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ABSTRACT

In this contribution we reveal how the step-like topology of a microstructure can contribute to the formation of a single high-intensity nanojet (NJ) beam located on its axis of symmetry. The proposed method for generating condensed optical NJ beams relies on the complex electromagnetic phenomenon associated with the light diffraction on the edges of step-like dielectric microstructures embedded in a host medium with lower refractive index. The possibility of NJ beam intensification in the near zone of such microstructure illuminated by a plane wave is demonstrated and explained by the recombination of multiple NJ beams associated with different edges or edge segments of the step-like microlens. We demonstrate that by changing materials of the layers we can intensify the NJ beam. We examine the dependence of the generated beam on the step size, shape and material.

Keywords: photonic nanojet, edge diffraction, microlens, near field focusing.

1. INTRODUCTION

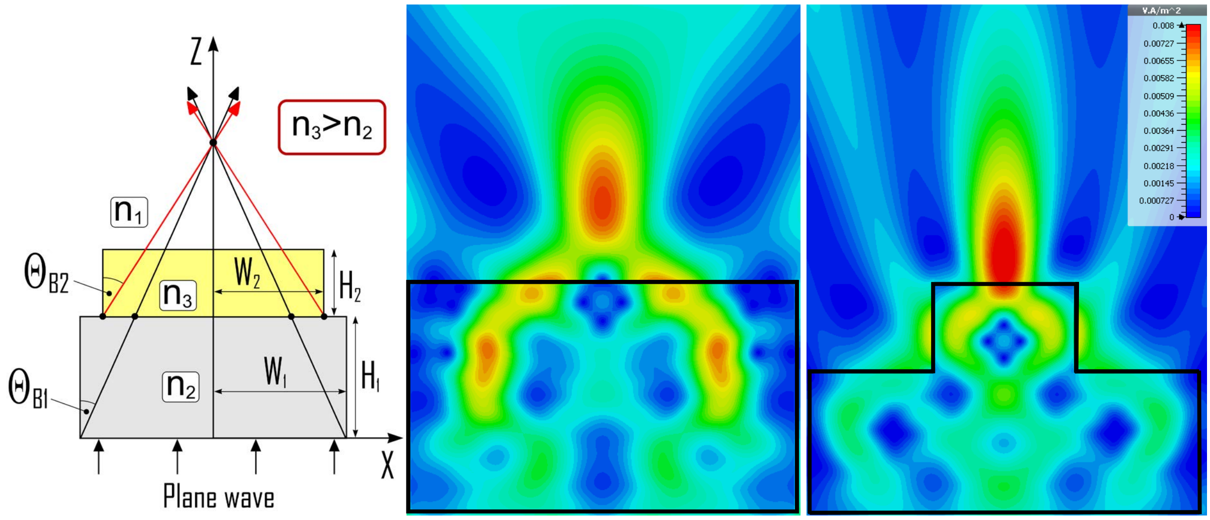
NJ-based near-field focusing components attract strong interest. This is driving by the growing number of applications across different domains, which require near-field light processing with the highest possible resolution [1]. As well, advances in technology, enable the fabrication of highly-integrated components with structural elements having nano-scale dimensions. The photonic NJ is a narrow focused high-intensity electromagnetic beam at the shadow side surface of a plane-wave illuminated lossless dielectric microparticle of size greater than the wavelength of incident plane wave [1,2]. For the case of spherical or cylindrical particles, this effect is fully predicted by the Mie theory. It was demonstrated that to control and tune the nanoparticle optical response we should change the nanoparticles' size, shape, and environmental conditions [3-6]. The electromagnetic fields in the complex systems of arbitrary shape can be calculated using different numerical techniques and analytical approaches (for example, discrete dipole approximation method [7]). Accurate, efficient and general solution of such diffraction problems still remains a topic of high interest. The applications of photonic NJs have been investigated in various fields, including optical data storage, high-resolution imaging, spectroscopy, maskless sub-wavelength lithography, and optical networking [1,2,8].

In this work, we propose to transform the shape of a NJ microlens in a such a way that all NJ beams, originating from different edges (associated with different layers) of the step-like microstructure, recombine and contribute to the formation of a single high-intensity NJ beam located on the axis of symmetry of the system. As we demonstrate in this paper, the desired effect can be achieved using a step-like shape of the focusing element and combining two or more materials with different refractive indexes. It was shown that the characteristics of NJ beams are controlled by the parameters of the corresponding layers (i.e. refractive index ratios between the lens and host medium, base angle and size/shape of the step). A potential additional advantage of the proposed step-like microlens is the increase of the NJ beam length and/or intensity as the result of the partial contributions of multiple NJ beams, associated with different layers.

