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Realizing transmissive and reflective focusing with an on-chip metalens

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A metalens made of compact planar metastructure exhibits an excellent capability of focusing. The high-quality transmissive and reflective focusing simultaneously provides Fourier transform (FT) operation for optical information processing. Here we show a transflective on-chip metalens (TOM) made of orthogonal nano-grooves (ONGs). The TOM simultaneously converges transmitted and reflected (T&R) waves to the designed focal points. By adjusting the phase gradient profiles provided by the ONGs, the focal lengths of the T&R in-plane waves can be independently tuned. Our simulations show that the TOM possesses the advantages of broadband (>400 nm bandwidth) and high-focusing-efficiency (~60%) dual-focusing capability. Further, we utilize the TOM to build a one-to-two 4-f optical system. Two different spatial filtering operations based on FT can be simultaneously implemented in axial transmission and off-axis reflection channels for one input signal. We expect that the dual-focusing metalens approach can realize parallel optical processing in on-chip optical computing, spatial filtering, and beyond. © 2022 Optica Publishing Group

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Convex lenses and concave mirrors are the most widely used optical elements with focusing features [1]. The focusing provides a Fourier transform (FT) operation of light, where the optical signal can be transformed from the spatial domain to the spatial-frequency domain and vice versa [2]. FT operation is one of the fundamental approaches of optical processing [3]. However, conventional lenses and mirrors are unlikely to meet the critical requirements in size and weight of integrated photonics. Recently developed metalenses possess ultrathin and lightweight characteristics compared with conventional lenses and mirrors [4–6]. By designing meta-atoms, the phase gradient of transmitted and reflected (T&R) waves can be engineered in a compact space. So far, metalenses have shown a variety of exotic functionalities in controlling the phase [7], amplitude [8], and polarization state [9] of electromagnetic waves.

By arranging meta-atoms in a 1D array, in-plane waves propagating on 2D surfaces can be flexibly modulated [10-12]. In-plane Airy beams can also be generated in an integrated 2D photonic chip [13]. Compared with a 2D array metalens, a 1D on-chip metalens is inherently compatible with on-chip photonic systems [12]. The on-chip computing metalens can even be compatible with graphene material [14]. Recently, with different on-chip metalenses, optical computing operations, such as convolution [12], differentiation [15], and integration [16], have been realized. For most current on-chip photonic systems, a metalens focuses the input light either to a transmissive focal point or to a reflective focal point. Theoretically, once the metalens focuses both the T&R waves simultaneously, the FT operation of light can be performed in both transmission and reflection channels simultaneously.

Compared with conventional homogeneous material surfaces, a metasurface may possess a specially introduced phase gradient, allowing light to refract/reflect in any direction [17]. Such a unique feature helps realize dual-focusing lenses or even more complicated multifunctional optical devices. By decomposing and adjusting the two orthogonal polarization components separately, some 2D array metalenses have realized dual focusing in 3D free space [18].

In this Letter, we demonstrate a dual-focusing transflective on-chip metalens (TOM) made of orthogonal nano-grooves (ONGs). This is the first demonstration of T&R wave focusing with a single on-chip metalens to the best of our knowledge. Furthermore, we constructed a one-to-two 4-*f* optical system with the TOM. Different optical spatial filtering operations can be parallelly implemented in transmission and reflection channels by adjusting the spatial-frequency domain profiles in the two Fourier planes. We introduce an off-axis optical design to the reflective focusing path considering practical application. In this way, the incident light and the reflected light are spatially separated.

