Wide-angle Reconfigurable Refraction by Silicon Fourier Metasurfaces

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Abstract. We design metasurfaces based on silicon films with smooth relief described by several Fourier harmonics and study their ability to redirect the refracted light over a wide angular range controlled by subtle variations of the optical setup. We use semi-analytical approach based on the Rayleigh hypothesis as well as full-scale numerical solutions to optimize the relief shape. To illustrate the reconfigurability potential, we design metasurfaces efficiently redirecting the refracted light from $83^\circ$ to $73^\circ$ with respect to the normal, when the angle of incidence is varied from $0^\circ$ to $2^\circ$, and from $80^\circ$ to $74^\circ$, when the substrate permittivity is altered from 2.3 to 2.2.

1. Introduction
The key advantage of metamaterials and metasurfaces is their ability to precisely manipulate electromagnetic waves upon careful design of structural elements and their arrangement. While typical building blocks of the optical dielectric metasurfaces are nanoridges, nanorods and nanodisks carved from thin high-index transparent layers [1], a novel type–Fourier metasurfaces based on smooth periodic reliefs–has been recently introduced. Such metasurfaces can be fabricated by the thermal scanning probe lithography [2] or by the focused ion beam milling [3]. Importantly, the periodic relief described in terms of amplitudes of several Fourier harmonics allows fast optimization. As has been exemplified for the efficient anomalous refraction in near-grazing directions [4], Fourier metasurfaces can outperform even the most efficient to date analogues which counterintuitive complex unit cell shapes are obtained by a topology optimization requiring substantial computational resources [5].

Efficient anomalous refraction is a basic metasurface functionality necessary for creating versatile meta-lenses and beam steering devices [6]. It critically relies on the formation of a single dominating diffraction order collecting the most part of the outgoing light. For the refraction in near-grazing directions, the light wavelength has to be close to the cutoff of the corresponding diffraction order. Accordingly, subtle modifications of the system shifting the cutoff wavelength can trigger a drastic redistribution of the outgoing energy from the previously prevailing diffraction order to other channels. Ensuring that this redistribution occurs to another single dominant channel, one can achieve highly efficient optical reconfigurability in a wide range of deflection angles. Here we theoretically analyze the potential of reconfigurable Fourier metasurfaces and, for definiteness, focus on those redirecting the incident green light upon small variations of the angle of incidence and of the substrate permittivity.
Figure 1. Silicon Fourier metasurface optimized using the RH-based (dashed lines) and FEM-based (solid lines) approaches for two dominant diffraction channels activated by a subtle variation of the angle of incidence: (a) dependencies of the diffraction efficiencies $\eta_{\pm 1}$ at the wavelength $\lambda = 532$ nm on the angle of incidence $\theta_{in}$ with the stars marking the maximized efficiency values. The inset schematically shows the reconfigurability scheme. (b) Spectra of the diffraction efficiency $\eta_{\pm 1}$ of the optimized metasurface for the normal incidence with the inset showing the distribution of the magnetic field component $H_y$ at $\lambda = 532$ nm; (c) same as (b) for the light incident obliquely at $\theta_{in} = 2^\circ$.

2. Results

For the light of a wavelength $\lambda$ incident at an angle $\theta_{in}$ on a metasurface of a period $\Lambda$ supported by a substrate with permittivity $\varepsilon$, the in-plane component of the wavevector of $m$-th transmission diffraction order reads as: $k_m = 2\pi\lambda^{-1}\sqrt{\varepsilon - (\sin \theta_{in} + m\lambda/\Lambda)^2}$. Thus by increasing the positive angle $\theta_{in}$ or by decreasing $\varepsilon$ one can transform $k_{+1}$ from real to imaginary while sustaining $k_{-1}$ real. As there always exist other open outgoing channels (the direct transmission, specular and diffracted reflections) one has to precisely optimize the structure to ensure that the outgoing light is efficiently collected into a single desired direction in the both regimes.

We consider metasurfaces based on layers of monocrystalline silicon possessing the experimental permittivity values [7] patterned with 1D periodic profiles described by two Fourier harmonics and focus on controlling the propagation of TM-polarized light. The optimization goal is to maximize the transmission diffraction efficiencies $\eta_{+1}$ and $\eta_{-1}$ for the corresponding combinations of the angle of incidence and substrate permittivity. Technically, we employ two approaches: the semi-analytical model based on the Rayleigh hypothesis (RH) [4] and more extensive full-scale numerical solution using the finite element method (FEM) by COMSOL Multiphysics. Comparing the results also allows us to clarify the otherwise uncertain limits of applicability of the RH to dielectric Fourier metasurfaces.

