher the resolution that can be processed.

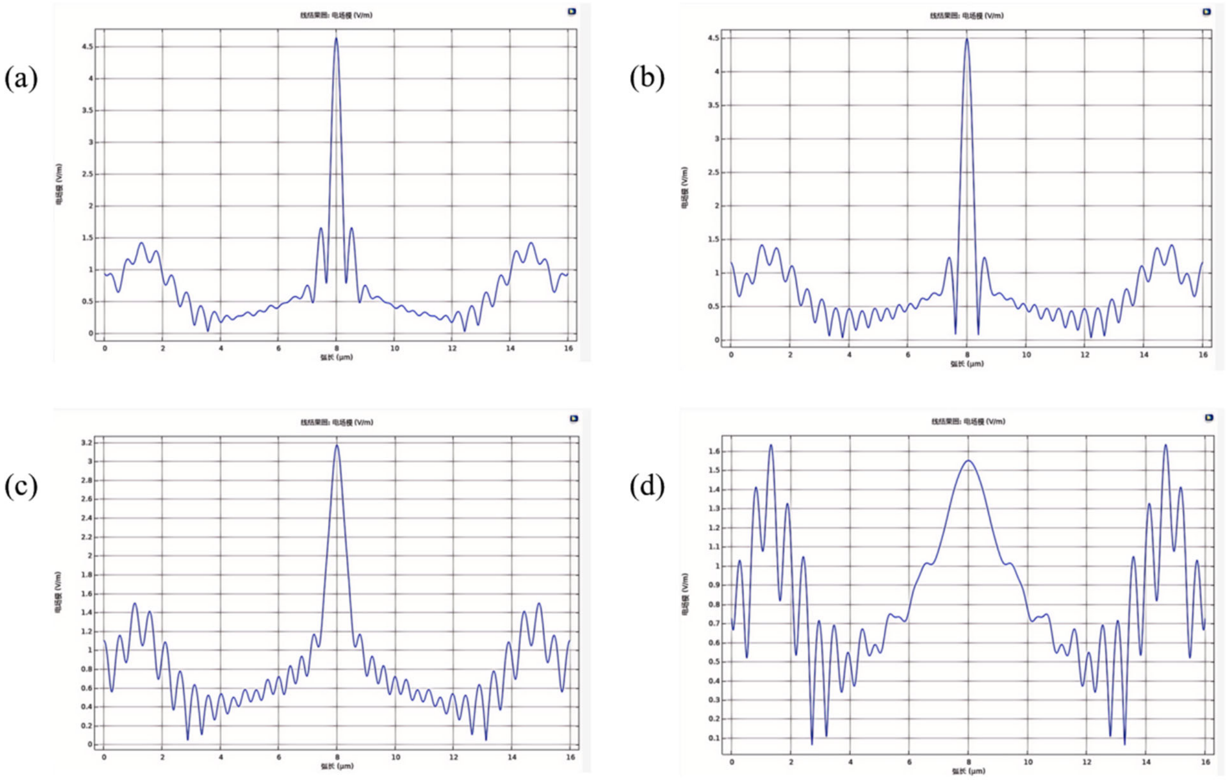

Figure 3. The trend of the half-height width (FWHM) of photonic nano-jets from microspheres with different refractive indices as a function of the diameter of the microspheres and the wavelength of the laser is shown for the refractive indices of (a)n=1.46, (b)n=1.50, (c)n=1.59 and (d)n=1.93.

In order to further carry out a more specific study, this paper selects the dielectric microspheres with a refractive index of 1.50 and investigates the effect of microsphere diameter change on PNJs.And the peak electric field, electric field intensity distribution curve and FWHM with the irradiation of the laser wavelength and microsphere diameter changes in the size of the map.

