Metalens for creation of the longitudinally polarized photonic needle

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Abstract. In this work, we develop a mathematical apparatus to describe continuous subwavelength diffraction gratings for creation of cylindrical beams with arbitrary order. We consider special degenerated cases of gratings periods expressions and propose to introduce nonlinearity to avoid these cases. Also, we propose a metalens based on subwavelength relief that is intended to create the longitudinally polarized photonic needle. The element combines two functions: polarization and phase transformation of the incident beam. The element transforms the incident linearly polarized beam into the radially polarized beam. Simultaneously, the incident field is provided with axicon phase. The numerical simulation is provided with Comsol software. The simulation verifies the efficient creation of longitudinally polarized photonic needle.

1. Introduction
Metasurfaces is a type of optical metamaterials that have a subwavelength thickness and provide an ability to control different parameters of light [1-3]. The main advantage of metasurfaces is fewer sizes, fewer losses, and simpler manufacturing procedure in comparison with three-dimensional metamaterials [4]. There is a review in the work [3] where the authors gather publications about electromagnetic phenomena that are observed in dielectric metamaterials: high refractive index nanoresonators, metasurfaces, metamaterials with zero refractive index, and anisotropic metamaterials. In paper [5] the authors show the ability to control the parameters of infrared light using very thin plasmon layer (~λ/50). In the work [6] the lens is produced with NA ~ 0.75 and the transmission efficiency is 90% and focusing efficiency achieves 40%.

Metasurfaces can be considered as optical devices, particularly in paper [7] the authors design focusing metalens which has the efficiency of about 90% as a classical lens. In the work [8] authors demonstrate an ability to control the phase of the light with rectangular nanoholes in the gold film with a thickness of 250 nm. In [9] the authors consider 2d lenses that focus light with two different wavelengths. This effect is based on two resonances that occur in two types of silicon microcylinders.
for two wavelengths of 1550 and 915 nm. The efficiency achieves 65% for the wavelength of 1550 nm.

Metasurfaces with metal meta-atoms and holes can be used as sensors [10-12]. It should be noted that the nonlinear properties of metasurfaces provide a high sensitivity of sensors. In [12] there is a detailed comparison of linear and nonlinear sensor scheme.

Also, one of the applications of metasurfaces is polarization recognition [13, 14] where the authors develop a conception of polarization-analyzer as a metasurface that consists of three types of meta-atoms. In the paper [15] it is shown an ability to use a metasurface as a polarization-converter like a quarter-wave plate. The metasurface described in [15] converts a linearly polarized light into circularly polarized.

It should be noticed that metasurfaces can be used as optical diodes [16], holograms [17, 18], analog computing device [19]. In the paper [20] the authors develop a metasurface for the generation of an optical vortex which can be used to increase the bandwidth of optical communication systems. In the paper [21] the planar waveguide joint is designed as a metasurface. Calculated efficiency of the joint achieved 98%.

One of the most common applications of metasurfaces is the creation and focusing the cylindrical vector beams [22-28] where metasurfaces are dielectric subwavelength grating. In contrast to sectorial gratings [26, 27], in this work, we consider continuous relief which provides more homogeneous polarization transform. The main advantage of the proposed method is the subwavelength grating period that varied with the position in the coordinate system. It makes it possible to increase the efficiency of polarization transform. Period variation with coordinates is described in [29].

In this paper, we propose a metalens that is based on subwavelength relief for longitudinally polarized photonic needle creation. As a rule, the needle is generated with sharp focusing of the radially polarized beam [30, 31], among others using an axicon [32, 33]. However, most of commercially available lasers produce linearly polarized light. Thus, there are some papers where the authors investigate an ability to increase the longitudinal component of the electric field introducing vertical phase singularity into the linearly polarized beam [34-36]. Nevertheless, the most efficient conversation of initial energy into a longitudinal component of the electric field is observed when the radially polarized beam is focused [37]. Thus, it is rational to combine the polarization converter and the focusing lens into one optical element.

2. Special aspects of subwavelength gratings for cylindrically polarized vector beams creation

It is well known, that the strongest longitudinal component of the electric field is provided with a focused radially polarized beam of the first order. However, cylindrical vector beams are used in various applications like optical data transferring multiplexing [38], amplitude-polarization modulation of focal distributions [39], optical tweezers [40, 41], inverse energy flux generation [42-44], exoplanet imaging [45, 46]. Thus, it is advantageous to consider the creation of cylindrical vector beams with different orders including fractional.

