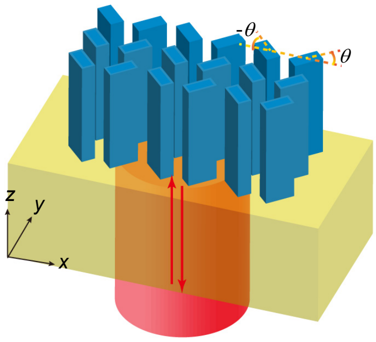
Opto-Electronic Engineering

Article

2017, Vol 44, Issue 3

Reflection tuning via destructive interference in metasurface



Yang Li[1†], Yang Li[1,2†], Lianwei Chen[1] and Minghui Hong[1*]

[1]National University of Singapore, 4 Engineering Drive 3, Singapore, 117576, Singapore; [2]State Key Laboratory of Optical Technologies for Nano-Fabrication and Micro-Engineering, Institute of Optics and Electronics, Chinese Academy of Sciences, Chengdu 610209, China

Abstract: Reflection engineering plays an important role in optics. For conventional approaches, the reflection tuning is quite challenging in a loss-free component. Therefore, a simple approach to tune the reflection is highly desired in plenty of applications. In this paper, we propose a new design of metasurface with just one single layer dielectric structure to tune the reflection of an interface by destructive interference in a subwavelength scale. By arranging the orientation of nano-antennas, the reflectivity tuning from 20% to 90% can be achieved at the wavelength of 1550 nm. Moreover, such reflectivity tuning of the designed metasurface works at the tunable wavelength from 1500 nm to 1600 nm. This ultra-thin solution can achieve similar performance as the traditional bulky components without diffraction orders, while the design and fabrication are much simple and flexible. The ultra-thin and tunable properties indicate the great potentials of this method to be applied in laser fabrication, optical communication and optical integration.

Keywords: metasurface; reflection; tunable; destructive interference

DOI: 10.3969/j.issn.1003-501X.2017.03.005 **Citation:** *Opto-Elec Eng*, 2017, **44**(3): 313−318

1 Introduction

Reflection is one of basic optical phenomena, which has extensive applications in various optical systems, such as reflective mirror, laser cavity, coupler and lens. For these applications, the requirements are different. For instance, reflective mirror requires a high reflectivity but lens requires a high transmittance. Conventionally, reflection components mainly rely on reflective coating [1]. For the metal coating, the loss cannot be avoided, which limits its applications in high-power laser cavity and has low tunability in spectral response. For the dielectric coating, multi-layer design is required. It is not only sophisticated in design but also complicated in manufacture, especially when the devices require different reflectivities [2]. For the applications that require spectral filtering to reduce noise for particularly wavelengths or the spatial filtering for the special transmission mode, the design becomes even more difficult [3]. Therefore, it is highly demanded to propose a feasible solution that can easily achieve the flexible control of reflection by a simple manufacturing process. It would be favorable for many devices if we can design a strategy that provides a large range of reflection tuning with a simple fabrication process.

Metasurface is an array of scattering elements with sub-wavelength dimensions and periods, which can provide electromagnetic properties in demand [4-11]. It is well-known for its capability of controlling light properties, such as wavefront, phase, and polarization. Metasurface has proved to be a very powerful tool to achieve many types of novel optical functionalities, such as the optical cloaking, 3D imaging for naked eyes, and planner lens. As metasurface is a one-layer ultrathin structure, it is also very promising for many integrated optical devices, such as optical computational circuits. The new strategies brought by the metasurface indicate an innovative way of designing optical components [6-7, 12-13]. Furthermore, it is also favorable for industry as the fabrication process is compatible to the current semiconductor manufacturing, making it possible for large scale production with the modification on the existing manufacturing lines. Therefore, it is feasible to achieve different reflectivities by rearranging the optical antennas in a simple and flexible way. For the conventional methods, the same purpose can only be achieved by redesigning complicated structures. In addition, the single layer structure on dielectric is loss-free and has high damage

Received 23 November 2016; accepted 07 January 2017

† These authors contributed equally to this work

* E-mail: elehmh@nus.edu.sg

threshold for high energy lasers [14-17]. Hence, a solution based on metasurface can replace traditional reflective components, such as mirrors inside a laser cavity.

