Ultra-long photonic nanojet formed by dielectric cubes

Cheng-Yang Liu*[a], Li-Jen Chang[a]
[a]Department of Mechanical and Electro-Mechanical Engineering, Tamkang University, New Taipei City, Taiwan

ABSTRACT

The capability of generating photonic nanojets using dielectric cubes working in the visible light region is introduced and investigated numerically. The simulation of electric intensity distributions for a dielectric cube is performed using the finite-difference time-domain method. The focusing characteristic of the photonic nanojets is evaluated in terms of both focal length and transversal full width at half maximum along both transversal directions. Moreover, the ultra-long photonic nanojet is studied by theoretical calculations for a dielectric cube. By changing the dimension of the dielectric cube, it has been demonstrated that the focus point is moved from inside to outside the cube with a high intensity nanojet. The super resolution imaging of the dielectric cube can be expected from the focal length and the maximum intensity. The photonic nanojet enhancement and super resolution technique could be functional for the imaging of nano-scale targets on substrates and films.

Keywords: Photonic nanojet, dielectric cube, subwavelength

INTRODUCTION

The direct observation of nano-scale targets with conventional microscope is difficult because of the diffraction limit [1]. The evanescent waves store subwavelength information of targets and are missed before reaching the focal plane. Focusing of lightwave into a subwavelength range is a well known issue in application of nano-photonics. One of the available solutions to overcome this issue is focusing lightwave with a dielectric microcylinder or microsphere [2-6]. In particular, a microsphere with 3 μm diameter and refractive index n = 1.59 illuminated by a plane wave of wavelength λ = 500 nm is presented to shape a high intensity spot of full width at half maximum 0.325λ. These focal spots generated by use of microspheres are designated photonic nanojets. The photonic nanojet is a highly focused electromagnetic field with a subwavelength waist and low divergence. The capability of generating photonic nanojets using dielectric cubes working in the visible light region is introduced and investigated numerically. The simulation of electric intensity distributions for a dielectric cube is performed using the finite-difference time-domain method. The focusing characteristic of the photonic nanojets is evaluated in terms of both focal length and transversal full width at half maximum along both transversal directions. The utilization of photonic nanojet is limited by the short length of nanojet. Because short length only allows nanojet to detect the near surface targets, we are interested in photonic nanojet modulation for far-field system. For this reason, the ultra-long photonic nanojet is studied by theoretical calculations for a dielectric cube.

NUMERICAL APPROACH

The Lorenz-Mie theory is generally used to evaluate the spatial electromagnetic distributions in the vicinity of a dielectric microsphere illuminated by lightwave. The total electromagnetic field is separated into the incident, interior, and scattered fields with respect to the microsphere in the algorithm. However, the behavior of the photonic nanojet is affected by many factors that the Lorenz-Mie theory does not take into account. The finite-difference time-domain (FDTD) method is a precise numerical method that admits computer-aided design and photonic nanojet engineering in the dielectric materials [7]. In this paper, we investigate the internal and near external electromagnetic fields of plane wave illuminated dielectric cube by using three-dimensional (3-D) FDTD calculation. The computational region of the 3-D simulation is a cubic box. The lattice space increments in the x, y, and z coordinate directions are Δx, Δy, and Δz. The space and time derivatives are calculated by using centered finite difference expressions that are second-order accurate in the time and space increments.

