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Tuning the photonic nanojet based on the Babinet principle

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ABSTRACT

The diffraction limit of electromagnetic waves restricts the formation of sub-wavelength spots. The feasibility to generate scattered beams of light with a high-intensity main lobe, a weak sub-diffracting waist, and a very low divergence angle, named Photonic nanojets, was demonstrated traditionally with spherical particles. Various practical applications require the creation of different types of photonic jets or electromagnetic streams with specific characteristics and properties. For instance, photonic jets can be applied to ease the coupling into the optical waveguides. In this case, photonic jets play the role of a coupling element similar to the lens, grating coupler or prism. To address this challenge, we study the Fresnel Zone Plate (FZP) of rings-like shape. We show that the Babinet principle can be applied for studying the complementary diffractive structures for the formation of near-field photonic jets on a facet of the optical waveguide. Using COMSOL Multiphysics, we built a model of the Fresnel Zone Plate structure based on rings and demonstrate the applicability of Babinet's principle for the formation of photonic jets in the near-infrared.

Keywords*:* diffraction optics; nanophotonics; subwavelength focusing; optical forces, nanojet.

1. INTRODUCTION

Integrated photonic circuits provide an attractive platform for various devices and applications such as processing chip information, chemical and biological sensing. However, there are several challenges of integrating these devices into large-scale systems. These challenges include reducing the scale of an optical device, increasing their film width, resilience, and reducing device losses. A combination of optical waveguides and sub-wavelength dielectric structures may address some of these challenges. The integration of metasurfaces into integrated photonic circuits provides a high-cost platform for controlling the high-bandwidth and low-loss-bandwidth waves [1]. One of the challenges of creating integrated photonic circuits is the ability to distinguish between two adjacent points, that is, the ability to detect objects smaller than the Abbe's (half-wavelength) diffraction limit [2], which is essentially the so-called "super-resolution". Such an improved resolution provides the index ratio between the medium and the lens less than 2:1 [3,4].
One of the solutions for breaking the diffraction limit is using a Fresnel lens [5,6]. Due to its flat geometry, the Fresnel lens is an effective solution to the problem of reducing the device dimensions on one hand and improving the resolution on the other.
Using the finite element method (FEM method) with COMSOL Multiphysics software we designed the Fresnel lens on a fiber. We solved Maxwell's equations in each domain of the considered system shown in Figure 1.

2. METHODS

In the studied Fresnel lens configuration, only dielectric materials were used to avoid unnecessary losses. For simplicity, the lens is designed with rectangular profile ring areas. This paper reports on the flat lens that achieves a Photonic Nanojet beam based on Fresnel's diffraction principles as well as the principles of

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interference when the focal distance of the lens is half the wavelength. As one can see from Figure 1, the lens has both opaque and transparent areas.

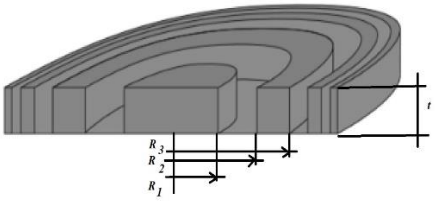

Figure 1: Schematics of the structure of a flat Fresnel lens while showing the radii of the rings.

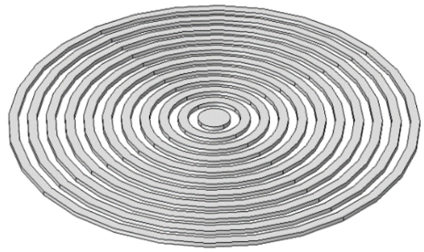

Figure 2: Lens structure designed in COMSOL Multiphysics software made of silicon with slots filled with air. The lens contains 10 rings and a middle disk.

The lens is illuminated from the top by a plane wave that propagates in the positive z-direction, with the light source far enough from the lens. The lens is made of silicon (n = 3.4) in COMSOL Multiphysics software with a disk having a radius of R1 and 10 rings as shown in Figure 2. The thickness of the rings (t) is determined by the following formula [5]:

$$t = \frac{\lambda}{2\left(|n|-1\right)} \tag{1}$$

Or t=1.1λ =1.705 µm in our case, when the wavelength is: λ = 1.55µm.
According to the Babinet principle, the lens can be designed in two complementary forms as shown in Figure 3. The diffraction pattern obtained by an opaque feature will be the same or similar to that obtained by a transparent feature, assuming that both features are identical in shape. However, it is known that between the two cases described, there may be differences in the intensity of the resulting pattern [7].