In this paper, a novel design of metasurface with just one single layer structure is proposed to tune the surface reflection. The mechanism is based on destructive interference in a subwavelength scale. By rotating the angle of nano-antennas, the reflectivity can be tuned in a large range (from 20% to 90%). It should be noted that the reflection tuning is not limited to a certain wavelength. The reflectivity is significantly raised at the wavelengths from 1500 nm to 1600 nm. We also analyze the requirement of the incident angle and how to avoid high order diffractions. Compared to the conventional methods to fabricate reflection or anti-reflection components, the proposed solution can substantially reduce the complexity of manufacturing processes by photo-etching fabrication. It has great potentials to be applied in many fields, such as laser fabrication, optical communication and optical integration.

2 Design and simulations

Metasurface has great capability to control different spatial frequencies. The metasurface composed of the phase-only optical antenna is widely used in practice, such as planar lens [10], vortex generator [11] and beam deflector [15]. When a beam goes through a metasurface with the gradient phase Φ, the direction of refracted beam follows the generalized Snell's law [8]:

$$n_{\mathrm{i}}k_0 \sin\theta_{\mathrm{i}} + \nabla\Phi = n_{\mathrm{t}}k_0 \sin\theta_{\mathrm{t}} , \quad (1)$$

where n_{i} and n_{t} are the refractive indices of the media in incident space and transmitted space, respectively; θ_{i} and θ_{t} the incident and transmitted angles, respectively; and k_0 the wave vector of the light in vacuum. When the gradient of phase is high, the transmitted light is deflected into the evanescent wave domain. For plasmonic metasurface, this portion of light is coupled as the surface plasmon polariton (SPP) wave. The energy corresponding to this wave is absorbed by the metasurface [18]. However, when the metallic metasurface is replaced with the loss-free dielectric one, light can neither be transmitted nor absorbed. It can only be reflected back to the media. Therefore, the reflection is enhanced.

Based on the principle discussed above, a metasurface is designed as shown in Fig. 1(a). The silicon nano-rod antenna is chosen for its low absorption in the near-infrared wavelengths (NIR, ~1550 nm). The optical antenna is designed to achieve high modulation efficiency similar to the concept of Dammann grating [19]. In theory, all the transmitted light can be modified with desired phases. We have conducted a series of simulations to find out the best dimension of the nano-rod antenna. The period P, length L, width W and height H of optical antenna are optimized as 620 nm, 445 nm, 190 nm, and 920 nm, respectively. The substrate is set as silicon and the transmitted space is air. The designed optical antenna and metasurface are simulated by Lumerical FDTD solution with 10 nm mesh grid. Fig. 1(b) shows the distributions of the electrical field in x axis (E_x component) with illumination polarized along and normal to the nano-rods at the wavelength λ=1550 nm, respectively. It is discovered that the transmitted field has almost the same amplitude $T_{\parallel} = T_{\perp}$ and π phase delay difference $\Phi_{\parallel} - \Phi_{\perp} = \pi$. This indicates that the optical antenna works similarly as a half-wave plate. Therefore, the right-hand/left-hand polarized (RCP/LCP) light can be transferred to LCP/RCP light with phase shifts 2θ and -2θ, corresponding to LCP and RCP incident light, respectively. The efficiency of phase modulation can achieve almost 100% in theory.

