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МОДУЛЯЦИЯ ФАЗЫ ТЕРАГЕРЦОВОГО ИЗЛУЧЕНИЯ С ПОМОЩЬЮ МЕТАПОВЕРХНОСТЕЙ ДЛЯ КОНТРОЛИРУЕМОГО ПРОХОЖДЕНИЯ ИЗЛУЧЕНИЯ

Д. Ма[1], С. Сонг[1], Ж. Ху[1], А.П. Балмаков[2], С.А. Хахомов[2], Д. Ванг[1], Т. Санг[1]

[1]*Университет Цзяннань, Китай*
[2]*Гомельский государственный университет им. Ф. Скорины*

THz PHASE MODULATION WITH BROADBAND METASURFACES FOR CONTROLLING LIGHT PROPAGATION

J. Ma[1], C. Song[1], Z.-D. Hu[1], A.P. Balmakou[2], S.A. Khakhomov[2], J. Wang[1], T. Sang[1]

[1]*Jiangnan University, China*
[2]*F. Scorina Gomel State University*

Предложено создание сверхтонких фазовых метаповерхностных структур на основе комплементарных квадратных расщепленных кольц по типу наноантенна для создания терагерцовых металинз, перестраеваемых и мультифокусси-рующихся. Резонансный режим резонатора Фабри – Перо может быть полезен при объяснении принципа распростра-нения пучка и эффективной передачи излучения. Терагерцовые металинзы могут эффективно функционировать как кросс-поляризатор при условии создания решеток на падающей плоскости. За счет локального изменения длины кром-ки и углов открытия расщепленных колец можно добиться полного контроля над изменениями фазы. Два симметрично распределенных параллельных фокальных пятна и два вертикальных фокальных пятна с произвольным расстоянием были получены путем размещения кольц-резонаторов на металинзах. Кроме того, мы применяем концепцию режима секционированной фазы для реализации двухфокусных металинз в продольном направлении, что обеспечивает гибкий и удобный метод фокусировки.

Keywords: *метаповерхность, фазовая модуляция, терагерцовое излучение, Фабри – Перо, оптическая фаза.*

The ultra-thin phase metasurface structures based on the complementary square split ring nanoantenna have been proposed to achieve the THz optical metalenses with multi-dimensional and multi-focusing. The Fabry – Pérot resonance mode could be usefully employed in explaining the principle of beam propagation and efficient transmission. The THz metalens can transfer the linear cross-polarization efficiently under the effect of the gratings on the incident plane. By locally tailoring edge lengths and opening angles of the split rings, full control over abrupt phase changes can be achieved. Two symmetrically distributed parallel focal spots and two vertical focal spots with arbitrary distance are obtained by arranging the SSRs units on the metalenses. Furthermore, we apply the concept of partitioned phase mode to realize the double-focusing metalens in the longi-tudinal direction, which provides a flexible and convenient method for focusing properties.

Keywords: *metasurface, phase modulation, THz, Fabry – Pérot, optical phase.*

Introduction

Metamaterials with artificially engineered new-type optical devices have been achieved in the manipulation of electromagnetic (EM) polarization, applying in optical vortexes [1], optical focusing [2], high resolution holography [3], [4], quarter-wave plates [5], and so on. The metasurface, which is a 2D counterpart to metamaterials consisted of individual structures, has attracted great interests due to their its unique properties and simplicity of fabrication in recent years [6]. Some metasurfaces rely on sub-wavelength nanoantennas which play a significant role in creating arbitrary phase profiles across 2π for cross-polarized scattered light and ensuring the uniform amplitudes [7]. Each of the nanoantennas acts as a unit cell and realizes the modulation of optical properties easily based on the fine tuning of both the geometrical parameters and rotation angles, e. g. The faculty to engineer the phase of the polarized light with high accuracy and high polarization transferred efficiency is perfectly suited for applications of metalens.

For conventional lenses, such as LED lens, Fresnel lens and Luneburg lens, are based on the reflection and refraction of light at the interface of the medium, and the phase accumulation along the optical path during the wave propagation in the medium to realize the manipulation of the wave front [8], [9]. Moreover, the thicknesses of these conventional optical components are generally greater than or comparable to the operating wavelength due to the optical properties such as refractive index and anisotropy of natural materials. Recently, optical metalens has been the indispensable tool under comprehensive study towards more integrated, planar and precision ways to operate the incidence [10]–[12]. Researchers have been fascinated by different principles and technologies to design metalenses with unusual functions.