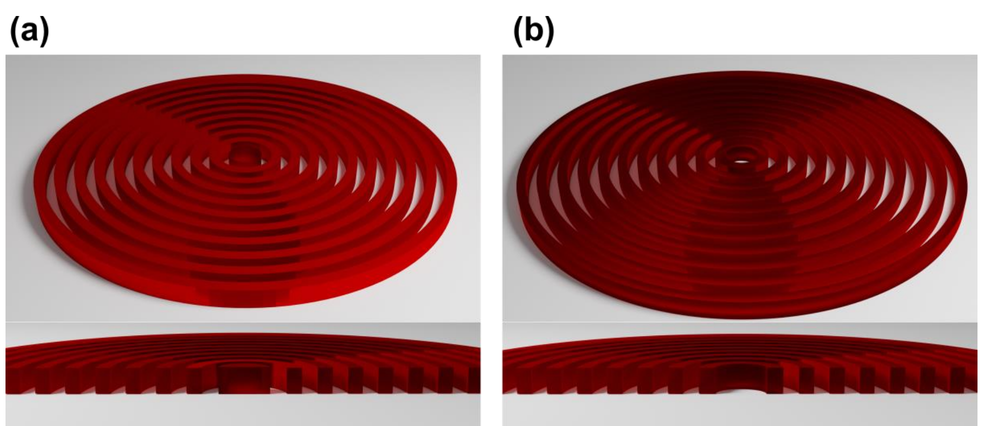

*Figure 3: Fundamental description of a Fresnel lens with opaque and transparent areas. (*a*) Lens with transparent odd areas. (*b*) Lens with transparent even areas.* Lens cross-sections are shown below each subplot. *This* renders illustrate *the* lens designed based on te *Babinet principle.*

To design the focusing device, we define the distance l_i between the rings i and the focus point, and the distance l_0 being the distance between the lens plane and the focus point on the optical axis. According to the diffraction principle, we obtain a point of constructive interference where the difference l_i-l_0 is an integer multiple of the wavelength (or, in terms of phase, an integer multiple of π), and we obtain a point of destructive interference when the difference is an integer multiple of half the wavelength (or in terms of phase, an integer multiple of π). So we would need:

$$\frac{(i-1)\lambda}{2} < l_i - l_0 < \frac{i\lambda}{2} \tag{2}$$

And we assume:

$$r_i = \sqrt{i\lambda f + \left(\frac{i\lambda}{2}\right)^2} \tag{3}$$

In general, a phase correction is added to formula (3) so that we get [8]:

$$r_i = \sqrt{i\lambda\sqrt{f^2 + r_0^2} + \left(\frac{i\lambda}{2}\right)^2 + r_0^2} \tag{3a}$$

where r_0 is an arbitrary parameter. This allows us to optimize the focusing properties of the lens. The width of each ring is defined by the following relation:

$$w_i = r_{i+1} - r_i \tag{4}$$

As mentioned, we aim to go beyond the Abbe limit and achieve super-resolution, so we need the ratio of the refractive index between the lens and the medium to be less than 2:1 [3,4].

RESULTS

We report on the devices which are designed to achieve the super-resolution and are semi-identical based on the Babinet principle. We studied two structures: one for opaque paired areas and transparent uneven areas and another one for transparent paired areas and opaque uneven areas. Figure 4 shows the calculated Photonic Nanojet generated by the ‘opaque’ and ‘transparent’ lenses, showing a similar photonic jet effect for both configurations.

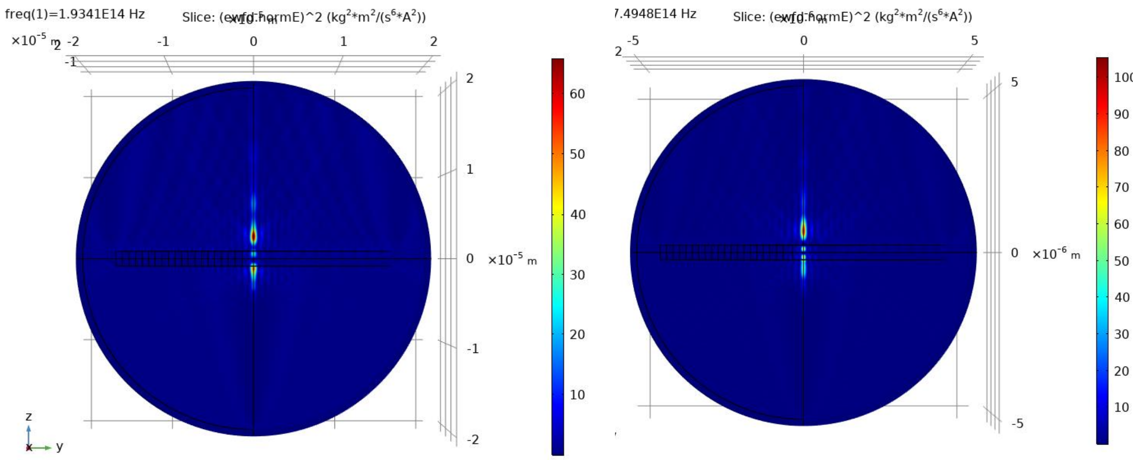

Figure 4: Photonic Nanojet beam generated by the lens. The colormaps show the cross section of the simulation area when the lens is in a plane perpendicular to the image plane. (Right) Transparent odd areas. (Left) Opaque even areas.