Radial polarization of the order $p$ is defined with the following Jones vector:

$$ C(\phi) = \begin{bmatrix} \cos(p\phi) \\ \sin(p\phi) \end{bmatrix}, $$

where $\phi$ – polar angle.

Azimuthal polarization of the order $p$ is defined with the following Jones vector:

$$ C(\phi) = \begin{bmatrix} -\sin(p\phi) \\ \cos(p\phi) \end{bmatrix}. $$

Let us denote Jones vector’s components as $(c_r(\phi), c_i(\phi))$.

Hence, local grating at each point of space can be described with the following equation:

$$ g(x, y) = \cos[c_r(\phi)x + c_i(\phi)y]. $$
It is well-known that a half-wave plate doubles the angle of the incident polarization and the subwavelength grating can be used as a half-wave plate [26]. Thus, the subwavelength polarizing grating that rotates the incident polarization by the angle \( \alpha \) can be described as:

\[
g_p(x, y) = \cos \left\{ -\sin \left[ (p\phi - \alpha) / 2 \right] x + \cos \left[ (p\phi - \alpha) / 2 \right] y \right\}. \tag{4}\]

In polar coordinates equation (4) has the following view:

\[
g_p(r, \phi) = \cos \left\{ -\sin \left[ (p\phi - \alpha) / 2 \right] r \cos \phi + \cos \left[ (p\phi - \alpha) / 2 \right] r \sin \phi \right\}. \tag{5}\]

Thus, to create a radially polarized beam with the order \( p \) from the linearly polarized beam (\( \alpha = 0 \)) we can use the subwavelength grating with the following relief:

\[
g_{p}^{\text{Rad}}(r, \phi) = \cos \left\{ r \sin \left[ \phi (p - 2) / 2 \right] \right\}. \tag{6}\]

Similarly, to create an azimuthally polarized beam with the order \( p \) from the linearly polarized beam (\( \alpha = 0 \)) we can use the subwavelength grating with the following relief:

\[
g_{p}^{\text{Az}}(r, \phi) = \cos \left\{ r \cos \left[ \phi (p - 2) / 2 \right] \right\}. \tag{7}\]

It can be concluded from Eq. (6) that for the second order radial polarization there is an obstacle for using it. To avoid it, we can introduce a grating period that nonlinearly depends on coordinates. For example, we can raise \( x \) and \( y \) to the \( n \)th power:

\[
g_{p}^{n}(x, y) = \cos \left\{ -\sin \left[ (p\phi - \alpha) / 2 \right] x^n + \cos \left[ (p\phi - \alpha) / 2 \right] y^n \right\}. \tag{8}\]

In Tables 1-4, there are relief templates of subwavelength gratings for creation of cylindrically polarized vector beams with arbitrary orders. The templates are shown both as continuous and sectorial cases. In tables 3 and 4 we use Eq. (8) to plot the gratings templates.

**Table 1.** Subwavelength gratings for the generation of the first and the minus first orders cylindrical polarization.

| Order of polarization | Polarization orientation | Subwavelength gratings patterns in case of continuous and 4-sectors cases for the incident x-polarization |
|-----------------------|--------------------------|--------------------------------------------------------------------------------------------------|
| **Rad, \( p=1 \)**   | ![Image](image1.png)     | ![Image](image2.png)                                                                                |
| **Rad, \( p=-1 \)**  | ![Image](image3.png)     | ![Image](image4.png)                                                                               |
| **Az, \( p=1 \)**    | ![Image](image5.png)     | ![Image](image6.png)                                                                               |
| **Az, \( p=-1 \)**   | ![Image](image7.png)     | ![Image](image8.png)                                                                               |
Table 2. Subwavelength gratings for the forming of cylindrical polarization with one-half- and minus one-half-orders.

| Order of polarization | Polarization orientation | Subwavelength gratings patterns in case of continuous, 4-, and 8-sectors cases for the incident x-polarization |
|-----------------------|--------------------------|-----------------------------------------------------------------------------------------------------|
| Rad, \( p=0.5 \)     |                          |                                                                                                     |
| Rad, \( p=-0.5 \)    |                          |                                                                                                     |
| Az, \( p=0.5 \)      |                          |                                                                                                     |
| Az, \( p=-0.5 \)     |                          |                                                                                                     |