The rotation angles of each pair are 45° or -45° to the

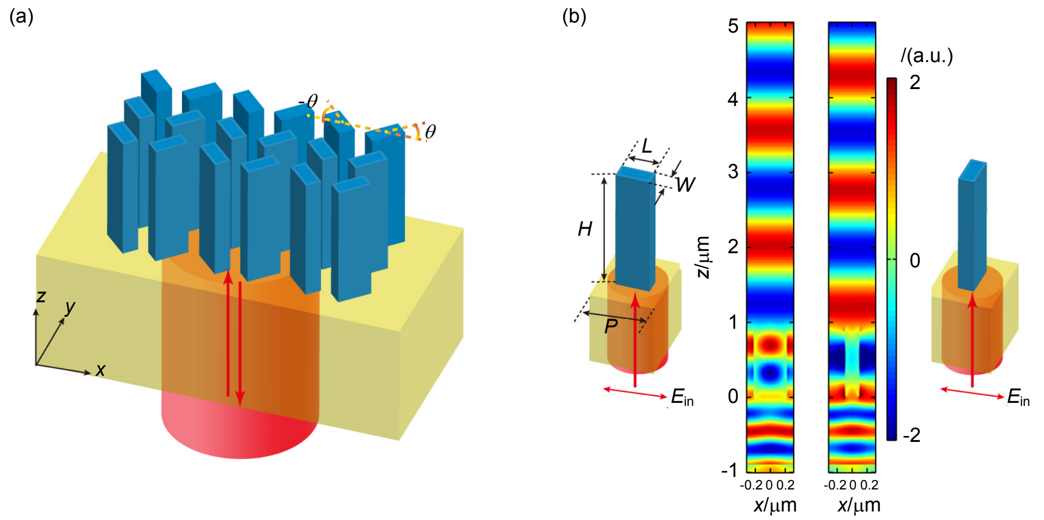


Fig. 1 Schematic of the metasurface and unit cells. (a) The structure of the metasurface. (b) The E_x distribution of a single optical antenna at different polarizations.

DOI: 10.3969/j.issn.1003-501X.2017.03.005

x-axis. This arrangement can generate $\pm\pi/2$ and $\mp\pi/2$ phase shifts corresponding to RCP/LCP incident light. Meanwhile, this design can also be applied to linear polarized light for the same phase shift. By the calculation according to Eq. (1), the metasurface provides $\pm1.25k_0$ transverse wave vector. The transmitted wave vector can be expressed as

$$k_z = \sqrt{(n_t k_0)^2 - (k_{x\mathrm{meta}} - k_{x\mathrm{in}})^2 - (k_{y\mathrm{meta}} - k_{y\mathrm{in}})^2}\ , \qquad (2)$$

where $k_{x\mathrm{meta}}$ and $k_{y\mathrm{meta}}$ are the wave vector components provided by the metasurface along x and y axes, respectively; $k_{x\mathrm{in}}$ and $k_{y\mathrm{in}}$ the wave vector components of the incident light along x and y axes, respectively. At the normal incidence, the light is deflected to the evanescent wave domain in transmission space, which means that the metasurface modulates the light and reflects it back. In simulation, 91.8% reflection is achieved by the designed metasurface illuminated by the incident light polarized along x axis (including both LCP and RCP components). It should be noted that for the individual nano-antenna with uniform arrangement, the reflection is only around 20%. In other words, our design can increase the reflection by more than 4.5 times. It shows that the reflectivity of the metasurface can be modified by the arrangement of antennas efficiently.

Another advantage of our design is the flexibility on the reflectivity control. To tune the reflectivity, one method is to rearrange the optical antennas to provide a different transverse wave vector. However, this strategy would generate deflected beams in transmission space which is different from the traditional reflection or filtering film. While this method can achieve efficient transmission tuning, the direction of transmitted light is changed following the generalized Snell's law, which would change the design of optical system. It does not match the requirement in most applications. The common target is to achieve the modification for intensity, instead of the modification for direction of transmitted beam. To realize this target, the antennas can be arranged in pairs, with $-\theta$ and θ angles to x-axis as shown in Fig. 1(a). When θ changes from 0 to 90 degrees, the reflectivity can be tuned from 20.1% to 93.1% while the transmission can be tuned from 5.8% to 77.5% as shown in Fig. 2(a). The loss is very low in Si at 1550 nm, therefore the sum of reflection and transmission is almost 100%. Fig. 2(b) shows the x-y plane section of the cross-polarized y-component E fields (E_y) in optical antenna. The E_y distribution for rotation angles of 0 and 90 degrees are very low in average while the average E_y for θ=45° is much higher, which means most of the light is not transferred from E_x to E_y. However, only the cross-polarized light E_y has π phase differences which can interfere with each other destructively. Therefore, the un-modulated E_x can go through the interface. The E_x distribution in Fig. 2(c) shows that the transmitted E_x at θ=0° and 90° are much stronger than that at θ=45°. Thus, the reflection is as low as 20% at θ=0° and 90° while it is higher than 90% at θ=45°.