A schematic diagram of the TOM is shown in Fig. 1(a). The metalens is constructed with ONG meta-atoms arranged along the *y* direction. The TE-polarized (*y*-polarized) in-plane incident light propagates toward the TOM. The axial transmitted light beam and the off-axis reflected light beam converge to the designed focal points. As shown in Fig. 1(b), the meta-atom is constructed with two orthogonally arranged nano-grooves: a nano-groove along the *x* direction (NGx) and a nano-groove along the *y* direction (NGy). Both nano-grooves are created in a standard silicon-on-insulator (SOI) substrate. As shown in Fig. 1(b), one end of the NGx is at x = 0 and the other end is



Fig. 1. (a) Schematic diagram of the TOM. (b) Structural parameters of the ONG meta-atom. Simulated distributions of E_y at 1550 nm: (c) $l = 0.80 \,\mu\text{m}$ and $d = 0.20 \,\mu\text{m}$; (d) $l = 2.00 \,\mu\text{m}$ and $d = 0.35 \,\mu\text{m}$. The white lines show the outlines of the ONG metaatoms. The black dashed lines indicate the E_y maximums near the position of $x = 3.0 \,\mu\text{m}$ and $x = -2.0 \,\mu\text{m}$. The cross section is at the *x*-*y* plane in the middle of the silicon layer.

located at x = l. The separation between NGx and NGy is *d*. Among different ONG meta-atoms, all the structural parameters are identical except for *l* and *d*. The finite-difference time-domain (FDTD) method is applied for simulation at a wavelength of 1550 nm. The optical parameters of Si and SiO₂ are from Palik [19]. The calculated distribution of the *y* component of electric field (E_y) is shown in Figs. 1(c) and 1(d). Black dashed lines indicate E_y maximums near the positions of $x = 3.0 \,\mu\text{m}$ and $x = -2.0 \,\mu\text{m}$. It is found that the transmissive and reflective phases of the in-plane waves are changed by choosing different *l* and *d*.

We investigate the amplitudes (|t| and |r|) and the phase retardations (φ and ψ) of the T&R waves by tuning the structural parameters l and d. Figures 2(a) and 2(b) show that by tuning l from 0.1 to 2.2 μ m and d from 0.2 to 0.5 μ m, |t| varies accordingly from 0.50 to 0.82 for the transmitted wave. For the reflected wave, |r| varies from 0.57 to 0.87. Figures 2(c) and 2(d) show that for the transmissive phase retardation φ , when we fix d and change l from 0.1 to 2.2 μ m, φ may vary from 2π to 0. However, if we fix l and change d, φ does not change much. The trend for ψ , shown in Fig. 2(d), is the opposite. When we fix d and change l, ψ remains almost unchanged. However, if we fix l and change d from 0.2 to 0.5 μ m, ψ changes from 2π to 0. This scenario means that φ and ψ can be independently tuned by changing l and d separately. ψ is determined by the spatial position of the reflecting surface, which is the position of NGy (the parameter d). φ is determined by the optical path accumulated by the transmitted light passing through the ONGs. Since the length of NGys is constant, φ is only determined by the length l of NGx. Based on this mechanism, it is possible to build an ONG meta-atom with a free combination of φ and ψ .

To enable the dual-focusing functionality, the relative phase profiles for T&R waves along the *y* axis should follow [20]



Fig. 2. Normalized amplitudes of (a) transmitted wave and (b) reflected wave as functions of *l* and *d*. Phase retardations of (c) transmitted wave and (d) reflected wave as functions of *l* and *d*. For both φ and ψ , $l = 0.1 \,\mu\text{m}$ and $d = 0.2 \,\mu\text{m}$ is set as the reference point.

$$\varphi(y) = \frac{2\pi}{\lambda} n_{\text{eff}} (f_{\text{T}} - \sqrt{f_{\text{T}}^2 + y^2}),$$

$$\psi(y) = \frac{2\pi}{\lambda} n_{\text{eff}} (\sqrt{f_{\text{R}}^2 + y_{\text{off}}^2} - \sqrt{f_{\text{R}}^2 + (y - y_{\text{off}})^2}),$$
(1)