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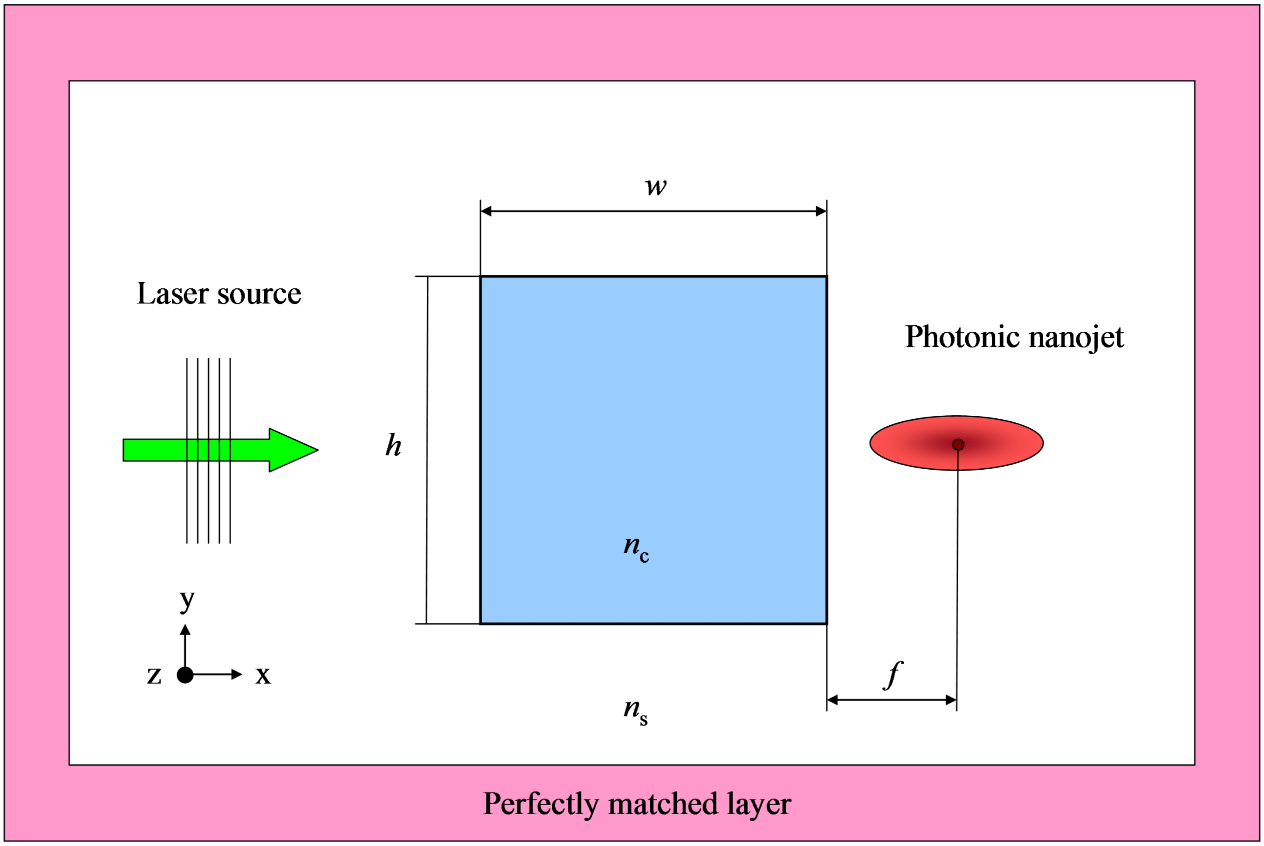
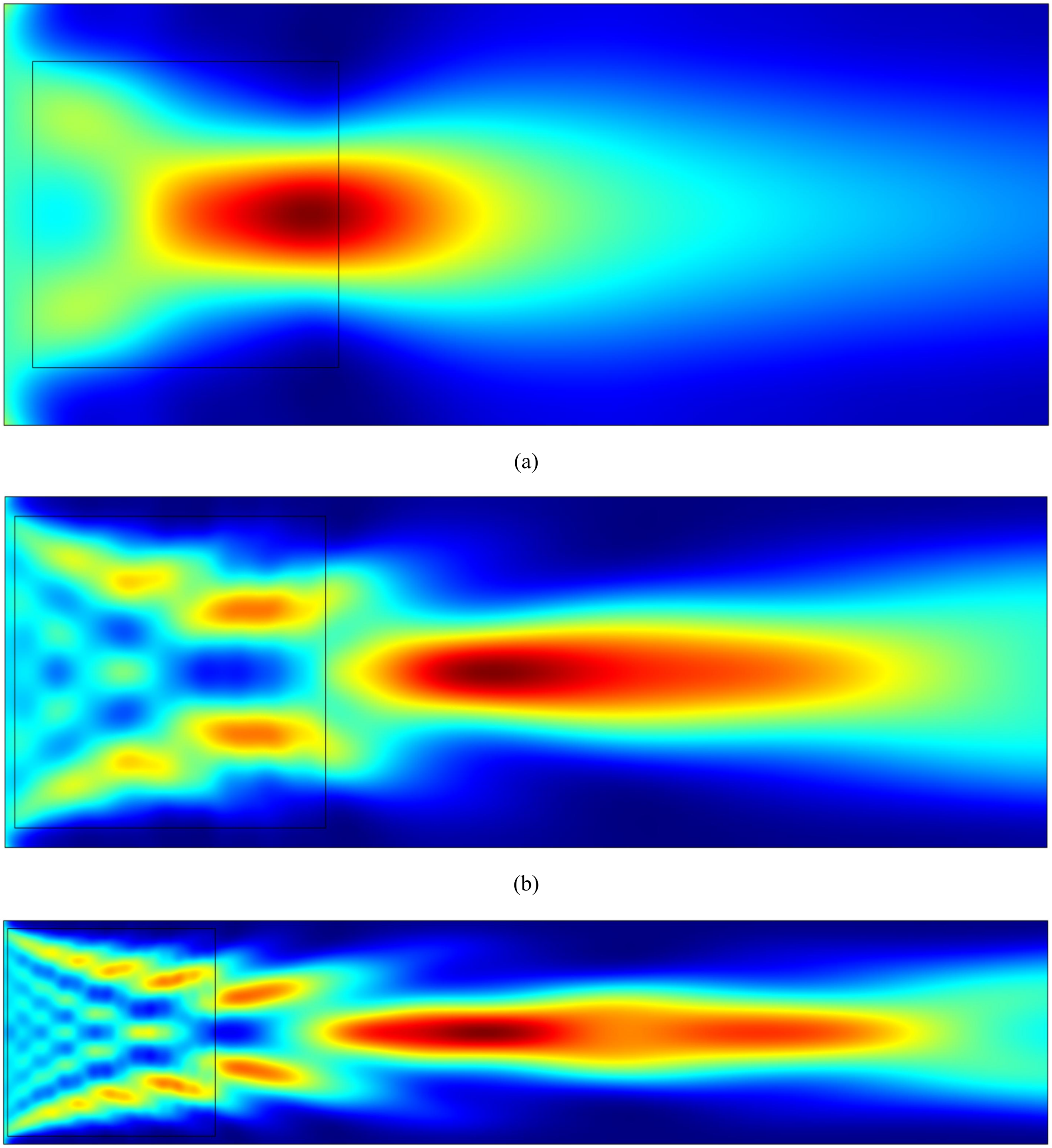