In physics, such kind of reflection in metasurface is similar to the photonic crystal. The cross-polarized mode is like a forbidden band while the co-polarized mode is like a conductive band. Mostly, the photonic crystal can only generate a forbidden band or a conductive band in one design. For our case, the metasurface can generate both forbidden band and conductive band simultaneously by more detailed phase modulation rather than the simple lattice in photonic crystal. A photonic crystal is composed of periodic refractive index variation, while a metasurface can control the phase distribution in a period. In photonic crystals, another dimension of structure

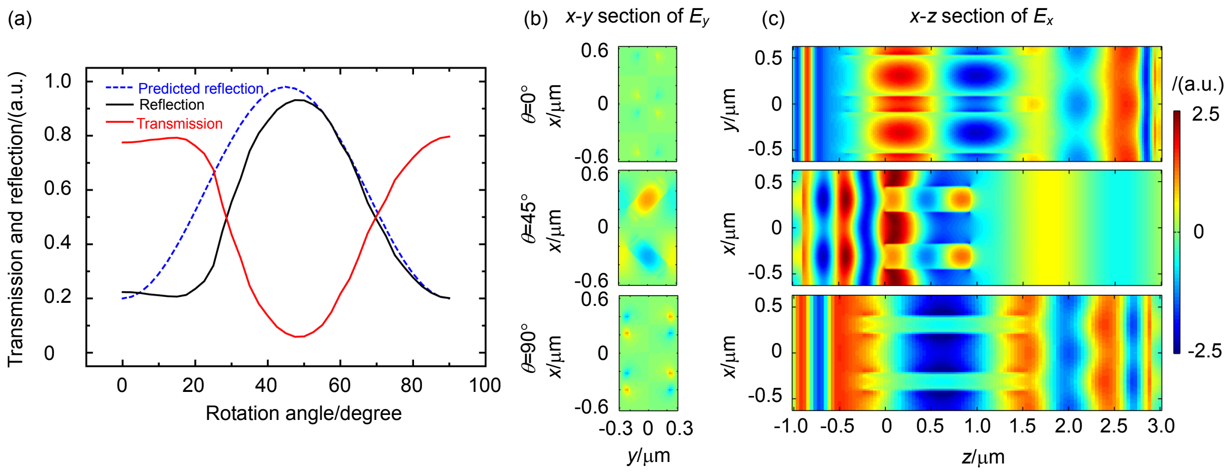


Fig. 2 Reflection characterization. (a) The transmission and reflection of metasurface at various rotation angles. (b) x-y section of E_y distribution in optical antenna at 0°, 45° and 90° rotation angles, respectively. (c) x-z section of E_x distribution in optical antenna at 0°, 45° and 90° degree rotation angles, respectively.

2017, Vol 44, Issue 3

is required to modify the k_z due to weak light-material interaction. However, in metasurface with high modulation efficiency, k_z is decided by the additional wave vector generated by the gradient of phase distribution. Therefore, one layer of metasurface can replace the bulk photonic crystal. From another perspective, the gradient of phase distribution offers the opportunity to hybrid multiple modes by a non-linear phase distribution. In our approach, the designed metasurface has a conductive mode with $\nabla\Phi=0$ and forbidden modes with $\nabla\Phi=\pm1.25k_0$. Our phase distribution corresponding to the phase of electrical distribution:

$$\Phi(x)=\arg(A_1 e^{0ik_0x}+A_2 e^{1.25ik_0x}), \quad (3)$$

where A_1 and A_2 are the intensity coefficients of conductive and forbidden modes, respectively. Therefore, the metasurface can control the forbidden band and conductive band arbitrarily. Dielectric metasurface has great potentials to be used to improve the properties of photonic crystal.

