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Amplitude modulation technique for designing metalenses with apodized and enhanced resolution focal spots

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ABSTRACT

In this paper we show that engineering both phase and amplitude of the scattered light can be employed in designing metalenses with either higher resolution or apodized focal spots. C-shaped split-ring micro-resonators (CSRRs) with different geometrical parameters are selected to have a full control of amplitude and phase. While phase engineering is necessary for light focusing, amplitude modulation of the scattered wave can be applied to characterize the focal point properties such as resolution gain and sidelobe level. We show that both axial and transverse resolution improvement or apodization is possible in the far-field region by applying proper amplitude function. Amplitude modulation technique, which is introduced in this paper, paves a new way to design efficient lenses which can be utilized in imaging and lithography applications in all frequency ranges.

1. Introduction

Light focusing with enhanced far-field resolution power and lower sidelobes are desirable in imaging and lithography applications. In recent years, far-field superresolution is studied in different structures [1]. In the frequency range of infrared to ultraviolet, conversion of free-space propagating low-wave-vectors to the high-wave-vector plasmons enables us to increase the resolution of image-forming systems significantly [2,3]. These structures are mainly composed of a plasmonic waveguide which is combined with a metamaterial slab, which couples the high-wave-vectors to propagating waves [4,5]. Another proposed approach to control resolution power and sidelobe height is super-oscillation, which is based on the idea of finding a band-limited function which is oscillating faster than the contained highest Fourier component. Super-oscillation technique increases the resolution without the help of evanescent waves and just with setting the destructive interference of waves with different frequencies by setting the proper amplitude for each frequency [6–8]. Quasi-crystal arrays and optimized Fresnel zone plates are commonly used for super-oscillating resolution improvement [9]. Historically, applying an amplitude filter in front of conventional lenses is another approach to achieve increased resolution power which was proposed long time ago [10,11]. More recently, parametrization of the resolution power with new figures of merit applied to axial and transverse orientation of the focal volume has allowed us to design novel pupil-plane filters in front of conventional lenses to achieve three dimensional resolution [12]. Particularly, the proposed filters can be in the form of rings or continuous modulating transmission filters [13–15].

In this paper, different from previous studies, we propose to use an arrangement of meta-atoms, that is a metasurface, to simultaneously focus light and mold the focal volume in the transverse and axial directions. In the other word, instead of using a separate transmission filter in front of the designed metalens, all along the metalens, meta-atoms are positioned according to their phase and amplitude of the scattered wave to play both roles of focusing and resolution improvement/apodization. For simplicity we consider cylindrical configurations to achieve enhanced resolution power and to manipulate the sidelobe height in the vicinities of the focus. Therefore, the one-dimensional distribution of meta-atoms will tune the characteristics of the point spread function by manipulating light scattering. For this purpose, our micro-resonators should be able to modify both phase and amplitude of the incident signal simultaneously. By controlling the phase, meta-atoms are an efficient tool to produce constructive interference at a specific point (focal point) [16–18]. While, with the amplitude modulation, full width at half maximum (FWHM) and sidelobes height of the focal intensity can be modified both in the transverse and axial directions. To have a full control of the phase and amplitude of the scattered wave in the frequency range of terahertz

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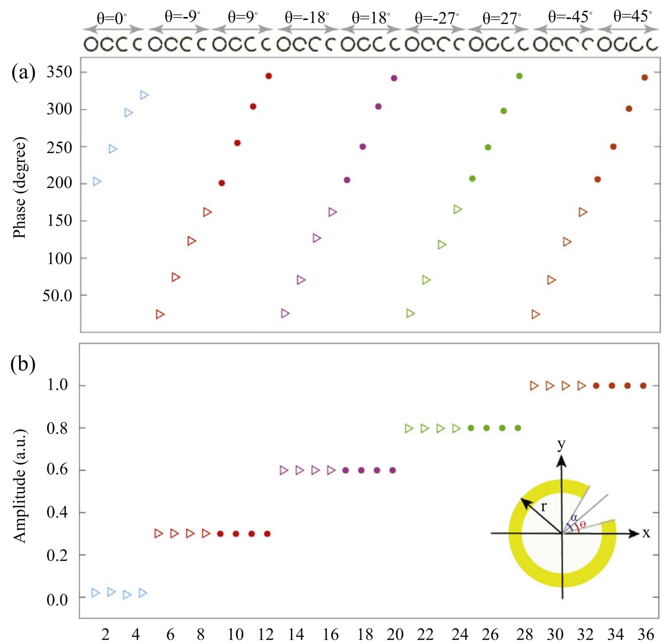

Fig. 1. (a) Phase and (b) normalized amplitude distribution of the cross-polarized component of the electric field that is scattered by our CSRRs. For negative values of θ and θ=0, triangle sign and for the positive values of θ, circles are used.

(THz), we designed 36 different C-shaped split-ring resonator meta-atoms. The CSRRs are designed to exhibit a phase shift of multiples of $\pi/4$ in the scattering field, with five different values of its amplitude for a given phase. To shape the lens, the CSRRs are arranged transversally according to their scattered phase for focusing purposes and in agreement with their scattered amplitude to fulfill the condition of the desired filter function. As a rule of thumb, when the FWHM decreases, sidelobes will grow and vice versa. Therefore, in any direction (axial or transverse) the filter can operate as an apodizer or an improver for the resolution power. By studying the Strehl ratio (SR) for each lens, we will discuss changes in the lens efficiency for all applied amplitude modulation functions.

