Original Research Article

NUMERICAL MODELING OF PHOTONIC JET BEHIND TRIANGULAR PRISM

ABSTRACT

The scattering of electromagnetic plane waves by triangular prism and its truncated form (the isosceles triangle and the trapezoid are transverse sections, respectively) has been studied in order to determine possibility of high field intensity (photonic jet) formation. Using high-resolution finite-difference time-domain simulation, an optimal relationship between the wavelength and the size of the prism was found to form photonic jet with subwavelength waist on the shadow side of the prism. Truncation of the prism (with trapezoids as transverse sections) leads to an improvement in the characteristics of photonic jets (intensity, length and waist). A qualitative explanation of the simulation results obtained is presented.

Keywords: Electromagnetic wave, FDTD, Intensity, Photonic jet, Triangular prism

1. INTRODUCTION

The scattering of electromagnetic wave has been studied for more than 100 years. However, only in this century has the so-called nanojet been discovered; that is, a narrow high-intensity beam of light generated on the shadow-side surface of a dielectric cylinder illuminated by plane waves [1]. Subsequently, the effects of various factors on the nanojet parameters [2-6] along with their generation by other objects have also been studied [7-9]. Considerable interest has been aroused in the study of nanojet due to the possibility of its practical application in the following aspects. Photonic nanojet increases the volume-integrated electric field within the subwavelength active volume of the photodiode by a factor of 26 [10]. The potential for portable nanojets was demonstrated in [11] by imaging different sub-wavelength structures. The effect of photonic nanojets on microsphere imaging has been studied in [12]. Some other potential applications were reviewed in [13]. The study of the various geometric objects in relation to the formation of photonic nanojets makes it possible to determine the optimal shape, and also leads to new insights into the formation and the parameters of the nanojet. In this sense, it is surprising that the triangular prism (a prism of triangular cross-section), which has been known for a long time and is widely used in optics, has not actually been studied for the purpose of obtaining a photonic jet; whereas, triangular shaped objects were studied in different works for other purposes: the scattering of electromagnetic waves from a thin triangular dielectric disk was theoretically described in [14], and scattering from dielectric triangular cylinder was calculated by boundary integral equations [15]. Internal modes in a triangular prism were studied in [16]. The numerical analysis of backscattering from a dielectric cylinder of triangular cross-section has been performed in [17]. However, in fact, the initial data set (scatterer sizes and refractive index n) in the above-mentioned references did not match those for which jet generation was expected. Besides, there was no such task. The point is that for a sphere, the focal length moves within the sphere for $n > 2$. Therefore, to study the jet, we must operate in the refractive index range of $n = 1 \div 2$. Similarly, the typical characteristic value of the sphere radius r used in the study of photonic jets is of the order of several wavelengths. Consequently, the value of k·r (wave vector $k=2\pi/\lambda$, λ - wavelength) is of the order ≥ 15. However, such a combination of parameters was not used in the above-cited works. The photonic nanojet generated by a triangular prism has been described in [18], but miniature prism sizes of the order of wavelength were used. In addition, no further studies have been performed.

Thus, despite the development of various corresponding methods for calculating diffraction problems and the well-known object, the problem of scattering in a triangular prism has not been fully studied, as recent publications confirm this [14,17,19,20]. A possible gap in the photonic jet (PJ) data for a triangular prism can be associated with low expectations of a jet due to the weak focusing ability of the triangular prism. However, as a result of internal reflections, there are many secondary modes that can create constructive interference near the prism. The finite-difference time-domain (FDTD) simulation is a suitable research tool to examine that. We used it in this work to find out the following: is it possible formation of PJ via scattering of electromagnetic wave by triangular prism, and what should be the characteristic sizes of the triangular prism for that case?

2. SCATTERER AND SIMULATION DETAILS

This paper studies the scattering of electromagnetic plane waves by a triangular prism and its truncated form (the isosceles triangle and the trapezoid are transverse sections, respectively) (Figure 1). To obtain the electromagnetic field distribution as a result of the scattering process, we need to solve the Maxwell's equations. There are many numerical techniques for finding the appropriate solutions. In this paper, we will deal with the finite-difference time-domain (FDTD) method introduced by Yee [21]. The FDTD method solves the time-dependent Maxwell's equations in a spatially finite computational domain. The presence of the boundaries in the model can significantly affect the simulation results, which is caused by the spurious reflection from the boundaries of the electromagnetic waves incident on them. Therefore, in the implementation of FDTD, the layers of a hypothetical material are set up along the boundaries of the specially designed computational area in such a way that it completely absorbs the radiation incident on it. Such layers have been called a perfectly matched layer (PML) and were first described by Berenger [22].

