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خواص نانو جت های فوتونی ساخته شده از استوانه های دی‌الکتریک دایروی و بیضوی

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چکیده- در این تحقیق نشان داده شد که نانو جت های فوتونی با استفاده از میله های دی الکتریک دایروی و استوانه ای در زمینه هوا ایجاد می‌شود. بنابراین به منظور به دست آورد نانوجت هایی با شدت بالا و فاصله کانونی بزرگ با استفاده از روش تفاضل های متناهی در حوزه زمان، به ازای تمامی پارامترهای ساختاری ممکن، مشخصات نانو جت های فوتونی حاصل مورد مطالعه قرار گرفت . نتایج محاسبات نشان می دهد که شدت نانو جت های به دست آمده با میله های دایروی بیشتر است در حالی که نانو جت های تولید شده با میله های بیضوی دارای فاصله کانونی بزرگتری هستند. نتایج این محاسبات می‌تواند در ساخت ادوات فوتونی پیشرفته مانند حسگرهای فوق العاده حساسِ ذرات به کار رود.

کلید واژه- نانو جت های فوتونی ، روش تفاضل های متناهی در حوزه زمان ، شدت و فاصله کانونی.

Properties of photonic nanojet made of circular and elliptical dielectric cylinders

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Abstract- In this paper, photonic nanojets are achieved using circular and elliptical dielectric cylinders in air background. Therefore, for obtaining high intensity and large focal length photonic nanojets, using high-resolution finite difference time domain method, the optical properties of obtained nanojets are studied for all possible geometrical parameters. Numerical results show that the field intensity of circular photonic nanojet is higher than the elliptical one, while the focal length of elliptical photonic nanojet is greater than that of circular one. These results can be helpful in designing advanced photonic components such as ultra-sensitive particle sensors.

Keywords: photonic nanojets, finite-difference time-domain method, intensity, focal length

1. Introduction

Optical microscopy and spectroscopy technologies are well established and are remarkably powerful. Critical to any discussion of them is the fundamental limitations of conventional microscopy. The observation of sub-wavelength targets with conventional lenses is difficult because of the diffraction limit [1, 2]. There is a fundamental maximum to the image resolution of any optical apparatus which is due to diffraction. The evanescent waves store sub-wavelength messages of the object and are missed before reaching the image plane. Recently, the phenomenon of photonic nanojets (PNJ) has been investigated by several scientific literatures [3-6]. When an electromagnetic plane wave is perpendicularly incident to a lossless dielectric cylinder or to a dielectric sphere, a PNJ is obtained with special choices of material dimensions and refractive index instead of having a shadow region behind the dielectric material. PNJ can be defined as a narrow electromagnetic beam having high intensity with low divergence. This beam propagates into the background medium, in which the dielectric martial is embedded. In order to obtain a PNJ, the dielectric micro-cylinder or micro-spheres must be lossless dielectric materials and of diameters relatively greater than the illuminating wavelength. The phenomenon is named as PNJ due to the unique nature of the light distribution at the focal area [7].

PNJs have several important applications. They are mainly utilized in the following applications: Nano spectroscopy (detection and manipulation of nanoscale objects), sub-diffraction resolution, enhanced Raman scattering, waveguiding, and high-intensity optical storage. Low-loss optical wave guiding, high-density data storage, lithography, high-resolution microscopy, and nonlinear optical effects are the other applications of photonic nanojets [8].

In this paper, at first, we theoretically study the characterizes of a PNJ, consists of a two dimensional circular dielectric cylinder, by illuminating it with a plane wave. At the next step, the circular cylinder is replaced by an elliptical one. The features of the second structure such as intensity and focal length were compared with circular structure.