Table 3. Subwavelength gratings for the forming of cylindrical polarization with the second and minus second orders.

| Order of polarization | Polarization orientation | Subwavelength gratings patterns in case of continuous and 8-sectors cases for the incident x-polarization |
|-----------------------|--------------------------|-----------------------------------------------------------------------------------------------------|
| Rad, \( p=2 \)       |                          |                                                                                                     |
| Rad, \( p=-2 \)      |                          |                                                                                                     |
| Az, \( p=2 \)        |                          |                                                                                                     |
| Az, \( p=-2 \)       |                          |                                                                                                     |
It follows from tables 1-4 that the azimuthal and radial polarizations are identical if not taking into account the rotation by a certain angle. Exceptions occur for the second and fractional orders of polarization. For the second order, it is well known a simple solution that has a view of both radial lines originated from the center and concentric rings that are perpendicular to the radial lines at every point of space. The second case corresponds to subwavelength axicon.

Obviously, the higher the order of polarization the more complex the pattern of subwavelength grating and more sectors are necessary to approximate continuous lines (Tabs. 3 and 4). The similar case occurs for the fractional orders.

**Table 4.** Subwavelength gratings for the forming of cylindrical polarization with the third and minus third orders.

| Order of polarization | Polarization orientation | Subwavelength gratings patterns in case of continuous and 8-sectors cases for the incident x-polarization |
|-----------------------|--------------------------|--------------------------------------------------------------------------------------------------|
| Rad, \( p=3 \)       |                          | ![Image](image1)                                                                                                                                 |
| Rad, \( p=-3 \)      |                          | ![Image](image2)                                                                                   |
| Az, \( p=3 \)        |                          | ![Image](image3)                                                                                   |
| Az, \( p=-3 \)       |                          | ![Image](image4)                                                                                   |

3. **Metalens for creation of longitudinally polarized light distribution**

In this work, we propose a combined element that creates longitudinally polarized elongated light distribution which is commonly called “photonic needle.” Proposed element is subwavelength relief that combines polarization and phase transform. The proposed subwavelength grating is based on Eq. (8) if \( n = 0.5 \). The element transforms the incident linearly polarized beam into a radially polarized beam with the first order. Also, the element introduces into output beam the phase of the axicon that is why the beam is focused.

The binary phasing is realized by the positioning of subwavelength gratings with perpendicular grooves in adjacent rings of the axicon [29]. The numerical aperture of the axicon is chosen to be 0.99 (very close to 1 as it is done in [28]). We propose to implement the subwavelength element at a substrate surface that is made of silicon with refractive index 4.206 + 0.42174j for our case that the wavelength is 633 nm. We use Comsol software for numerical simulation of considered laser beam diffraction.

In Figure 1 there is a ring amplitude distribution of incident linearly polarized beam (Figure 1a), the template of the element (Figure 1b), the amplitude of longitudinal electric field component in longitudinal and transverse cuts (Figure 1c and 1d), and longitudinal component diagrams in the focal...
plane cuts. In this paper, we call as a focal plane a transverse crosscut where the amplitude maximum is observed. In these simulations, the radius of the element is chosen to be 5.5λ. Conducted numerical simulation shows that the focal plane occurs at a distance of 1.12λ from the surface of the metalens.

![Figure 1](image)

**Figure 1.** Longitudinally polarized photonic needle generation with proposed metalens. (a) the amplitude distribution of the incident linearly polarized beam; (b) the template of the proposed metalens; (c) the amplitude of longitudinal electric field component in longitudinal cut; (d) the amplitude of longitudinal electric field component in focal plane; (e) full amplitude (red dashed line) and longitudinal component in focal plane cut.

As can be seen from Figure 1, the simulation shows that the proposed metalens can efficiently create longitudinally polarized photonic needle. The thickness of the needle is 0.51λ, the length is 2.37λ. In addition, we have a reason [33] to assume that the length of the needle depends on the incident beam radius and the element radius. Perhaps, it can be possible to make the needle longer just enlarging the entrance aperture or incident beam radius.

### 4. Conclusions

In this work, we investigate the type of subwavelength gratings for creation of cylindrically polarized beams with arbitrary orders. We propose the combined elements to create longitudinally polarized elongated light distribution that is called in the literature “photonic needle.” Using numerical simulation we verify the working of the proposed element.

### 5. References

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