2.1. Reconfigurability by angle of incidence

Here we maximize the diffraction efficiency $\eta_{+1}$ for the light incident normally at $\theta_{in} = 0$ and $\eta_{-1}$ for the slightly oblique incidence at $\theta_{in} = 2^\circ$. We set the metasurface period to $\Lambda = 535$ nm and assume it to be suspended in the vacuum ($\varepsilon = 1$). For the green light with $\lambda = 532$ nm, the anomalous refraction into the +1 diffraction order occurs at an angle of $83^\circ$ from the normal. Inclining the incident wave by $2^\circ$ cancels the +1 diffraction order while the waves diffracted into the −1 order propagate at $-73^\circ$ from the normal, see the sketches in the insets in Figs.1(a-c). Both the RH-based and FEM-based optimizations yield the same metasurface relief. The corresponding dependencies of the efficiencies $\eta_{\pm 1}$ on the angle of incidence $\theta_{in}$ in Figs. 1(a) show that the 67%-efficient refraction at an angle of $83^\circ$ is reconfigured into similarly strong
Figure 2. Silicon Fourier metasurface optimized using the RH-based (dashed lines) and FEM-based (solid lines) approaches for different dominant diffraction channels activated by a subtle variation of the substrate permittivity \( \varepsilon \). Spectra of the diffraction efficiencies \( \eta_{\pm 1} \) are shown for \( \varepsilon = 2.3 \) in (a) and for \( \varepsilon = 2.2 \) in (b) with the insets illustrating the distribution of the magnetic field component \( H_y \) at \( \lambda = 532 \text{ nm} \). The stars mark the maximized efficiency values.

refraction at an angle of \(-73^{\circ}\) by a very subtle alteration of the angle of incidence. Figs. 1(b) and (c) present the diffraction efficiencies spectra for the both cases. As seen in the insets in Figs. 1(b) and (c), the spatial distribution of the only magnetic field component \( H_y \) clearly indicates the formation of plane waves directly under the metasurface and their propagation in the corresponding directions.

2.2. Reconfigurability by substrate permittivity

Our next goal is to achieve similarly efficient wave deflection controlled by weak variations of the substrate permittivity \( \varepsilon \) in the case of slightly oblique incidence at \( \theta_{\text{inc}} = 2^{\circ} \). For definiteness, we choose the substrate permittivity range characteristic to standard transparent optical materials (e.g. glasses, polymers or liquid crystals) and set \( \varepsilon = 2.3 \) for the case with maximum \( \eta_{+1} \), and \( \varepsilon = 2.2 \) for the case when the +1 order is an evanescent wave and the efficiency \( \eta_{-1} \) is to be maximized. The corresponding value of the metasurface period is \( \Lambda = 365 \text{ nm} \), which provides the refraction angles \( 80^{\circ} \) and \(-74^{\circ}\) from the normal for the +1 and −1 diffraction orders in the corresponding cases. Both the RH-based and FEM-based optimizations yield the profile, schematically sketched in the insets in Fig. 2. The spectra of diffraction efficiencies \( \eta_{\pm 1} \) shown in Fig. 2 for \( \varepsilon = 2.3 \) and \( \varepsilon = 2.2 \) illustrate how the optimized maximum values, \( \eta_{+1} \approx 88\% \) and \( \eta_{-1} \approx 78\% \), are provided by the same metasurface supported by a substrate with slightly different permittivity.

3. Discussion

We have shown how dielectric Fourier metasurfaces relatively simply described by two harmonics of their periodic relief can be optimized for efficient light deflection in the directions different by more than \( 154^{\circ} \) controlled by subtle variations of the optical setup. However remarkable such reconfigurability might seem per se, its true practical potential will be fully revealed in combination with tunable metasurfaces. The latter are being developed based on very different physical principles and offer the options of convenient control by voltage, external fields or laser
irradiation [8]. As a trade-off, they often produce relatively weak direct effects on light. For example, liquid-crystal metasurfaces are capable of efficient low-voltage-driven millisecond-fast deflection of visible light, but their angular range is limited by several degrees [9]. Apparently, the above Fourier metasurfaces reconfigurable by the angle of incidence can be used to amplify this range by orders of magnitude.

On the other hand, the sensitivity to substrate properties can be directly employed to create tunable configurations provided that the substrate allows controlling its permittivity if even in a narrow specific range. In this regard, the required effect can be also achieved by realigning the liquid crystal adjacent to the metasurface.

Finally, it is worth noting that the material of Fourier metasurfaces supporting anomalous refraction in near grazing directions is not restricted to silicon [10]. We expect that similarly designed reconfigurable metasurfaces can be produced from other transparent high-index materials such as gallium phosphide or titanium dioxide.

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