2. CSRRs-based metasurface with tunable scattered fields in phase and amplitude

Meta-atoms in the form of CSRRs are appropriate for our lens design due to their capability in controlling both phase and amplitude of the scattered wave [19,20]. In the inset of Fig. 1(b) sketch of CSRR unit is illustrated with its opening angle (α), outer radius (r) and width (w). These three parameters determine phase, while θ, which is the CSRR orientation angle toward x-axis, determines the amplitude of the cross-polarized scattered wave. Geometrical parameters of all 36 CSRRs (r, α and θ) are introduced in Table 1. To compute phase and amplitude of the cross-polarized scattered wave from a CSRR unit, we applied x-polarized incident light and used finite element method simulations. Periodic boundaries surround the meta-atom in the x- and y-directions with the period of 80 μm in both directions. The 5 μm thick aluminum CSRRs with w=5 μm and conductivity of 3.7×10^7 S m^{-1} are placed on silicon substrate with refractive index of $n_{Si} = 3.45$. With this design and size of meta-atoms, proper working frequency range for these building blocks of the metalens would be THz [19]. Fig. 1(a) and (b) shows the phase and normalized amplitude of the cross-polarized scattered wave from these 36 CSRRs at the wavelength of $\lambda_0 = 476$ μm (equivalent to the frequency of 0.63 THz), respectively. It can be seen that with our designed CSRR meta-atoms, it is possible to generate various combinations of phases spanning the entire 360° range, in addition to the normalized amplitude covering the entire 0–1 range. Maximum light transmission reaches 20 percent

Table 1
Geometrical parameters of the 36 CSRRs introduced in Fig. 1.

θ =0°			θ =−18°			θ =27°		
CSRR no.	r (μm)	α	CSRR no.	r (μm)	α	CSRR no.	r (μm)	α
1	34	11	13	34	11	25	34	11
2	32.3	47	14	32.3	47	26	32.3	47
3	34.4	117	15	34.4	117	27	34.4	117
4	29.8	140	16	29.8	140	28	29.8	140
θ =−9°			θ =18°			θ =−45°		
CSRR no.	r (μm)	α	CSRR no.	r (μm)	α	CSRR no.	r (μm)	α
5	34	11	17	34	11	29	34	11
6	32.3	47	18	32.3	47	30	32.3	47
7	34.4	117	19	34.4	117	31	34.4	117
8	29.8	140	20	29.8	140	32	29.8	140
θ =9°			θ =−27°			θ =45°		
CSRR no.	r (μm)	α	CSRR no.	r (μm)	α	CSRR no.	r (μm)	α
9	34	11	21	34	11	33	34	11
10	32.3	47	22	32.3	47	34	32.3	47
11	34.4	117	23	34.4	117	35	34.4	117
12	29.8	140	24	29.8	140	36	29.8	140

which is a reasonable amount compared with the previously reported cross-polarized transmission through ultra-thin metasurfaces of 25 percent [21]. This amount will be reduced further considering fabrication technology restrictions in the THz frequency range due to the roughness and non-idealities which lead to increasing metallic loss. Fig. 1(b) demonstrates that CSRRs with equal values of θ have the same scattered amplitude, while with different values of θ the scattered cross-polarized amplitude span the range of 0–1 at a step of 0.25. Setting a sweep over the values of r, α and θ enables us to control the scattered wave phase and amplitude continuously which in comparison with selecting 36 meta-atoms gives us more precise focusing but with the cost of a more complex design.

3. Light focusing using CSSRs

To design our cylindrical lens, a hyperboloidal phase profile with the form of Eq. (1) should be satisfied by the scattered field along the x-axis (the direction transverse to the wave field propagation):

$$\phi(x) = \frac{2\pi}{\lambda}(\sqrt{x^2 + f^2} - f), \tag{1}$$

provided that the monochromatic wave evolves in the time domain as $\exp(i\omega t)$. In agreement with Eq. (1), depending on the focal length of the lens, f, and wavelength of the incident light, λ, one meta-atom with proper phase $\phi(x)$ of its scattered field should be placed at each transverse position x of the lens. No amplitude modulation is necessary to be considered in order to focus the incident wave, thus we choose a unitary field amplitude $A_0(x) = 1$. In our simulations, meta-atoms are placed on a silicon substrate. Here we set the focal length of the lens to be $f = 10\lambda$ with $\lambda = \lambda_0/n_{Si}$ equal to 138 μm in the silicon substrate, that is in the medium where the wave field is focused. In Fig. 2(a), the intensity distribution of the cross-polarized component of the electric field illustrates focusing at $f = 10\lambda$ with a cylindrical lens that consists of 29 CSRRs along the x-axis. Numerical results presented in this paper are simulations based on the finite difference time domain (FDTD) method. The designed lens structure is terminated by perfect matched layers (PMLs) in the x- and z-directions, which is the beam propagation direction, and periodic boundary conditions are set along the y-direction. To reduce the noise, the substrate is stretched up to the size of 340 μm from the last meta-atom to the PML boundaries of the lens