where λ is the designed wavelength in free space, f_T and f_R represent the transmissive and reflective focal lengths, y_{off} represents the reflective y offset, and n_{eff} is the effective refractive index of the in-plane wave confined in the SOI substrate, which equals 2.82. The metalens is designed based on single-mode operation. To build a TOM, we first calculate the required phase retardations $\varphi(y)$ and $\psi(y)$ according to Eq. (1). Then we determine the structural parameters l and d of each ONG meta-atom according to Figs. 2(c) and 2(d). The performance of TOMs with different f_T and f_R is numerically evaluated in Fig. 3. The y offset is $-10 \,\mu\text{m}$ and the operating wavelength is 1550 nm. The input beam is performed right behind the metalens to show the intensity distributions of reflective focusing more clearly. The



Fig. 3. (a)–(e) Optical intensity distributions in the x–y planes and the FWHM profiles for TOMs with different focal lengths. The cross section is at the x–y plane in the middle of the silicon layer.



Fig. 4. (a) Optical intensity distributions in the x-y planes at different wavelengths. (b) FWHM values and (c) focusing efficiencies of the metalens versus incident wavelength. (d) Optical intensity distributions in the x-y planes with different reflection off-axis angles. (e) FWHM values and (f) focusing efficiencies of the metalens versus off-axis angle.

intensity distributions in Fig. 3 show that the T&R waves converge to the designed focal points after passing through or being reflected by the TOMs. The transmissive/reflective focusing efficiencies (η_T/η_R) and the full width half maximum (FWHM) profiles [15] are also illustrated in Fig. 3. It is noteworthy that η_T , η_R , and the FWHM values vary with the designed focal length. The total focusing efficiency η_{total} , the sum of η_R and η_T , is higher than 60%. Focusing efficiency η_{total} can reach 69.3% for a metalens with $f_R = 30 \,\mu\text{m}$ and $f_T = 30 \,\mu\text{m}$. The relatively high focusing efficiency is mainly due to the full dielectric design and the accurate phase profiles provided by the ONG meta-atoms.

To verify the feasibility of the design, we explore the range of operating bandwidth and reflection off-axis angle. The optical intensity distributions at different wavelengths are plotted in Fig. 4(a). The designed focal lengths are $f_{\rm R} = f_{\rm T} = 30 \,\mu{\rm m}$ at 1550 nm, and the y offsets are all $-10 \,\mu\text{m}$. The TOM shows clear T&R wave focusing functions for 1400-1800 nm. The focal lengths of T&R waves decrease gradually as the wavelength increases. The FWHM values at different wavelengths are presented in Fig. 4(b). For focusing of both T&R waves, the FWHM values are around 0.90 µm in the range 1400-1800 nm. The focusing efficiencies $\eta_{\rm R}$, $\eta_{\rm T}$, and $\eta_{\rm total}$ are illustrated in Fig. 4(c). The value of η_{total} is around 70% in the broadband wavelength range. To investigate the off-axis reflective focusing, we change the off-axis angle θ (= tan⁻¹|y_{off}/f_R|) from 10° to 50° and plot the optical intensity distributions at 1550 nm in Fig. 4(d). One may see that when we increase the off-axis angle of the reflective focusing, the position of the transmissive focal point remains unchanged. As illustrated in Fig. 4(e), the FWHM values of reflection increase as the off-axis angle increases. Figure 4(f) shows the focusing efficiencies at different off-axis angles. The reflective focusing efficiencies decrease when the off-axis angle increases. For the transmissive focusing, the FWHM values and the focusing efficiencies hardly change with the reflection off-axis angle. The TOM exhibits a focusing effect in the broadband wavelength range of 1400-1800 nm. In addition, the TOM can work with an off-axis angle of 30° with a reasonable total efficiency of 55.9%, making the metalens design practical and robust.



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(a)

Fig. 5. (a) Schematic diagram of the on-chip 4-*f* system. (b) optical intensity distribution in the x-y plane. The white dashed lines indicate the Fourier planes and image planes. (c) Input signal. Optical intensity distributions in (d) IP₁ and (e) IP₂. The black dashed lines are the analytical results based on FT.

