Universal narrowband wavefront shaping with high quality factor meta-reflect-arrays

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Abstract

Optical metasurfaces offer unprecedented flexibility in light wave manipulation but suffer weak resonant enhancement. Tackling this problem, we experimentally unveil a new phase gradient metasurface platform made entirely from individually addressable high-quality-factor (high-Q) silicon meta-atoms. Composed of pairs of nearly identical nano-blocks, these meta-atoms support dipolar-guided-mode-resonances that, due to the controlled suppression of radiation loss, serve as highly sensitive phase pixels when placed above a mirror. A key novelty of this platform lies in the vanishingly small structural perturbations needed to produce universal phase-fronts. Having fabricated elements with Q-factor~380 and spaced by $\lambda/1.2$, we achieve strong beam steering, up to 59% efficient, to angles 32.2°, 25.3° and 20.9° with variations in nanoantenna volume fractions across the metasurfaces of $\leq2.6\%$, instead of >50% required by traditional versions. Aside from extreme sensitivity, the metasurfaces exhibit nearfield intensity enhancement over 1000x. Taken together, these properties represent an exciting prospect for dynamic and nonlinear wave-shaping.

Introduction

The field of flat optics promises to dramatically reduce the size and weight of optical components while matching or even surpassing the performance of conventional refractive bulk optics$^{1,2}$. For example, lenses with comparable resolution to high-end infinity corrected objectives 1000 times their size$^3$; and bright computer-generated holograms free from artifacts have been realized with this technology$^4$. Often called phase gradient metasurfaces, these ultra-thin, or flat, optical elements rely on nanoscale antennas to precisely control the phase of scattered light, along with amplitude and polarization in some cases$^5,6$. This control is almost always achieved by harnessing one or more optical resonances. A light field can be made to oscillate with a specific phase at some operating frequency by red or blue shifting the resonant wavelengths of a nanostructure via alterations to its shape, size, or composition$^7$. Instead of manipulating a device's surface morphology as with refractive components, waves are transformed by placing distinct nanoantennas at different positions across the surface. Distinguishing them from other diffractive optics, metasurfaces uniquely boast subwavelength separated units, each with continuously variable scattering characteristics, providing the opportunity to realize almost any desired optical wavefront with unprecedented precision$^8$-$^{10}$.

Beyond tailoring the shape of scattered waves, resonances also enhance the strength of light-matter coupling. Such enhancement will be crucial for reaching the next flat-optics horizon of adding efficient dynamic and nonlinear functionality$^{11}$. Impressive experiments have been performed in this domain$^{12}$-$^{20}$, however, metasurfaces continue to suffer from poor nonlinear efficiency and tunability due to large radiation losses$^{21}$-$^{24}$. The impact of radiation losses can be quantified in terms of the Quality factor (Q-factor). Measured by dividing the center wavelength by the spectral width (full-width-at-half-max), the Q-factor physically tracks the degree to which the circulating optical intensity within a resonator is
enhanced relative to the excitation\textsuperscript{25}. Most nanoantennas used within phase gradient metasurfaces have a Q of order 10, meaning that they leak light rapidly and therefore exhibit weak nearfield amplitudes\textsuperscript{26,27}.