So far as we know, realizing focusing metalenses on basic substrates possesses many characteristics. Firstly, many research results on matalenses are devoted to the design of multifocal, which have been allowed to focus at different focal length in the directions of longitudinal or the transverse [13]–[16]. Additionally, the metalenses with many focusing spots have been proposed mainly based on the phase retrieval algorithm and the parabolic phase variation algorithm [11], [17]–[19]. Few investigations have been attempted to design the metalenses with multi-dimensional and multi-focusing based on the holistic and partitioned mode, simultaneously [20], [21].

In this paper, we have proposed several novel polarization-independent multi-dimensional and multi-focusing metalenses in the horizontal and longitudinal direction based on the metasurface of the designed square split ring nanoantenna structure on the thin silicon film. The focusing lengths and focusing intensities of every focusing spots from the multi-focusing metalens can be controlled and modulated by the concrete designs effectively. The simulation results show that the perfect focusing phenomenon of cross linearly-polarized (LP) wave can be achieved due to the modulation of gold grating layer that acts as a polarizer and the novel complementary square split ring nanoantenna. The results can provide a reliable method for the enhanced tunability and selectivity of designing plasmonic devices. And this structure will lead to improved approaches for the miniaturization and integration of THz systems.

2 Results and discussion

As shown in Figure 2.1 (a), the structure consists of a gold gratings film, silicon substrate and an array of square split ring gold antennas.

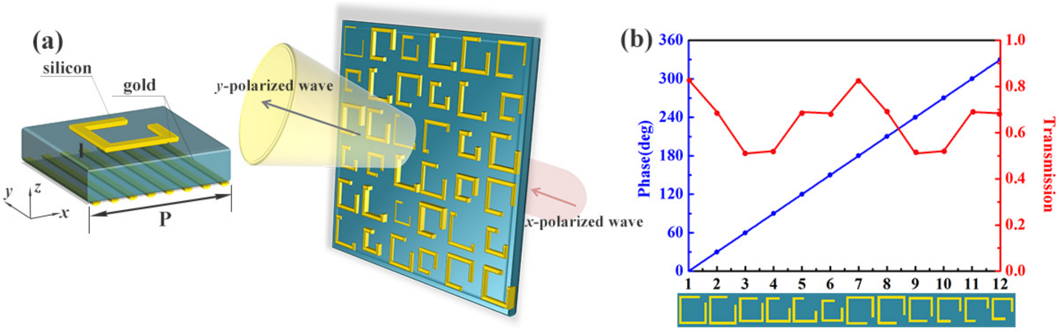

Figure 2.1 – (a) Schematic view of the nanoantenna unit. (b) An illustration of 2D multi-focusing metalens consisted of the square split ring gold nanoantennas array. (c) Phase shifts and transmitted amplitudes of the cross-polarized electric field of the proposed twelve units under LP normal incident wave