2. Structure and Method

In this study, we use two dimensional circular and elliptical dielectric cylinders, separately. The refractive indices of the dielectric cylinders and surrounding medium are n_d and n_b , respectively. The focal length (f) is defined as the distance between the surfaces of the cylinders to the point of the maximum intensity of PNJ. The radius of the circular cylinder is r and the radii of the elliptical cylinder along the x and y axes are r_x and r_y, respectively. In this paper, the refractive index of the cylinders are $n_d = 1.738$ corresponding to Indium Tin Oxide (ITO) and the cylinders are surrounded by air medium $(n_b = 1)$. A plane wave light with wavelength $0.6759\ \mu m$ is incident from the left and impinges on the cylinders. The schematic diagram of an elliptical cylinder of ITO in air background for creating PNJ is shown in Figure 1.

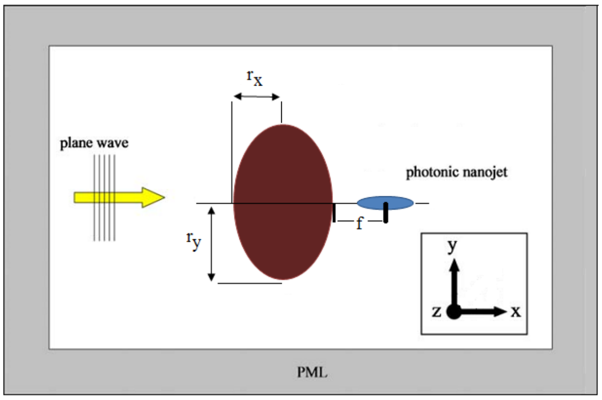

Fig.1: Schematic diagram of an elliptical dielectric cylinder for photonic nanojet.

The optical transmission properties of PNJ can be calculated via many different methods. A unique calculation technique is needed for a circular or elliptical cylinder. The finite-difference time-domain (FDTD) method is one the most popular technique for finding electromagnetic properties. In this paper, PNJ properties of circular and elliptical cylinders are calculated by the FDTD method using the MIT Electromagnetic Equation Propagation (MEEP) package [9]. In our simulations, by using a high-resolution FDTD technique, we study internal and near external field distribution of plane wave illuminated dielectric cylinders. The perfectly match layer (PML) absorbing boundary conditions, is used to our FDTD simulations to terminate efficiently the outer boundary of the computational region. The centre of micro cylinders is laid out in the $x-y$ plane. The propagation is along the x direction. The sampling in time is selected to ensure the numerical stability of the algorithm. The transverse electric wave propagation is considered in the present letter wherein the incident electric field vector is in the propagation plane.

3. Results and Discussions

In this paper, the PNJ properties of circular and elliptical dielectric cylinders in air background, illuminated with a plane wave, will be separately analysed in the next two subsections.

3.1. Circular dielectric cylinder

In this case, we consider an infinite circular dielectric cylinder of radius r and refractive index of $n_d = 1.738$ embedded within an infinite vacuum medium of refractive index of $n_b = 1$. The cylinder is normally illuminated by a rightward-propagating sinusoidal plane wave of wavelength $\lambda = 0.6759$ μm in medium. We have investigated PNJ properties of the mentioned structure for different values of r. Our simulations reveal that when $2r$ ranges from 6.075 μm to 12.825 μm, PNJs are observed. The focal length and maximum intensity of nanojets in terms of r are shown in Figure 2. In this figure intensity is defined as the ratio of nanojet intensity to that of the incident wave. Also figure 3 represents the intensity distribution of the mentioned structure for $2r = 10.125$ μm.