Beyond the reflection tunability, spectral property and incident angle limitation are two important factors for a reflector. When θ is fixed at 45°, the spectrum is simulated to investigate the dispersive property of the designed metasurface as shown in Fig. 3(a). The reflectivity is high at the wavelengths from 1500 nm to 1600 nm. However, at the wavelengths lower than 1500 nm or higher than 1600 nm, the reflectivity drops down. This phenomenon can be explained by the dispersion of the antenna. The dispersion makes the $T_{\parallel}\neq T_{\perp}$ and $\Phi_{\parallel}-\Phi_{\perp}\neq\pi$ at the wavelength far from the designed λ_0=1550 nm. Thus, the metasurface cannot be considered as a perfect phase modulated unit so that the light is not fully modified anymore. Only a portion of transmitted light follows coherent subtraction so that the reflection decreases. However, this phenomenon means that such kind of meta-reflector has potentials in the design of frequency selection reflector.

Except for the dispersion, another key factor of a surface reflector is the incident angle tolerance. Fig. 3(b) indicates the transmission and reflection of metasurface at variant incident angles. The reflectivity is very high near the zero incident angle. When the incident angle is more than 5°, the incident transverse wave vector is greater than $0.3k_0$, while the additional wave factor of metasurface is $\pm1.25k_0$. Therefore, half of the deflected light is transferred from evanescent wave $k_x=-1.25k_0$ to propagated wave $k_x=-0.95k_0$ ($|k_x|<k_0$), which leads to the about 50% transmission. As the incident angle becomes larger, the efficiency of optical antenna decreases and the transmission also decreases close to zero because the unmodulated light is in total internal reflection at the incident angle above 16.4°. This kind of meta-reflector has great benefits in the design of spatial frequency selection.

3 Analyses

As discussed previously, this type of metasurface works like a half-wave plate to the linearly polarized light and has $\pm2\theta$ phase shift to RCP and LCP. When the antenna is illuminated by a linearly polarized light, the part of cross-polarized light is $E_y=E_{\rm in}\sin(2\theta)$. Based on coherent subtraction, E_y would not be radiated to the far-field. Therefore, the reflection of metasurface can be expressed as:

$$R(\theta)=R_0+T_0\sin^2(2\theta), \quad (4)$$

where R_0 and T_0 are the reflection and transmission of the periodic optical antennas array. In our design, the R_0 and T_0 are about 20% and 80%, respectively. The reflection curve predicted by this equation as shown in Fig. 2(a) matches the simulation results. However, it should be noted that a perfect reflection surface cannot be achieved when θ=45° as predicted. The reason is that when the deflected angle of the metasurface is set at a high value,

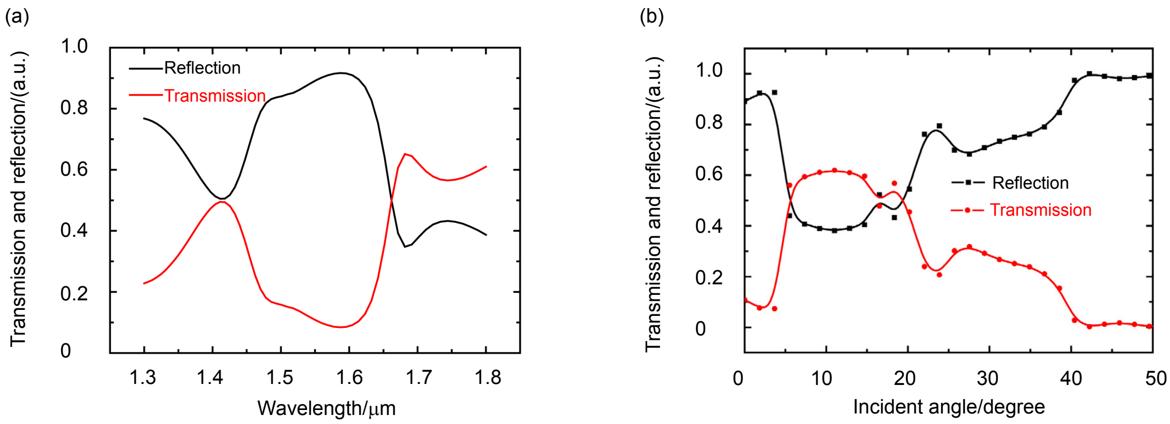


Fig. 3 Spectra and incident angle tolerance. (a) The transmitted and reflected spectra of metasurface at θ=45°. (b) The transmission and reflection at variant incident angles.