Recently, it has been shown that collective resonances, often referred to as lattice, guided mode, or quasi bound state in continuum resonances, can dramatically amplify nonlinear and dynamic optical phenomena by taming radiation losses and realizing huge Q-factors\textsuperscript{28-31}. Unfortunately, the extended nature of these modes has so far prevented their benefits from being applied to phase gradient metasurfaces, the defining feature of which is the ability to produce arbitrary phase profiles with sub-wavelength resolution. Carefully tuned destructive interference between pairs of high order Mie modes has been shown to produce Q-factors of \( \sim 200 \) in sub-wavelength dielectric nanoparticles\textsuperscript{32}. But the corresponding radiation patterns have complicated high order features, making them poor candidates for metasurface building blocks\textsuperscript{33,34}. Nonlocal metasurfaces exhibiting high-Q extended modes that have shaped instead of flat phase distributions have also emerged\textsuperscript{35-37}. Rather than applying a tailored transfer function to incoming waves, these structures can resonantly enhance specific wavefronts, which is useful for focusing incoherent emission\textsuperscript{38}, for example. Therefore, targeting phase gradients with a local response, we have demonstrated through a series of studies that dipolar-guided-mode-resonances (DGMRs) with subwavelength cross-sections can achieve experimental Q-factors of \( >2500 \), and theoretical Q-factors orders of magnitude larger\textsuperscript{39}. Moreover, we embedded DGMR supporting nanoantennas in phase gradient metasurfaces, showing that the dipolar radiation patterns of DGMRs make them excellent high-Q substitutes for Mie resonators\textsuperscript{40}. Numerical studies have confirmed that nonlinear and dynamic wave shaping can be achieved at drastically reduced optical powers and bias voltages using this approach\textsuperscript{41,42}. Still, high-Q phase gradient metasurfaces made entirely from DGMR pixels and thus capable of arbitrary wavefront engineering have yet to be realized.

Here we report a high-Q phase gradient metasurface platform capable of universal reflective wavefront shaping. To unveil this platform, the specific design we present consists of arrays of almost identical Si nanoantennas each supporting an independent high-Q factor magnetic DGMR, which radiates just like a magnetic dipole. As with previous resonant metasurfaces the scattered phase distribution is tailored by structural variations from nanoantenna to nanoantenna. Due to the low radiative loss of DGMRs however, the required variations are extremely subtle. For example, a linear \( 2\pi \) phase gradient is formed by adjusting 240 nm wide nano-blocks by just 14 nm, which corresponds to a volume fraction of only 2.6\%. The universality is demonstrated by fabricating and testing beam steering metasurfaces with different steering angles as well as a metasurface beam splitter.

\section*{Results}

Here in Figure 1(a), we schematically illustrate the architecture and function of the strategy we are introducing. Each meta-reflect-array is designed to steer a y-axis polarized incident beam to a specific angle in the diffraction plane (yz plane). This is achieved with a structure consisting of Si nanoantennas atop a sapphire substrate, covered with PMMA, and finished with a reflective Ag layer. An example of a
fabricated meta-reflect-array prior to encapsulation with PMMA and Ag is shown in Figure 1(b). As highlighted in blue, each column of nano-blocks acts as a single nanoantenna to form one phase-pixel on the y axis. Within each nanoantenna, a pair of nano-blocks, one with longer length $L_A$ and one with shorter length $L_B$, are periodically arranged. Each antenna is made of this primary pair, an example of which is highlighted in orange in Figure 1(b).

The metasurface in Figure 1(b), after coating with PMMA and Ag, acts as an excellent mirror when illuminated at normal incidence through the sapphire substrate by a y-polarized infrared laser, specularly reflecting almost all the incident light. However, when the wavelength of the laser is tuned to 1486nm, three reflective diffraction spots appear. These spots correspond to diffraction angles of $0^\circ$ and $\pm 32.3^\circ$ which indicates that the metasurface period is 2800nm. Moreover, Figure 1(c) plots the measured far-field spectra for the three diffraction orders, showing that at 1486nm more than 58.0% of the incident light is deflected to the $+1^{\text{st}}$ diffraction order at $+32.3^\circ$. Known as anomalous reflection, or beam-steering, this behavior implies that the metasurface imparts a linear phase gradient on the incident beam on resonance, varying from 0 to $2\pi$ in a span of 2800nm\textsuperscript{39}. Therefore, given the 700nm spacing between nanoantennas, the diffraction signature in Figure 1(c) implies that Figure 1(b) contains four unique nanoantenna geometries, despite the lack of any obvious variation across the array (Figure S1 in SI). This apparent contradiction represents the key finding of this paper. In fact, to achieve the linear phase profile, the width of block B, denoted by $W_{1,2,3,4}$ in Figure 1(b), has been adjusted by just -7, -1, 1, and 7nm from 240nm. This corresponds to a maximum variation in nanoantenna volume of 2.6%. In contrast, traditional resonant approaches require changes in the volume of metasurface elements approaching 50%, to achieve a full $2\pi$ phase gradient\textsuperscript{43,44}. This extreme sensitivity to nanoantenna dimensions, while intriguing in its own right, will also be incredibly useful for active and nonlinear applications\textsuperscript{40,42,45}. Below, we elaborate on the mechanism underlying this prototypical metasurface platform and describe how it can be generalized to many different optical transfer functions.

