Multifocal Autofocused Airy Beam Metasurfaces

M. Mahdi Shanei\textsuperscript{1}, Mahdieh Hashemi\textsuperscript{2}, A. Naresh Kumar Reddy\textsuperscript{3}, Carlos. J. Zapata Rodríguez\textsuperscript{4}
\textsuperscript{1}Department of Electromagnetic Engineering, KTH Royal Institute of Technology, SE-100 44 Stockholm, Sweden
\textsuperscript{2}Department of Physics, College of Science, Fasa University, Fasa 74617-81189, Iran
\textsuperscript{3}Department of Technical Cybernetics, Samara National Research University, 34 Moskovskoye Shosse, Samara 443086, Russia
\textsuperscript{4}Department of Optics and Optometry and Vision Science, University of Valencia, Dr. Moliner 50, Burjassot 46100, Spain

Abstract. To focus the incident light, both convex metalenses with hyperbolic phase profile and autofocused Airy (AFA) beams are widely used. To obtain AFA-based bifocal metalenses, we propose two methods in this article. One is to bring the two conjugate focal points of an AFA beam into the real space by applying a proper convex lens phase profile. The other is to use the inefficient central space between the two launched Airy beams with zero amplitude and constant phase profile as an independent metalens. We also show that combining the two introduced methods, leads the design to upgrade to a multifocal structure.

1. Introduction

The bent nature of the time-invariant Airy beams causes formation of two conjugate focal spots \cite{1,2}. The one that is formed in front of the structure is the real focus. The virtual one, which is formed behind the structure, remains not accessible. Utilizing a convex lens in the way of propagation of the AFA beams will bring the virtual image into the real space \cite{3}. To design a bifocal AFA-based metasurface which transforms the virtual focal spot to the real space we use a thin layer of metasurfaces for hybrid lens combination to the AFA beams \cite{4}. With generating the two launched mirror symmetric Airy beams in the Cartesian coordinate for light focusing, the space between the two Airy beams remains empty. We reach a bifocal design by using this ineffective space as an independent metalens \cite{5}.

We show that using the inutile space between the two Airy beam as an independent lens together with applying a converging lens profile to the AFA beam profile leads to the multifocal AFA generation \cite{4}. We apply the required phase and amplitude profiles of the desired structure at the launching plane to an arrangement of metaatoms. With advantageous like reduced size, lower weight and ease of fabrication, metasurfaces are commonly used in the field of fabricating the photonic components \cite{6}. In this paper we utilize C-shape silicon Metaatoms at the wavelength of 700 nm that enable us to have full control over the transmitted light phase and amplitude \cite{7}.

2. Bifocal AFA-Based Metasurfaces

To provide the required amplitude and phase control, we use C-shaped high-index silicon meta-atoms to support both electric and magnetic dipole resonances. Highly efficient designed silicon-based
metasurfaces at the wavelength of 700 nm are totally compatible with CMOS technology. Suitable amplitude and phase coverage are achieved for the co-polarized transmitted electric field component with sweeping the inner radius and the opening angle of the c-shapes over the range of 0 to 130 nm and 0 to 160°, respectively. While keeping the outer radius, R_o, thickness, t, of each metaatom and period of the substrate, P_s, fixed as 140 nm, 200 nm and 360 nm, respectively.

2.1. Transformation of the virtual focal spot to the real space: bifocal AFA design

Multiplying the phase profile of the two mirror symmetric launched airy beams with the focal point around z_f=70λ of the AFA to that of a convex metalens with f=z_f/2=35λ leads to the transportation of the virtual focal spot to z=23λ, which is shown in Fig. 1(a) and is consistent with the lens-maker formula. With the phase distribution of the Airy beams that are oscillating between two values of 0 and 180°, multiplication of the AFA beam profile to that of the lens causes the lens phase to be mirrored at positions with 180° phases of the AFA beam. Phase profiles of the AFA beam, lens, and their multiplication are indicated in Fig. 1(b) by purple dotted, dashed green, and solid blue lines, respectively.

![Figure 1(a, b)](image1)

**Figure 1(a, b).** (a) Intensity distribution of the focused AFA beam (f =35λ); (b) Phase profile of the AFA beam, lens, and their multiplication.

2.2. Subjoining a metalens to the space between the two mirrored Airy beams of the AFA beam

The space between the two launched mirrored converging Airy beams which are used for light focusing is left ineffective with zero amplitude transmission and constant molding phase profile.

![Figure 2(a, b)](image2)

**Figure 2(a, b).** (a) Co-polarized electric field intensity distribution; (b) Spatial distribution of the required phase profile (solid black line) and selected metaatoms (red stars).
We show that exploiting this unused space as an independent metalens not only interfere in the focusing operation of the AFA beam, but it will add the flexibility in light focusing at the second focal spot. For example, we set the focal length of the included metalens to be \( f = 30 \, \mu m \) in Fig. 2(a) while AFA beams are focused at \( z_f = 60 \, \mu m \). Parabolic phase profile of the central metalens which is added to the 0 and 180° phase distribution of the AFA beams is shown in Fig. 2(b). The red stars demonstrate selected metaatoms with the closest phase for fulfilling this phase distribution in the \( z=0 \) plane in Fig. 2(b).

3. Bifocal AFA-Based Metasurfaces

To increase the number of focal points to three by adding the focusing spot of the metalens to the two images of the focused AFA beam, amplitude modulation technique is necessary. To include focal spot of the metalens, amplitude distribution of the AFA beam should be modified toward the required unit amplitude of the metalens, at least, at the center of the metaatoms arrangement. It is important to note that the value of the transmitted light should be selected cautiously not to deteriorate the AFA image formation. Amplitude distribution of such design for the modified focused AFA (MFAFA) of Fig. 1 is illustrated in Fig. 3b as the dashed green line. Intensity distribution of this arrangement of metaatoms is included in Fig. 3a. Three distinct images at \( Q_1 = 70\lambda \), \( Q_2 = 23\lambda \) and the focal point of the metalens \( f = 35\lambda \) can be distinguished clearly.

![Figure 3(a, b). (a) Co-polarized electric field intensity distribution; (b) Spatial distribution of the required phase profile (solid black line) and selected metaatoms (red stars).](image)

4. Conclusion

The two presented methods in this article illustrate bifocal AFA-based focusing with using single layer of thin metasurfaces. The first method is based on the AFA focusing with a convex lens which leads to the imaginary focal spot transformation to the real space. Applying necessary phase profile of an AFA and a convex lens in a single metasurface arrangement leads to the bifocal AFA-based design. Within the other method, central metaatoms in the unused space between the two launched mirrored Airy are set to play the role of an independent metalens.

Flexibility in designing a bifocal metalens with enhanced focusing efficiency is achievable by the introduced methods. To add the focal spot of the metalens to the two images of the focused AFA beam, amplitude profile of the AFA beam should be modulated to get close to the amplitude distribution of the lens. Such an amplitude modulation of the focused AFA beam will lead to the formation of three focal spots in front of the metaatoms arrangement. The introduced method in this paper is a promising way to replace bulky photonic imaging and holographic tools with subwavelength arrangement of metaatoms.
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