We further use the TOM to build a one-to-two 4-f optical system. As shown in Fig. 5(a), a TOM ($f_R = f_T = 30 \,\mu\text{m}$) is placed at $x = 0 \mu m$, $y = 0 \mu m$. The y offset of the reflective focusing is $-10\,\mu\text{m}$. The radius of the TOM is $20\,\mu\text{m}$, and the numerical aperture (NA) value of the TOM is 1.56. Two transmissive metalenses ML₁ and ML₂ with identical focal lengths ($f = 30 \,\mu m$, NA = 1.56) are placed at $x = 60 \,\mu\text{m}$, $y = 0 \,\mu\text{m}$ and $x = -60 \,\mu\text{m}$, $y = -20 \,\mu\text{m}$. The phase gradients of ML₁ and ML₂ are designed according to Fig. 2(c). The incident wave with a double Gaussian intensity profile is used as the input signal. The object plane of the input signal is placed at $x = -30 \,\mu\text{m}$. For the transmission channel, the TOM converts the input signal into its spatial FT and projects the Fourier components to the Fourier plane FP₁ at $x = 30 \,\mu\text{m}$. We block the zerth-order maxima with a mask to demonstrate a spatial filtering process. The Fourier components are then recombined by ML_1 , and the signal is reconstructed in the image plane IP₁. For the reflection channel, the TOM can also project the Fourier components of the input signal to the Fourier plane FP₂ at $x = -30 \,\mu\text{m}$. Here in FP₂, we block all the orders of the maxima except for the zeroth order. The zeroth order of the Fourier component is then recombined by ML₂, and the filtered signal is constructed in IP_2 . Figure 5(b) shows the intensity distribution in the x-y plane of the one-to-two 4-f optical system. Individual optical processings in transmission and reflection channels with different Fourier components and reconstructed profiles can be observed. Figure 5(c) shows the input double Gaussian intensity profile. The intensity distributions in the image planes IP_1 and IP_2 are shown in Figs. 5(d) and 5(e), which are consistent with analytical results. Due to the dual-focusing capability of the TOM, the one-to-two 4-f optical system provides a parallel optical processing possibility for on-chip optics.

In the optical system, the limited diameter of the TOM causes a high-spatial-frequency cutoff. The signal portion that exceeds the cutoff frequency will be lost in the FT processing [2]. It is also for this reason that when increasing the distance of the input port, more high-spatial-frequency components cannot enter the metalens. In this case, a TOM with a larger NA value will be more favorable for input signals with finer profiles or further input ports. The off-axis angle of the reflective focusing can also be changed in the design. However, off-axis angles larger than 30° decrease the reflective focusing efficiency. This is because for large-angle reflection, in addition to the designed anomalously reflected wave, undesired waves will be excited to satisfy the power conservation and the boundary conditions, leading to parasitic reflections [21]. The efficiencies of the large-off-axisangle reflections can be improved by allowing the loss and gain designs in metasurfaces [22]. When the in-plane waves interact with microstructures, some may be scattered into the free space [23,24]. Our calculation shows that the scattering loss is about 20%. This loss can be reduced by lowering the index contrast between the device layer and the nano-grooves [25]. It is also important to control the intensity ratio of the transmitted wave to the reflected wave [26,27] in the TOM. This ratio can be adjusted by changing the widths of the nano-grooves [15].

To summarize, we numerically demonstrate a TOM based on orthogonally arranged nano-grooves. The on-chip metalens can efficiently focus the T&R waves to the designed focal points. A one-to-two 4-f optical system has been demonstrated to parallelly implement different optical processings in two channels. We expect the dual-focusing on-chip metalens design to stimulate on-chip optical processing technologies. The dual-focusing design might be extended to other optical systems, such as surface plasmon polariton waves [28].

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Data availability. Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

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