Figure 1. Schematic diagram of a dielectric cube for photonic nanojet

We construct 3-D FDTD computational model for a dielectric cube. Figure 1 shows the schematic diagram of a dielectric cube for photonic nanojet. The refractive indices of the dielectric cube and surrounding medium are $n_c = 1.46$ and $n_s = 1$. Light source of wavelength 532 nm propagates from left to right. The focal length from the surface of the cube to the point of maximum intensity of photonic nanojet is *f*. The height and width of the cube are *h* and *w*. We use Matlab code to construct three-dimensional FDTD calculation and investigate the property of photonic nanojet in the dielectric cubes. Figure 2 shows the power flow patterns of the dielectric cubes at different height and width. A plane wave of wavelength 532 nm is incident from the left side and impinges on the dielectric cube. By changing the dimension of the dielectric cube, it has been demonstrated that the focus point is moved from inside to outside the cube with a high intensity nanojet. The results show that the length of photonic nanojet is elongated greatly. The location and size of the photonic nanojet depend on the dimension of the dielectric cube.

Figure 3 depicts the focal length of photonic nanojet as a function of the dimension. The focal length increases as dimension increases. The super resolution imaging of the dielectric cube can be expected from the focal length and the maximum intensity. As a result, the focal length and the position of the photonic nanojets can be adjusted by the cube dimensions. This morphological type of the dielectric cubes combines the high spatial resolution of the photonic nanojets with sufficiently high intensity. At large dimension, the photonic nanojet is formed rather far from the shadow of the dielectric cubes, and a decrease in dimension the coordinate of the spot reaches the cube edge. The optimal balance between the key parameters of photonic nanojet can be achieved in the dielectric cubes. The incident wavelength of 532 nm is selected as an example. The photonic nanojet in the dielectric cubes is scalable in respect of the dimension and the incident wavelength. The photonic nanojet enhancement and super resolution technique could be functional for the imaging of nano-scale targets on substrates and films.



(a)

(b)

(c)

Figure 2. Power flow patterns of dielectric cubes at height and width (a) $h = w = 1\lambda$, (b) $h = w = 3\lambda$, and (c) $h = w = 5\lambda$