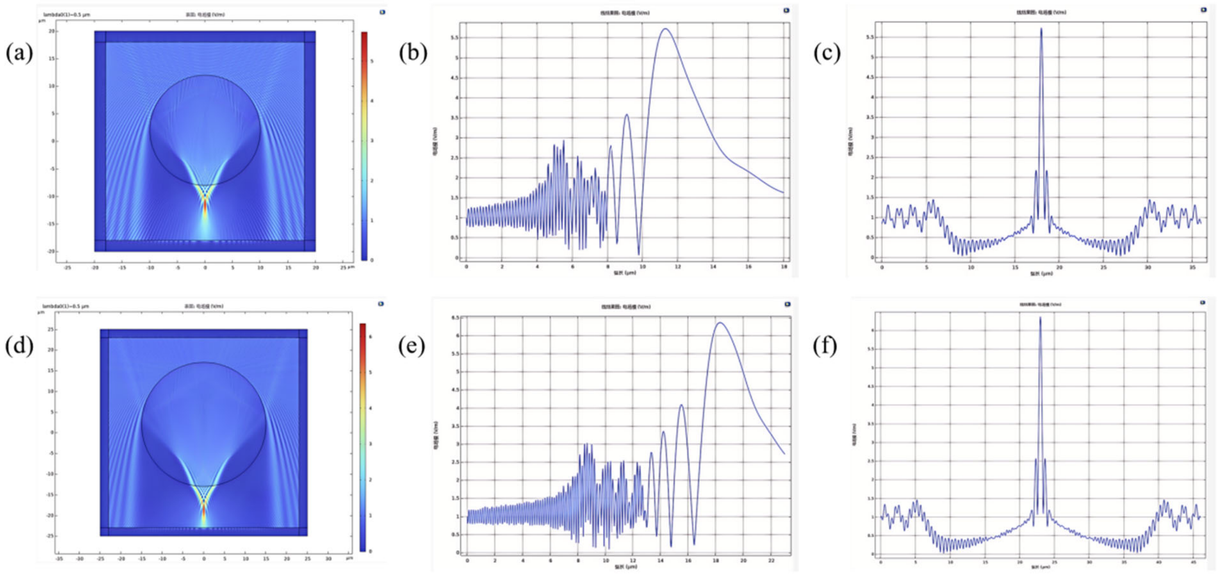

Figure 4. Effect of diameter size on the PNJ properties of microspheres (a)d=10 μm demonstrates the peak electric field, electric field intensity distribution, and half-height width (FWHM) of a photonic nano-jet for a microsphere with a diameter of 10μm in a medium with refractive index of 1.50, (d)d=15 μm, Demonstrates the peak electric field, electric field intensity distribution, and half-height width (FWHM) of a photonic nano-jet for a microsphere with a diameter of 15μm in a medium with a refractive index of 1.50.

The peak electric field was measured to be 5.73737 V/m for a radius d_μ of 1 0μm, respectively, with a focal length of 11.27 μm and a FWHM value of 0.756 μm.The peak electric field was measured to be 6.3686 V/m, the focal length to be 18.309 μm, and the value of FWHM to be 0.852 μm for a radius d_μ of 15 μm, respectively. When the microsphere radius was increased from 10μm to 15μm, the peak electric field increased from 5.73737 to 6.3686 V/m, the focal length increased from 11.27μm to 18.309μm, and the FWHM increased from 0.756μm to 0.852μm. These trends indicate that the increase in microsphere radius leads to the lengthening of the focal length of the PNJs and the increase in spot size, which may be related to the propagation and scattering characteristics of the light waves inside the microspheres. With the increase of microsphere radius, the propagation path of the light wave inside the microsphere becomes longer, leading to the increase of the focal length. At the same time, the FWHM increases due to the enhanced scattering effect of the light wave at the edge of the microsphere.

3. CONCLUSION

Photonic nano-jets have attracted remarkable attention in the field of optics since their discovery in 2004, and significant progress has been made in the study of this phenomenon over time. The discovery of PNJs opens up new possibilities for technologies such as optical detection, nano manipulation, super-resolution lithography, low-loss optical waveguides and high-density data storage. These electromagnetic waves have unique non-sudden propagation properties and subwavelength transverse beamwidths, and their formation and propagation are significantly affected by the refractive index of the medium, a property that provides an important physical mechanism for modulating PNJs. In this study, the effects of dielectric microspheres with different refractive indices on the properties of PNJs are deeply analyzed by numerical simulation techniques, especially the finite-difference in time-domain (FDTD) method, and the simulation process is optimized by accurately controlling the physical parameters of the dielectric microspheres, which in turn provides a new perspective for an in-depth understanding of the formation mechanism and propagation properties of PNJs. Our simulation results demonstrate the general trend that the girdle width of PNJs decreases while the electric field strength increases as the refractive index of the medium increases, suggesting the important role of the refractive index in modulating the properties of PNJs.

Looking ahead, research on PNJs will continue to make progress in a number of areas, including materials science, numerical simulation optimization, experimental validation, and technology development. With the development of new materials, especially the exploration of multilayer microsphere structures with gradient refractive index, it is expected that PNJs with longer propagation distances and smaller half-height widths will be realized. Further optimization of the numerical simulation algorithm will improve the accuracy and efficiency of predicting and controlling the behavior of PNJs. The experimental validation work will strengthen the combination of simulation results and experimental data, and promote the transformation of PNJs technology to practical applications.

In addition, the research on the application of PNJs in the fields of biomedical imaging, photocatalysis, and optoelectronics will be further expanded, while the application of new optical elements such as Lenberg lenses will bring a new direction for the development of PNJs technology.

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