the coupling effect between the neighboring nano-rod antennas would affect the efficiency of the light modulation.

In principle, this kind of reflector can achieve perfect reflection to replace the traditional mirror. However, when the period of optical antenna is larger than half of the effective wavelength in substrate, there is modulated light in high diffraction orders, which becomes the noise in the reflection space. The far-field angular spectrum of the designed metasurface is simulated as shown in Fig. 4(a). Most power follows specular reflection. Other portion of reflected beams has 47.3° or higher deflection angle along x axis.

For a reflective beam with much more pure spatial frequency, the period of optical antenna should be smaller than half of effective wavelength in substrate. For example, if SiO_2 is selected as the substrate, the refractive index is 1.44 at the wavelength of 1550 nm and the parameters of silicon optical antenna are optimized as P=500 nm, L=445 nm, W=190 nm and H=900 nm. The transmission and reflection curves in Fig. 4(c) show that the reflection can achieve 98% at θ=62.5° and 0.1% at θ=82.5°. Fig. 4(b) shows the angular spectrum of the reflective beam at θ=62.5°. In this case, only the 0$^{\text{th}}$ order can be observed, which means that it is quite similar to traditional mirrors with great range of tunable reflection. The simulated results show the similar relationship between rotation angle and the reflectivity. However, it is obvious that the simulated reflection curve is different from the predicted one. The reflection at θ=45° is not the highest. This difference is caused by the coupling between the neighborhood antennas [20]. The shortest gap between two antennas is about $d_{\text{gap}} = P - L \cdot \cos\theta$, which is not symmetric to the θ=45°. The coupling affects the efficiency and the phase shift of optical antenna. Fortunately, the arrangement of antennas in our designed metasurface is symmetric, which would not generate other orders in propagation wave domain. It just shifts the peak to another rotation angle and generates another peak, instead of a single peak. On the other hand, the coupling is very hard to be quantitatively calculated. Therefore, numerical optimization is applied. By fixing the period to a value smaller than half of the effective wavelength, H, W and L are optimized to achieve highest peak-to-valley ratio (~980:1). We get a series of optimized parameters. It is found that the reflection at the θ= 0° and 90° are not the same and are higher than the reflectivity at θ=82.5°. This phenomenon is caused by the