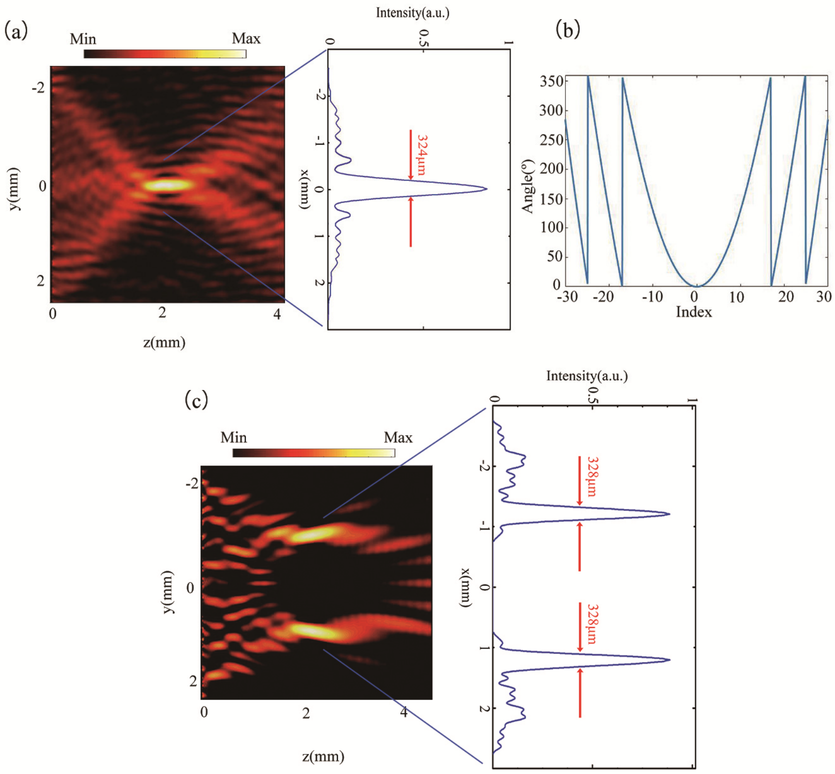

Figure 2.2 – (a) Intensity distribution and the FWHM of the y-polarized light for the designed 1-D single-focal metalens along the z-direction, which was simulated using commercial software. (b) The focusing phase distribution of metasurface arrays. (c) Intensity distribution and the FWHM of the y-polarized light for the designed 1-D double-focal metalens along the z-direction