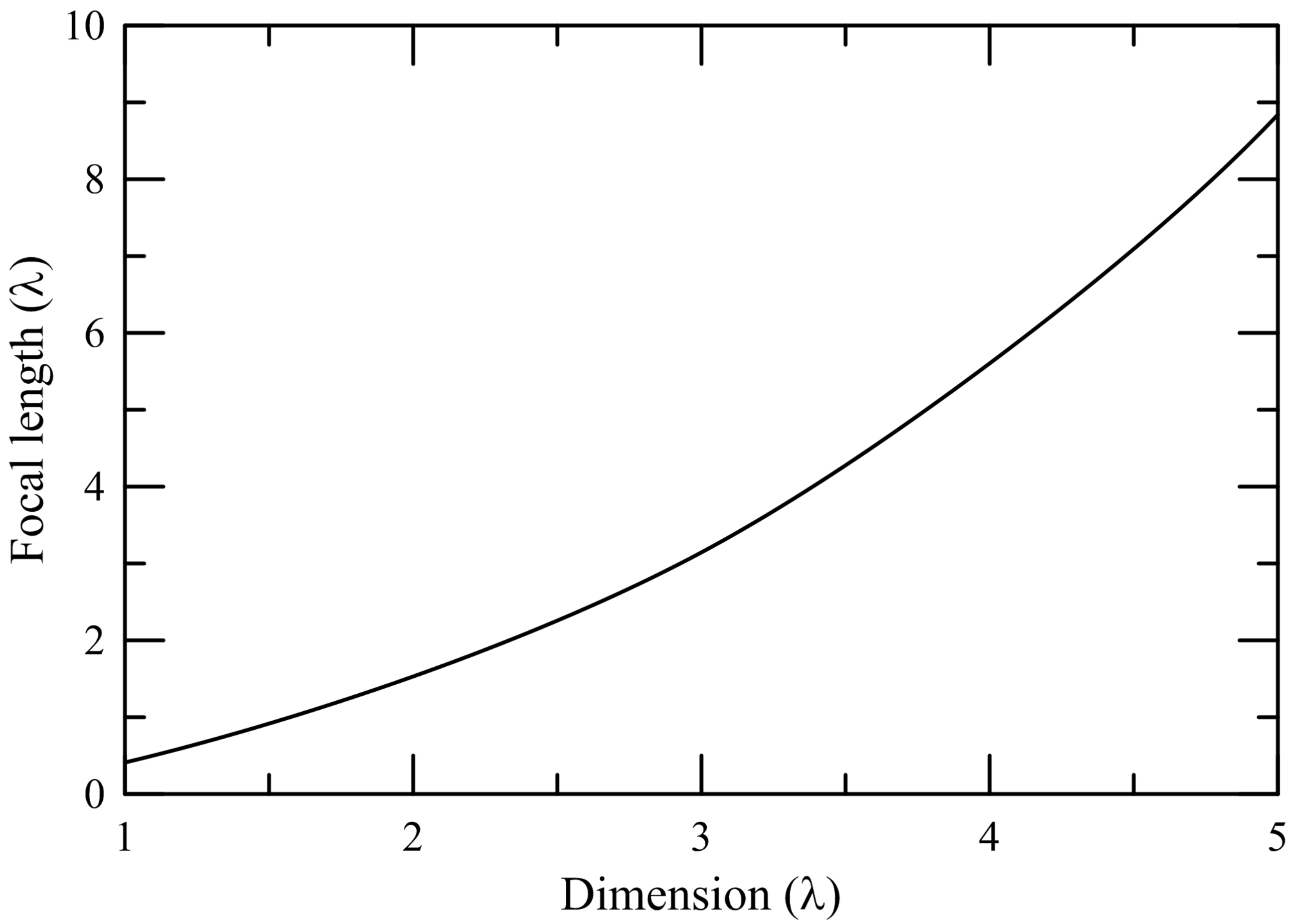


Figure 3. Focal length as a function of the cube dimension

CONCLUSION

In conclusion, we have numerically investigated the photonic nanojets generated at the shadow side surface of a dielectric cube illuminated by a plane wave. The basic characteristics of photonic nanojets formed in the vicinity of dielectric cubes with different dimensions are studied by using FDTD calculation. It is possible to adjust the photonic nanojet in the dielectric cubes. The dimensions and position of the photonic nanojet depending on the dielectric cubes are numerically investigated. The properties of photonic nanojet can be controlled by the variation of the dimensions of the dielectric cubes. This physical phenomenon for cubes could be a significant implement in the fields of photonic circuit. The photonic nanojets permit the lightwave coupling from the photonic molecule into other photonic components such as optical planar waveguides or coaxial cables. The photonic devices would be not only with extremely high power, but also with sub-wavelength spatial resolution in comparison with traditional optical coupling techniques. The photonic nanojets have the ability to measure nano-scale targets in the nano-optical system.

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REFERENCES

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

[2] Itagi, A. V. and Challener, W. A., "Optics of photonic nanojets," J. Opt. Soc. Am. A 22, 2847-2858 (2005).

[3] Ferrand, P. J., Wenger, J., Devilez, A., Pianta, M., Stout, B., Bonod, N., Popov, E. and Rigneault, H., "Direct imaging of photonic nanojets," Opt. Express 16, 6930-6940 (2008).

[4] Liu, C.-Y., "Superenhanced photonic nanojet by core-shell microcylinders," Phys. Lett. A 376, 1856-1860 (2012).

[5] Liu, C.-Y., "Tunable photonic nanojet achieved using a core-shell microcylinder with nematic liquid crystal," J. Mod. Opt. 60, 538-543 (2013).

[6] Liu, C.-Y., and Chang, L., "Photonic nanojet modulation by elliptical microcylinders," Optik 125(15), 4043-4046 (2014).