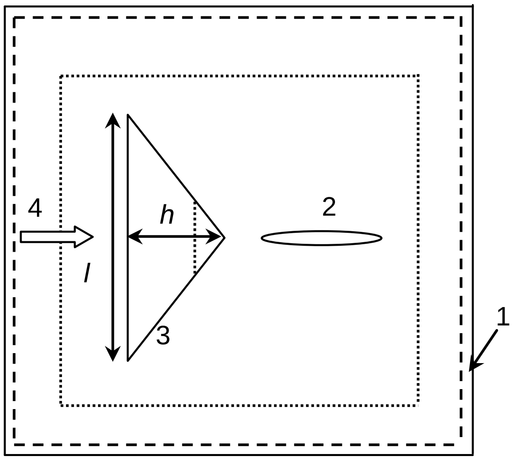

Figure 1: Scetch of the model: 1 – PML; 2 – photonic jet; 3- top view of triangular cylinder; 4 – plane wave. Dot line – border of TF area, while the dashed line is border of the computational domain.

To simulate an incident plane electromagnetic wave, we used the TF/SF (total field/scattered field) technique [23]. Here, the computational domain is divided into two regions: a TF region, in which all objects are placed, and an SF region surrounding the TF region, as shown in Figure 1. Then, the incident plane wave is imposed on the boundary between these two regions to compensate for the discontinuity caused by the different field values on both sides of the boundary. A more detailed treatment of the FDTD method is given in [23].

A schematic diagram of the computational area used is presented in Figure 1. The horizontal cross-section of the prism is a triangle lying in the x - y plane. The incident wave propagates along the x-direction. FDTD space lattice in the x and y directions $\Delta x=\Delta y$ is finer than 1/50 of an incident wavelength for all calculations. Sampling at time Δt is selected according to the Courant condition $c\Delta t/(\Delta x^2+\Delta y^2)^{1/2}< 1$ (c is the speed of light in free space) to ensure numerical stability of the simulation. The size (in wavelength) and the refractive indexes of the triangular prism are l = 10, $h = 1 \div .4$, n_A = 1.59. A TE-polarized plane wave (λ = 532 nm) falls on the prism along the x-axis.

3. PHOTONIC JET

Photonic jet relates to the phenomena that really exist and can be studied both experimentally [8, 24,25] and theoretically [24]. Here we concentrated on FDTD simulation results we get for the real parameters of triangular prism. One of that is refractive index n. Typical value of refractive index used in PJ study is $1<n<2$. As n decreases from $n>2$ toward 1, the focus of the electromagnetic field moves away from the object and the intensity at the focus decreases, while the length of the jet increases. Here we used intermediate value of refractive index $n=1.59$, which is corresponding to a kind of polymer widely used in optical components [6,24].

The typical diameter of a cylinder or sphere that generates a photonic jet is on the order of 10 wavelengths. Therefore, the base of our triangular prism is $l = 10\lambda$. Its height h has been varied in order to determine the optimal value to form a photonic jet. Maximal field intensity, waist and length of the photonic jet (PJ) are its main characteristics. The length of PJ was determined by the distance from the end of the prism to the point where the intensity does not decrease more than two times. The dependencies of these quantities on the size of the prism h are shown in Figure 2. The value of h is less than the value corresponding to an equilateral triangle. In this case, it is well known that standing internal modes of total internal reflection [16] are formed. With a further increase in *h*, the focus moves inside the prism. Among the dependencies presented, only the amplitude has a maximum value, but its value varies within a small range, while the other two dependencies are decreasing.