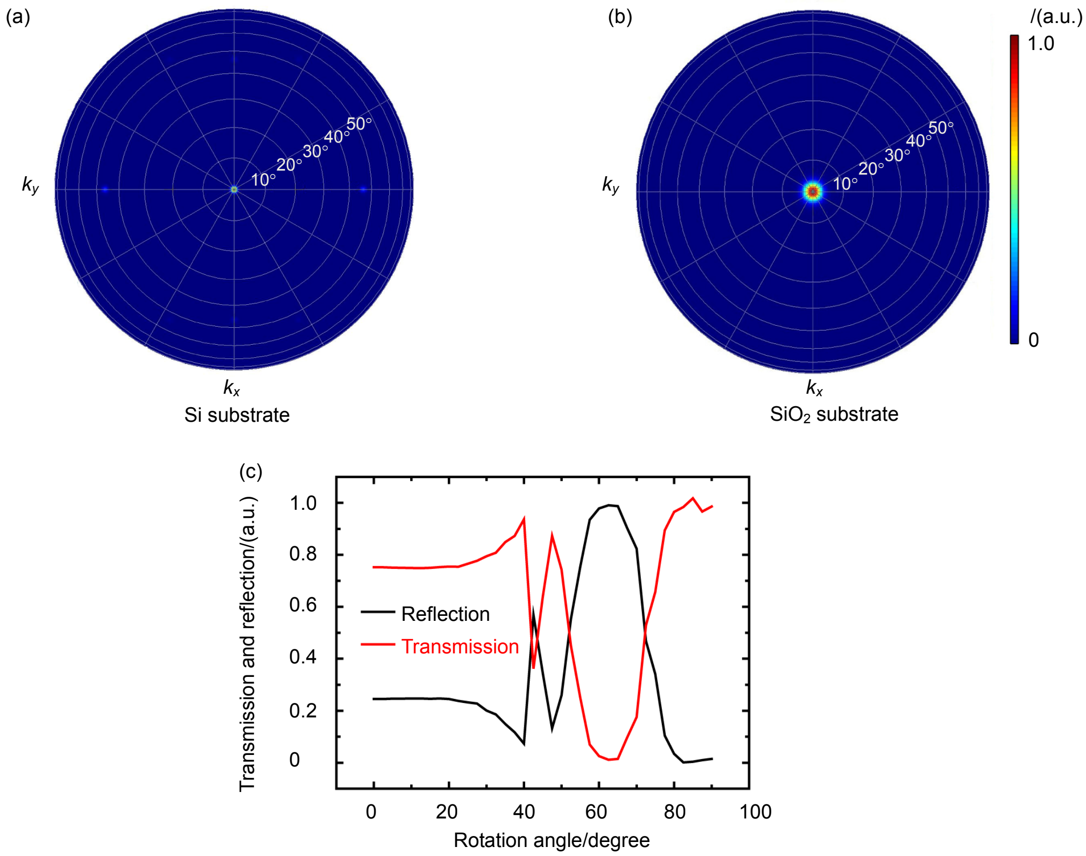


Fig. 4 Far-field angular spectra of reflected beams from the metasurface on (a) Si substrate at θ=45° and (b) SiO_2 substrate at θ=62.5° (20×20 optical antennas array). (c) Transmission and reflection of metasurface on SiO_2 substrate at variant rotation angle.

fact that the efficient refractive index of metasurface modified by the phase and amplitude coupling is between the refractive indices of transmitted and incident spaces, which can lead to even anti-reflection functions [21]. It means that it is hard to realize high reflection by antennas with high coupling in ultra-small period. High field localization is also required in antenna to minimize the coupling. Therefore, high refractive index antenna is preferred in the design of meta-reflector for efficient reflection tuning by the mechanism of destructive interference.

4 Conclusions

In summary, a tunable reflector based on metasurface is designed. A method is provided to link the phase-only metasurface and amplitude modulation together. The design is based on destructive interference among silicon optical antennas on a silicon/air interface which can achieve more than 90% reflection at 1550 nm. With the rotation of the angle of optical antennas, the reflection can be tuned from 90% to 20%. Meanwhile, the reflector has high performance at the wavelengths from 1500 nm to 1600 nm. The incident angle tolerance and angular spectra are analyzed as well. A design for the reflection without high diffraction orders is also designed by a high refractive index silicon antenna on a low refractive index silica substrate, which can achieve about 0.1%~98% reflection after numerical optimization. Since this metasurface design is low loss, tunable and made of same material as the substrate, the solution has great potential applications for mode selection in laser cavity [22], and high power laser shaping.

Acknowledgements

This work is financially supported by A*STAR, SERC 2014 Public Sector Research Funding (PSF) (Grant: SERC Project 1421200080), 973 Program of China (2013CBA 01700) and Chinese Nature Science Grant (61675207). Mr. Li Yang acknowledges the support from China Scholarship Council (CSC).

References

1 Born M, Wolf E. Principles of Optics: Electromagnetic Theory of Propagation, Interference and Diffraction of Light[M]. 7th ed. Cambridge: Cambridge University Press, 1999.

2 Stepanov D Y, Corena L. Bragg grating fabrication with wide range coarse and fine wavelength control[J]. *Optics Express*, 2014, **22**(22): 27309–27320.