2. IDENTIFICATION OF THE PHOTONIC NJ FOR A DIELECTRIC STEP-LIKE SYSTEM

The cross-section view of the step-like NJ lens is illustrated in Fig. 1a. The presented system may correspond to a double-layer rib, cuboid, or cylinder. It is assumed that the dielectric system with refractive index n_2 is embedded in a homogeneous dielectric host media with refractive index $n_1 < n_2$. As it will be demonstrated below, the material and size of the second layer with refractive index n_3 can be initially selected arbitrarily and then optimized depending on the parameters of the first layer in order to reach a maximum field intensity enhancement for the beam generated in the near zone resulting of the recombination of the NJ beams associated with the different edges of the step-like microlens.

To illustrate the effect of the step-like topology on the NJ beams we represent the power density distribution for single- (Fig. 1b) and double-steps (Fig. 1c) microlenses obtained using the electromagnetic field simulation software package CST MICROWAVE STUDIO. The lenses are assumed to be infinite along y-axis (rib-type) and are illuminated by a linearly-polarized plane wave $E = \{0, 1, 0\}$. The materials of the steps of the microlens are the same ($n_2 = n_3$). All presented simulations were done for 2D configurations. For simplicity, we assume that all the materials are lossless and non-dispersive. Comparison of these two figures shows that by choosing the optimal parameters of the layers we can adjust the focal lengths of the constitutive elements and get higher power density.



(a) (b) (c)

Figure1:(a) Geometry of the system; (b, c) Power density distribution in xz-plane for the microlenses illuminated by a plane wave at λ = 550 nm for the system with parameters: $n_1 = 1$, $n_2 = n_3 = 1.8$, $W_1 = 550$ nm, $H_1 = 400$ nm, $H_2 = 250$nm, (b) $W_2 = W_1 = 550$ nm – single step microlens, (c) $W_2 = 200$ nm – double step microlens. The scaling bar is the same for (b) and (c) figures

Let us present a set of equations to estimate the optimal dimensions of the layers for maximal enhancement of the field intensity of generated NJ beam. Our analysis shows that the beam-forming phenomenon is associated solely with the edge of the system and the NJ beam radiation angle can be determined as a function of the ratio between the refraction indexes of the host media and material of the steps, and the base angle of the element (in our case we analyse the elements with the vertical edges and the base angle is equal to 90°) [9]. For the constitutive elements the NJ beam radiation angle can be determined using the approximate formula:

$$\Theta_{Bj} \approx \frac{90^\circ - \Theta_{TIRj}}{2}, \tag{1}$$

where $\Theta_{TIRj} = \sin^{-1}\left(\frac{n_1}{n_{j+1}}\right)$ is the critical angle of refraction, $j = 1, 2$. The focal length of the steps can be estimated as:

$$F_j = W_j \gamma_j, \tag{2}$$

where $\gamma_j = \frac{1}{\tan \Theta_{Bj}}$, W_j is the half-width (radius) of constitutive element of the step-like system (see Fig. 1a).

The interference of the NJ beams, associated with the bottom edge of the first step (first layer) of the system, and the NJ beam, associated with the bottom edge of the second step (second layer), leads to the increase of the total response of the microlens. In this case, the two beams make an input into the total generated beam. To increase the intensity in the NJ hot spot in the case of small elements ($W_1 \leq \lambda/2$), we should adjust the focal lengths of the constitutive elements. Assuming that the maximal intensity of the NJ hot spot corresponds to the elements with the total height equal to the focal length, we can get approximate formulas for the optimal sizes of the top layer:

$$H_2 \approx W_1\gamma_1 - H_1,$$
$$W_2 \approx \frac{H_2}{\gamma_2}. \tag{3}$$

It is necessary to note, that if materials of the steps are different, we should take into account that for $n_3 > n_2 > n_1$ $\Theta_{B1} < \Theta_{B2}$ and for $n_3 < n_2$ $(n_{2,3} > n_1)$ $\Theta_{B1} > \Theta_{B2}$. It means that for a proper adjustment, the dimensions of the top step should be corrected: for $n_3 > n_2$ the total width (radius) of the top step will be bigger than for the case with $n_3 = n_2$, for $n_3 < n2$ the total width (or radius) of the top step will be less than the optimal one for a single material system.

3. SIMULATION RESULTS AND DISCUSSION

Figure 2a shows the power density distribution along z-axis for 3 different values of W_2 for the system with the following parameters: $n_1 = 1$, $n_2 = n_3 = 1.49$, $W_1 = 275$ nm, $H_1 = 350$ nm. Using the eqn. (3) we have obtained that the optimal dimensions of the second step are $W_2 = 107.5$ nm and $H_2 = 268.8$ nm. It can be seen, that the maximal power density is observed for the step-like microlens with $W_2 = 120$ nm (solid red curve). The dashed gray curve in this figure corresponds to the reference solution, namely a single step microlens of the same total height. Comparison of the red and blue curves in Fig. 2a shows that choosing the optimal parameters of the layers we can adjust the focal lengths of the constitutive elements and get more intensive total response of the system. The dependence of the maximal power density on the half-width (radius) of the second layer W_2 is presented in Fig. 2b. The dashed gray horizontal line shows the reference solution for the single step microlens. It can be seen, that if parameters of the second layer are close to the optimal, we can get the maximal value of power distribution. The increase of the field intensity observed in the simulations is about 11%.