The position of the maximum field amplitude is crucial to the length *L* of the nanojet. A decrease in *L* as *h* increases is caused by the movement of the focus (position of the maximum amplitude) inside the prism. Thus, it can be seen from Figure 2 that the range $h = (2 \div 4)\lambda$ corresponds to both the field amplitudes close to the maximum and the subwavelength waist of the photonic jet. It is worth noting that for circular cylinders of approximately the same size (about 10 wavelengths in diameter), the length of the nanojet is of the order of 2 wavelengths [1]. More precisely, we can conclude that for the given base length of triangle cross section $l=10\lambda$ its high of $\approx 3\lambda$ is optimal to get photonic jet of 6λ length with subwavelength waist.

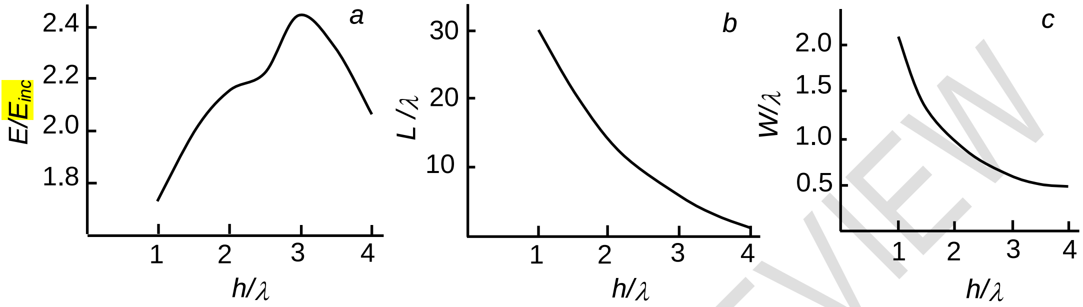

Figure 2: Main characteristics of photonic jet versus on size *h* of triangular prism: *a* – maximum of electromagnetic field amplitude (relative to the incident wave amplitude); *b* and *c* – length and waist of the photonic jet, respectively.

We also discovered how a decrease in the value of *h* (with the transformation of a triangular cross-section into a trapezoidal one) affects the main characteristics of the photonic jet. The same dependencies as in Figure 2, but against the magnitude of truncation Δh, are depicted in Figure 3.

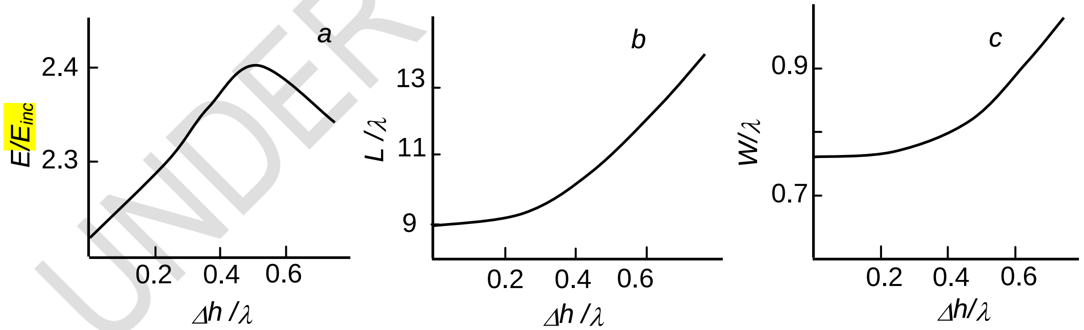

Figure 3: Same as in Figure 2 but versus on truncation Δh of the triangular prism with initial $h=2.5\lambda$.

Let's note that the truncation Δh and other distances in the present paper are measured in wavelength. Thus, as seen for $\Delta h>1$, the maximum field amplitude decreases, while the waist of the photonic nanojet increases and tends to exceed one wavelength. This is why all the dependencies are presented for a wide range $\Delta h<1$. The main conclusion here is that the truncation of *h* leads to a slight improvement in the main characteristics of photonic jet, which is because truncation increases the field intensity along the incident wave direction. However, a further increase in truncation decreases the focusing properties of the prism, and scatters and directs the field over a wider range.

4. CONCLUSION

The scattering of electromagnetic plane waves by a triangular prism leads to the formation of the photonic jet on the shadow-side of the prism. By means of FDTD simulation, a relationship between the size of the prism and the optimal wavelength for the photonic jet has been established. The dependencies of the main characteristics of the photonic jet (maximal field amplitude, length and waist) are presented against the size of the prism. It was found that the truncation of the triangular prism (trapezoidal cross-section) can improve the main characteristics of the photonic jet.

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