3.2 Elliptical dielectric cylinder

Now, we study an infinite elliptical dielectric cylinder in which the smallest and largest distance from the perimeter of the elliptical cylinder to its centre are shown as r_x *and* r_y. The refractive index of the elliptical cylinder is $n_d = 1.738$

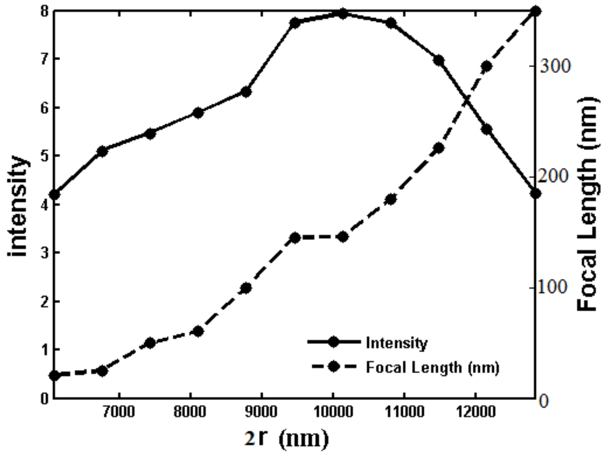

Fig 2: Intensity and focal length of PNJ created with circular cylinder versus radius of cylinder.

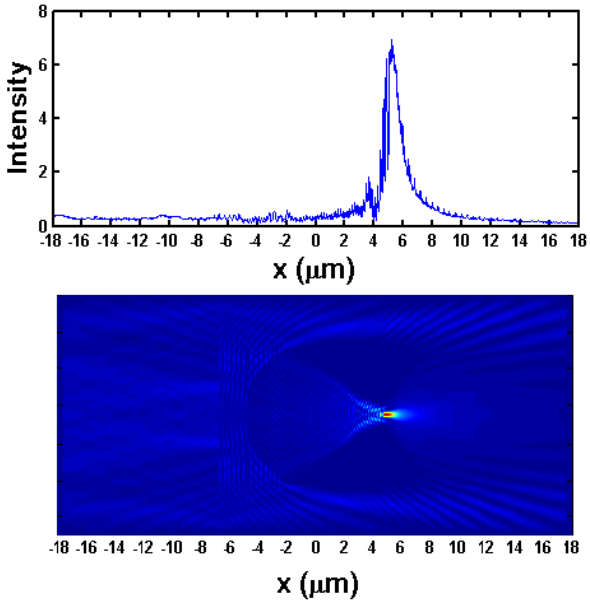

Fig 3: Intensity distribution of circular PNJ with diameter of 10125 *nm*.

which embedded within an infinite vacuum medium of refractive index of $n_b = 1$. The PNJ properties have been investigated for all possible values of r_x *and* r_y. In our simulations, for a given value of r_x the PNJ properties of the mentioned structure has been investigated as a function of r_y and this process repeated for other values of r_x. Our calculations show that when r_x *and* r_y are in the range of $1.012-4.725$ μm and $4.378-5.737$ μm, PNJs are observed. The variation of focal length and intensify of PNJs as a function of r_x for a constant value of

$r_y = 5.06\ \mu m$ are shown in figure 4. Also, figure 5 represents the intensity distribution of mentioned structure for $r_x = 3375\,(nm)$ and $r_y = 5060\ (nm)$.

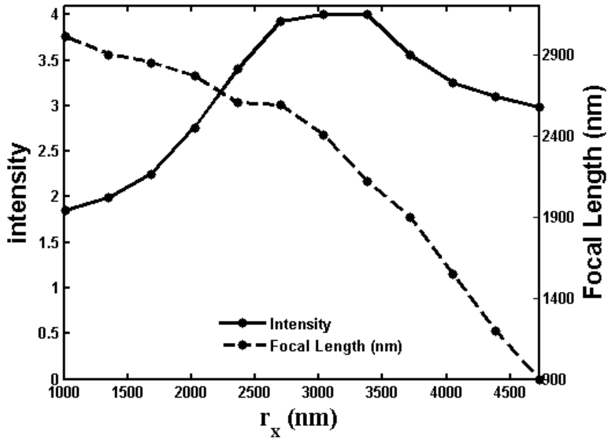

Fig 4: Intensity and focal length of PNJ created with elliptical cylinder as a function of r_x at fixed value of