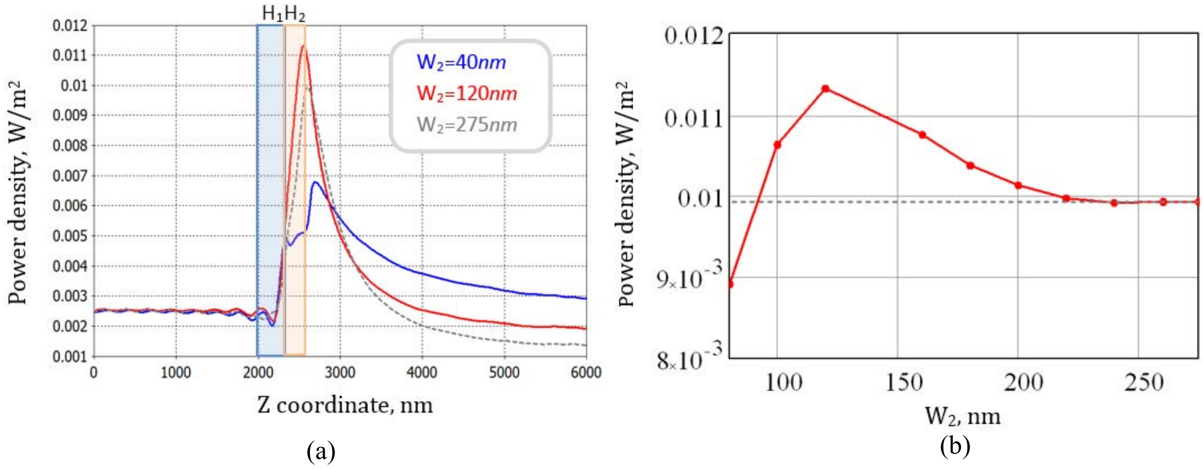


Figure 2. Power density distribution for a step-like microlens illuminated by the plane wave at λ = 550 nm for the systems with parameters: $n_1 = 1$, $n_2 = n_3 = 1.49$, $W_1 = 275$ nm, $H_1 = 350$ nm, $H_2 = 268$ nm: (a) distribution along z-axis for selected values of W_2, (b) peak power density versus W_2.

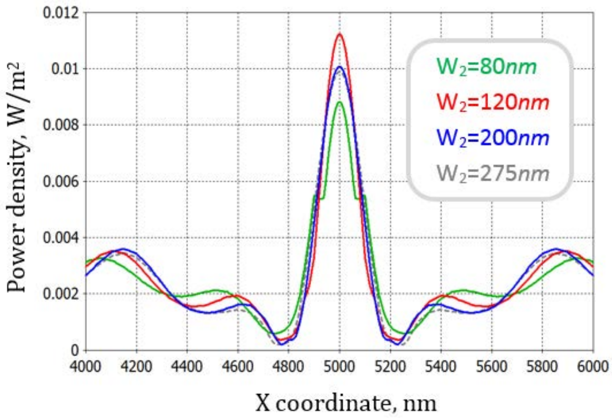


Figure 3. Power density distribution along x-axis at λ = 550 nm for the systems with such parameters: $n_1 = 1$, $n_2 = n_3 = 1.49$, $W_1 = 275$ nm, $H_1 = 350$ nm, $H_2 = 268$ nm.