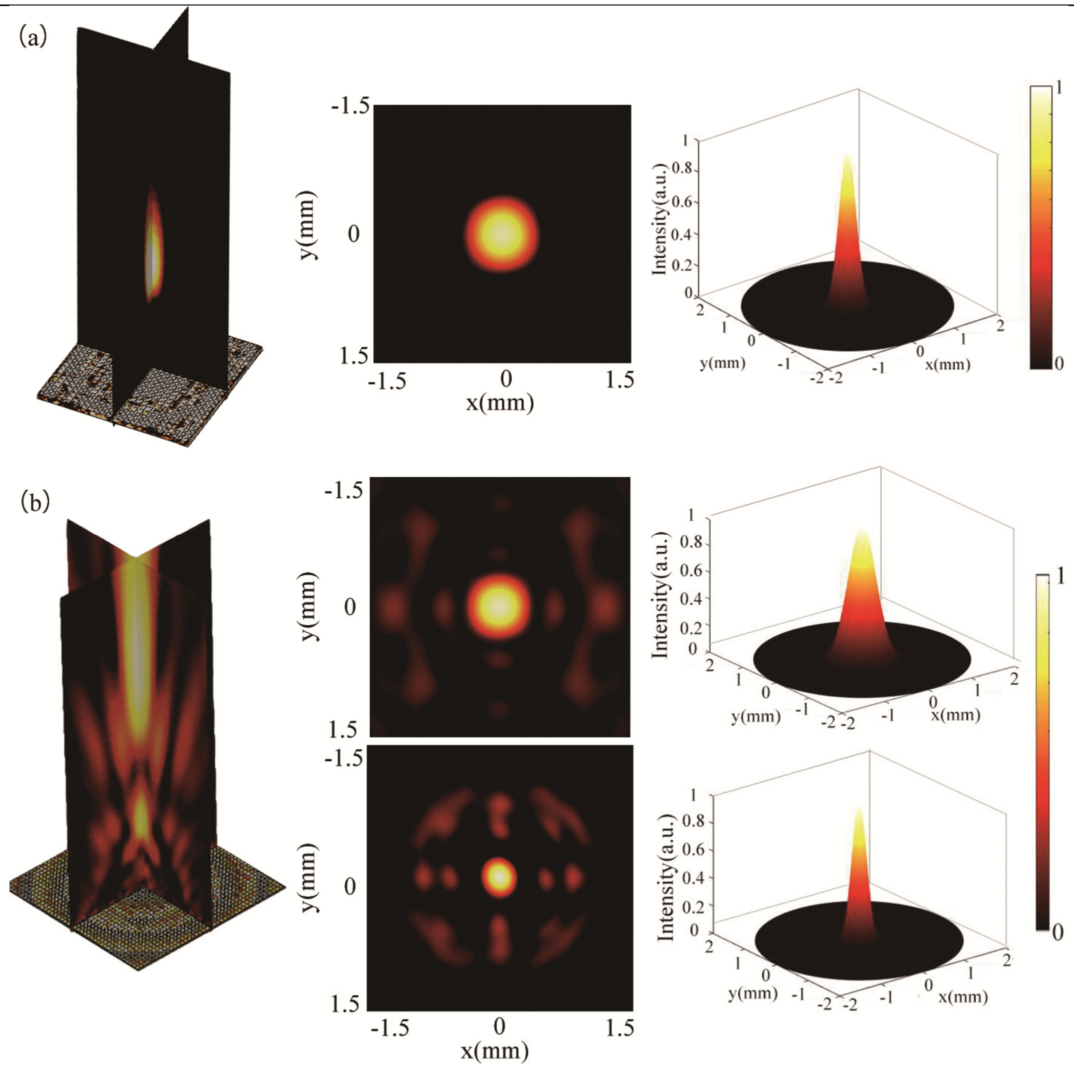

Figure 2.3 – (a) Intensity distribution, focusing on the x-y plane and the FWHM of the y-polarized light for the designed 2-D single-focal metalens. (b) Intensity distribution, focusing on the x-y plane and the FWHM of the y-polarized light for the designed 2-D double-focal metalens

Both the antennas and the gratings have the same thickness d of 200 nm, and the silicon layer thickness D is 25 μm. The period P of the unit cell is set as 80 μm to avoid coupling between the adjacent split ring nanoantennas, the width w and period Λ of the grating are 4 μm and 10 μm, respectively. The gold gratings act as the polarizer that can transmit the x-polarized radiation and reflect the y-polarized THz radiation almost completely. By optimizing both the frame length and the opening size the square gold nanoantenna, the phase of the transmitted y-polarized light can be modulated in the range between 0 and 2π with a constant phase diference of π / 6, while the amplitude transmission is maintained up to 0.5 at an operating frequency of 0.86 THz, as shown in Figure 2.1 (b).

The metalens can be designed based on equal optical path principle. Firstly, we have designed the polarization-independent 1-D metalens with single-focal by square gold nanoantennas array. According to the equal optical path principle, the phase profile can be expressed as

$$\varphi(x) = \frac{2\pi}{\lambda}\left(\sqrt{x^2+f^2}-f\right)-2\pi m.$$

Based on the phase distribution principle of the single-focal structure, under the incidence of LP light, the corresponding induced double-focal phase profile in the horizontal direction can be expressed as

$$\tan\varphi = \frac{\frac{1}{r_1}\sin kr_1 + \frac{1}{r_2}\sin kr_2}{\frac{1}{r_1}\cos kr_1 + \frac{1}{r_2}\cos kr_2}.$$

Where φ represents the abrupt phase shifts between an arbitrary point and the original point; λ is the incident wavelength at 0.86 THz; r_1 and r_2 represent the optical path between an arbitrary point and the original point, and f is the focal length. The intensity distribution of the *y*-polarized light on the *x-z* plane is as shown in Figure 2.2 (a). Additionally, it shows the focal point profiles (f = 2.5 mm) that correspond to the intensity distributions along the center of focus, which both show good sinc shapes with a full width at half maximum (FWHM) of 324 μm.

And the focusing phase distribution of one dimensional metasurface arrays are displayed clearly in Figure 2.2 (b). The electric intensity distribution of symmetric double-focal (f = 2.5 mm) is presented in Figure 2.2 (c), which the FWHM of the focal spots are 328 μm. The transmission efficiency and the focusing efficiency (power ratio toward the focus by the focusing metalens) can reach to 93% and 1.2% respectively.

For achieving the maximum density in the radial direction and designinig the multi-dimensional metalens to satisfy the realistic needs, simultaneously, the metalens with one focus (f = 2.5 mm) in Figure 2.3 (a) and the double-focusing metalens (f_1 = 2 mm, f_2 = 5 mm) based on the partitioned mode in Figure 2.3 (b) have been proposed. The designing plane of the multi-focusing metalens with 40×40 unit cells has been divided into different regions (the inner 20×20 unit cells), which is called partitioned mode. Both the focused intensity and FWHM of the upper focus are larger than the lower focus. The double-focusing metalens with different focal length can be realized by tuning the densities of the nanoatennas in the special rings.

Conclusion

We have proposed a series of multi-dimension and multi-focusing metalenses consisted of twelve gold SSRs nanoantennas and gold gratings used for the performance of polarization conversion. For the normal incidence of x-polarized with fixed frequency in the terahertz region, the simulated results of the constructed chain double-focusing with the foci position along horizontal and longitudinal agree well with the theoretical expectations and have excellent focusing features. Furthermore, a comparison of the chain-like lenses and the planar-like lenses for multifocal imaging has been made to facilitate the development of metasurface devices towards integration and practical applications. The approach of partitioned mode provides a flexible design for realizing a tunable multifocusing metalens, which would open a new avenue for the THz field modulated device.

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