$$r_y = 5060\,nm.$$

4 Conclusion

In summary, we have studied photonic nanojet properties, emerged from circular and elliptical dielectric cylinders in air background, using high-resolution finite-difference time-domain method. Our simulations show that both circular and elliptical cylinders create photonic nanojets for optimum parameters. The obtained results reveal that the circular cylinder yields a PNJ with higher intensity compared to the elliptical cylinder, while the focal length of the elliptical cylinder is greater than that of the circular one. The obtained results show that without using complex materials such as liquid crystals or optofluidics materials [5] high-intensity and long-length nanojets (5 micro-meter) has been observed in our paper. These results can be helpful in designing advanced photonic components such as ultra-sensitive particle sensors.

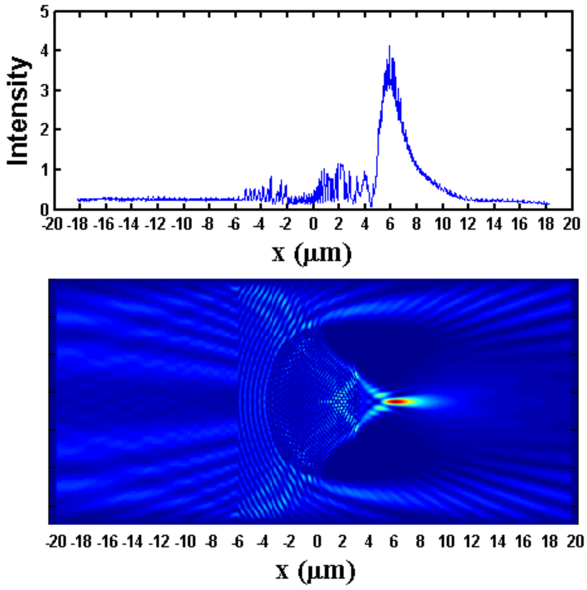

Fig 5: Intensity distribution of elliptical PNJ with $r_x = 3375\ (nm)$ *and* $r_y = 5060\ (nm)$.

References

[1] L. Novotny and B. Hecht, Principles of Nano-Optics, New York: Cambridge University Press, 2006.

[2] H. C. van de Hulst, Light Scattering by Small Particles, New York: Dover Publications, 1981

[3] Z. Chen, A. Taflove, and V. Backman, “Photonic nanojet enhancement of backscattering of light by nanoparticles: a potential novel visible-light ultramicroscopy technique,” Opt. Express, Vol. 12, pp. 1214-1220, 2004.

[4] A.V. Itagi, and W.A. Challener, “Optics of photonic nanojets,” J. Opt. Soc. Am. A, Vol. 22, pp. 2847-2858, 2005.

[5] N Eti, IH Giden, Z Hayran, B Rezaei, and H Kurt, “Manipulation of photonic nanojet using liquid crystals for elliptical and circular core-shell variations” J. Mod. Opt., Vol. 64, pp. 1566-1577, 2017.

[6] H. Zhang, “Enhanced subwavelength photonic nanojet focusing via a graded-index round-head microcylinder”, Optik, Vol. 203, pp. 163973, 2020.

[7] I. Mahariq, M. Kuzuoglu, I. H. Tarman, and H. Kurt, “Photonic nanojet analysis by spectral element method,” IEEE Photon. J., Vol. 6, No. 5, pp. 1-4, 2014.

[8] V. R. Dantham, P. B. Bisht, and C.K.R. Namboodiri, “Enhancement of Raman scattering by two orders of magnitude using photonic nanojet of a microsphere,” J. Appl. Phys, Vol. 109, No. 10, pp. 103103, 2011.

[9] A. F. Oskooi, David Roundy, Mihai Ibanescu, Peter Bermel, J. D. Joannopoulos, and Steven G. Johnson, “MEEP: A flexible free-software package for electromagnetic simulations by the FDTD method,” Computer Physics Communications, Vol. 181, pp. 687–702, 2010.