3 Heavens O S. Thin-film optical filters[J]. *Optica Acta: International Journal of Optics*, 1986, **33**(11): 1336.

4 Yu Nanfang, Capasso F. Flat optics with designer metasurfaces[J]. *Nature Materials*, 2014, **13**(2): 139–150.

5 Li Yang, Li Xiong, Pu Mingbo, *et al*. Achromatic flat optical components via compensation between structure and material dispersions[J]. *Scientific Reports*, 2016, **6**: 19885.

6 Li Yang, Li Xiong, Chen Lianwei, *et al*. Orbital angular momentum multiplexing and demultiplexing by a single metasurface[J]. *Advanced Optical Materials*, 2017, **5**(2): 1600502.

7 Ni Xingjie, Ishii S, Kildishev A V, *et al*. Ultra-thin, planar, Babinet-inverted plasmonic metalenses[J]. *Light: Science & Applications*, 2013, **2**(4): e72.

8 Luo Xiangang. Principles of electromagnetic waves in metasurfaces[J]. *Science China: Physics, Mechanics & Astronomy*, 2015, **58**(9): 594201.

9 Zheng Guoxing, Mühlenbernd H, Kenney M, *et al*. Metasurface holograms reaching 80% efficiency[J]. *Nature Nanotechnology*, 2015, **10**(4): 308–312.

10 Khorasaninejad M, Chen Weiting, Devlin R C, *et al*. Metalenses at visible wavelengths: Diffraction-limited focusing and subwavelength resolution imaging[J]. *Science*, 2016, **352**(6290): 1190–1194.

11 Pu Mingbo, Li Xiong, Ma Xiaoliang, *et al*. Catenary optics for achromatic generation of perfect optical angular momentum[J]. *Science Advances*, 2015, **1**(9): e1500396.

12 Aieta F, Genevet P, Kats M A, *et al*. Aberration-free ultrathin flat lenses and axicons at telecom wavelengths based on plasmonic metasurfaces[J]. *Nano Letters*, 2012, **12**(9): 4932–4936.

13 Chen Xianzhong, Huang Lingling, Mühlenbernd H, *et al*. Dual-polarity plasmonic metalens for visible light[J]. *Nature Communications*, 2012, **3**: 1198.

14 Arbabi A, Horie Y, Bagheri M, *et al*. Dielectric metasurfaces for complete control of phase and polarization with subwavelength spatial resolution and high transmission[J]. *Nature Nanotechnology*, 2015, **10**(11): 937–943.

15 Lin Dianmin, Fan Pengyu, Hasman E, *et al*. Dielectric gradient metasurface optical elements[J]. *Science*, 2014, **345**(6194): 298–302.

16 Xiao Shumin, Drachev V P, Kildishev A V, *et al*. Loss-free and active optical negative-index metamaterials[J]. *Nature*, 2010, **466**(7307): 735–738.

17 Jahani S, Jacob Z. All-dielectric metamaterials[J]. *Nature Nanotechnology*, 2016, **11**(1): 23–36.

18 Landy N I, Sajuyigbe S, Mock J J, *et al*. Perfect metamaterial absorber[J]. *Physical Review Letters*, 2008, **100**(20): 207402.

19 Li Zile, Zheng Guoxing, He Ping'an, *et al*. All-silicon nanorod-based Dammann gratings[J]. *Optics Letters*, 2015, **40**(18): 4285–4288.

20 Li Yang, Huang Q, Wang D C, *et al*. Polarization-independent broadband terahertz chiral metamaterials on flexible substrate[J]. *Applied Physics A*, 2014, **115**(1): 57–62.

21 Keshavarz Hedayati M, Elbahri M. Antireflective coatings: Conventional stacking layers and ultrathin plasmonic metasurfaces, a mini-review[J]. *Materials*, 2016, **9**(6): 497.

22 Rong Haisheng, Jones R, Liu Ansheng, *et al*. A continuous-wave Raman silicon laser[J]. *Nature*, 2005, **433**(7027): 725–728.