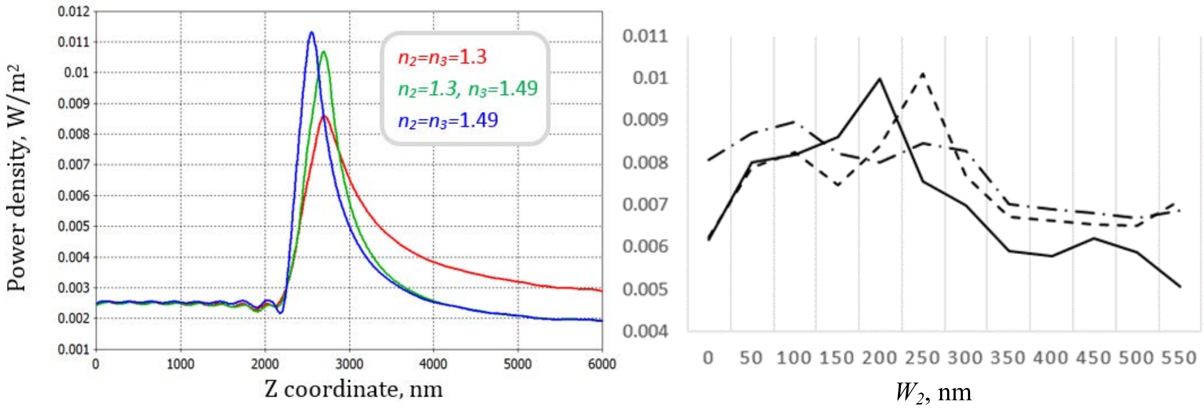
Figure 3 shows the power density distribution along x-axis for 4 different values of W_2 in the point of maximal intensity of the generated NJ beam, the dashed gray curve corresponds to the reference solution for the single step microlens. It can be seen, that in all cases the beam width at half power (BWHP) is about 200 nm, which is below the diffraction limit which predicts the smallest possible focal spot size of about $0.36\times\lambda_1$, where λ_1 is the wavelength in the host medium. As expected, the maximum power density is observed for the microlens with optimal parameters ($W_2 = 120$ nm), whose focal spot BWHP is about 170 nm. This is in part explained by the improved focusing ability of the step-like NJ microlens and the shift of the focal spot inside the lens with a refractive index value higher than that of the host medium.

We have observed that the peak power density is sensitive to the heights of the steps of the microlens. We can conclude that eq. (3) for two NJ hot spot adjustment does not work for the case when $H_{1,2} < \lambda/4$. In this case we observe two NJ hot spots.

The combinations of different materials qualitatively alter the power distribution along the z-axis (see Fig. 4a). Namely, we can observe that when $n_3 > n_2$ we can get higher peak (up to 25%) of power density distribution at smaller width of the second layer. But in this case the length of the NJ beam will be nearly equal to the length of the beam obtained for the step-like microlens with $n_3 = n_2 = 1.49$ and optimized smaller dimensions.

To illustrate the influence of the step-like topology on the parameters of the NJ beams in the case of lenses with bigger dimensions ($W_1 > \lambda/2$), we considered the system with the following parameters: $n_1 = 1$, $n_2 = n_3 = 1.8$, $W_1 = 550$ nm, $H_1 = 400$ nm. Using the eq. (3) we obtain that the optimal dimensions of the second step are $W_2 = 336.2$ nm and $H_2 = 689.8$ nm. Figure 4b shows the dependence of the maximal power density and

z-coordinate of NJ hot spot on the half-width (radius) of the second layer W_2 at 3 different wavelengths. Our numerical simulations demonstrate that eq. (3) does not work in this case. The constructive interference of the waves generated by the edges of the steps leads to the maximal intensity of generated NJ beam. So, the proposed system is very sensitive to the wavelength of electromagnetic wave. But it is possible to see that the step-like topology gives more intensive total response of the system (up to 200% in a case of $\lambda = 450$ nm for $W_2 = 200$ nm) compared to the single step system of the same height ($W_2 = W_1 = 550$ nm).



(a) (b)

Figure 4: (a) Power density distribution along z-axis at λ = 550 nm for the systems with optimized parameters: $n_1 = 1$, $W_1 = 275$ nm, $H_1 = 350$ nm, red curve – $n_2 = n_3 = 1.3$ ($W_2 = 150$ nm, $H_2 = 410$ nm) ; green curve – $n_2 = 1.3$, $n_3 = 1.49$ ($W_2 = 140$ nm, $H_2 = 410$ nm) ; blue curve – $n_2 = n_3 = 1.49$ ($W_2 = 120$ nm, $H_2 = 268$ nm); (b) – Peak power density versus W_2 for the step-like systems with such parameters: $n_1 = 1$, $n_2 = n_3 = 1.8$, $W_1 = 550$ nm, $H_1 = 400$ nm, $H_2 = 250$ nm illuminated by a plane wave at λ = 450 nm (solid curve), λ = 550 nm (dashed curve), λ = 650 nm (dash-dot curve).

4. CONCLUSIONS

Our analysis has revealed that diffraction of a plane wave on a step-like layered microlens, with the materials of the steps (layers) having a higher refractive index than that of the host medium, can result in the formation of more intensive NJ beams. The intensity, dimensions and shape of the beam can be controlled by the variation of the step size, shape and material.

Such a configuration can be of a particular interest to a number of applications requiring direct attachment of a lens to a receiving or emitting element, which is to be placed in the focus of the lens. The proposed components can potentially replace the conventional focusing devices in dense optic and photonic systems, like integrated optical sensors used in photo/video cameras that are essential components of the today and tomorrow mobile technology.

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