Figure 5 shows the calculated field intensities along the optical axis when even the lens areas are transparent.

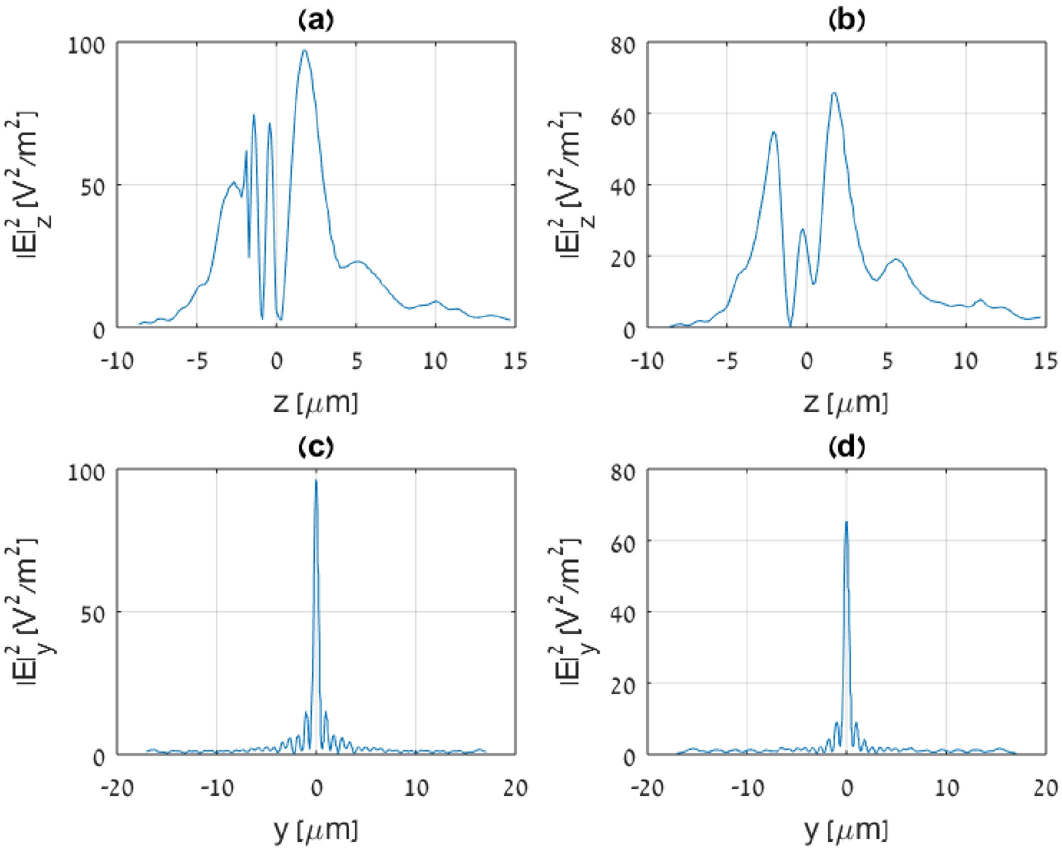

Figure 5: Field intensity along the optical axis (a) for the lens of even transparent zones rings. The edge of the lens is at the z = 0 plane. (b) opaque even zones rings (inverse complementary structure of a). (c) The intensity of the beam in the plane parallel to the lens plane for the lens structure with even transparent zones rings (like (a) but in x-y plane). (d) The intensity of the beam in the plane parallel to the lens plane for the lens structure with odd transparent zones rings (like (a) but in x-y plane).

The results show the effect of the Babinet principle and a super-resolution [5,6]. In both cases, the received beam has a $\mathrm{FWHM} \cong 0.35\lambda$ due to the focal spot which appears in the near field of the lens. Thus, it was demonstrated that in the near field of a single Fresnel lens, without the immersion medium, a resolution of about ~(0.3…0.4)λ can be achieved.

CONCLUSION

Based on the Fresnel zone plate principle, we showed that a narrow Photonic Nanojet beam can be achieved to break the Abbe limit and obtain a super-resolution effect of the features as small as up to the third of the telecommunication wavelength. We proved that the photonic jets produced by the complementary diffractive structures are nearly identical, based on the Babinet principle, with the main difference in the field intensities. This means that for the high NA FZP the Babinet principle is only approximately fulfilled. With the studied structure, a flat lens can be manufactured for a variety of applications, including optical communication, nanofabrication, microscopy, spectroscopy, and others. The proposed device can be manufactured easily and has very low losses. Moreover, the type of diffraction lenses we considered potentially makes it possible to obtain relatively easily a curved focus area (photonic hook) by introducing asymmetric apodization [9,10].

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