Our first and most important design principle is the generation and control of high-Q DGMRs in the individual nanoantenna. Looking closer at Figure 1(b), we see that a single primary pair of the given nanoantenna, contains block A and block B separated by exactly half of the internal nanoantenna period, fixed to 710nm throughout the paper. While the blocks clearly have different shapes in the fabricated device, if we set them equal, with both lengths $L_0=450$ nm and both widths $W_0=240$ nm, the nanoantenna essentially becomes equivalent to a nanoparticle waveguide with a 355 nm period shown in Figure 2(a). In the ideal case of lossless Si and perfect patterning, due to translational symmetry a set of perfectly bound guided modes are formed with a 710 nm guided wavelength\textsuperscript{46,47}. The specific guided mode we are interested in here is illustrated in Figure 2(a) with the electric and magnetic field distribution. Such a waveguide mode will therefore not interact with waves traveling in the plane perpendicular to the column. However, breaking the translational symmetry by, for example, introducing a difference in length ($\Delta L$) of the two blocks in the primary pair while keeping other dimensions unchanged opens a free-space channel for the guided waves to leak out\textsuperscript{43}. Standing guided waves then become guided mode resonances that can be excited from free space. With these structures, the leakage strength is tied directly to $\Delta L$, as seen...
in the curve in Figure 2(b) which plots the diverging resonant quality factor (Q) as $\Delta L \to 0$. Decreasing $\Delta L$ from 100 nm to 10 nm increases Q from a few hundred to $4 \times 10^4$, with accompanied enhanced near fields (Figure S2 in Supplementary Information). From the magnetic field maps in Figure 2(c), it is also clear that radiation is leaking isotropically, forming cylindrical wavefronts. This is unique when compared to two-dimensionally periodic guided mode resonances, which emit plane waves\(^{47,48}\). The near field distribution (Figure S1) and emission patterns in Figure 2(c) are equivalent to that of an out-of-plane magnetic dipole centered on the nanoantenna\(^{49}\). As such, we refer to these modes as magnetic dipolar-guided-mode-resonances (DGMRs). In view of Figure 2(c), Figure 2(a) also highlights another interpretation of how these objects scatter light. Each nano-block supports a magnetic dipole Mie resonance, but dipoles in neighboring blocks are $\pi$ out of phase. If these dipoles have the same strength, as is the case for $\Delta L=0$, their far-field radiation exactly cancels. Slight variations in the sizes of blocks A and B spoil this cancelation by changing the relative strengths of the out of phase dipoles. The benefit of DGMRs for manipulating free-space light waves can be seen in Figure 2(d). When arranging a set of nanoantennas with subwavelength spacing, a sharp resonant feature shows up in the simulated transmission $|t|^2$ and reflection $|r|^2$ spectra. Importantly, though the relative strength of the radiated field to nearfield clearly decreases in Figure 2(c) in proportion to $\Delta L$, pronounced resonant modulation occurs in both cases upon free-space illumination. Moving forward, we will use the lower Q, $\Delta L=100$ nm, design, but this is by no means a fundamental limit of the platform. Although not addressed in detail here, another useful feature of these high-Q resonances is dramatic, subwavelength, near field amplification, as the circulating intensity within the Si antenna increases in proportion to Q. Regulation of the antenna's resonance wavelength can also be achieved numerically and experimentally by controlling the spacing of the two blocks in the primary pair of each antenna.

Our second design principle involves placing the high-Q DGMR Si nanoantennas in the vicinity of a reflective metal plane. As can be seen in Figure 2(d), without the reflective plane, the transmittance and reflectance spectra vary significantly across the DGMR. Coupled amplitude and phase variations spoil the ability to form arbitrary wavefronts. As shown by the simulations in Figure 3(a), by reflecting the forward scattering from the nanoantennas to combine with the reverse scattering, virtually all of the wavelength dependence is removed from the reflectance $|r|^2$, while a steep resonant slope in the reflected phase remains. The phase also spans the full range of $2\pi$. As seen in Figure 3(b), we can translate the wavelength dependence into a structure dependent response at a fixed operating wavelength, which we choose to be 1495.5nm. Specifically, the width of smaller block B is adjusted by the amount $\delta_w$, as shown in the inset of Figure 3(b). Phase coverage of $\pi$ and almost $2\pi$ can be accessed with $\delta_w$ varying between -2.5nm to 2.5nm (grey area) and -15 nm to +15nm, respectively. These equate to volume fractions of only 0.9%, for $\pi$, and 5.6%, for $2\pi$. Such a strong response to tiny structural tuning is a direct consequence of working with a high Q-factor. This behavior exists irrespective of the spacer thickness, labelled $H$ in the left inset of Figure 3(a). However, interference between the direct and mirror mediated reflection does modulate the DGMR radiative loss rate. Counter intuitively, we choose $H=1.20 \mu m$ to minimize Q for a given nanostructure. This helps to reduce strong interactions between the DGMRs and the metal, which would add an extra dissipation channel, as well as interactions between neighboring DGMRs. Another
perspective on this is to recognize that the layered architecture supports a series of Fabry-Perot (F-P) resonances. When the DGMR aligns with an F-P, the two hybridize, increasing the DGMR Q-factor but also adding to it the undesirable F-P properties of strong spatial dispersion and strong metal absorption.

Indeed, the simulated Q factor of the reflectance dip ramps up first then drops off sharply when $H$ is increased before 1.20 μm and also after 1.20 μm (Figure S3 in SI). The depth of the resonant feature also increases with the rise in Q, showing that dissipation is setting in. Interestingly, the experimental Q factor obtained from the reflectance $|r'|^2$ of the fabricated fully periodic structure with $H=1.20$ μm (blue) is fitted to be 1712 in Figure 3(a), whereas the simulation result $|r|^2$ (black) is 383. This mismatch may be due to the imperfect PMMA deposition process, missing the target thickness. The inset of Figure 3a also reveals that a huge enhancement of light intensity inside the silicon accompanies the sharp jump in reflected phase. We thus expect many nonlinear phenomena, including third harmonic generation, stimulated Raman scattering and the Kerr effect, would be amplified by this structure.

Having confirmed that metasurfaces consisting of metal backed arrays of DGMR Si nanoantennas represent highly responsive reflective phase modulators, now we can exploit this behavior to engineer phase gradients. As discussed above in the context of Figure 2, the modes we have introduced are localized to individual nanoantennas. So, if instead of changing the structure of Block B in every metasurface column equally, as has been done in Figure 3(b), unique modifications are made to each column, we would expect the reflected phase to become nonuniform. Choosing a set of subtle perturbations to generate a desired wavefront is therefore the 3rd and final design principle. For ideal performance, nearfield coupling between neighboring elements should be avoided. This is particularly important for high-Q resonators because long decay times make them very sensitive to even small coupling rates. At the same time, small nanoantenna spacing is preferred to maximize wavefront accuracy and field of view, or equivalently the largest accessible diffraction angle. In our experiment we have a pixel pitch of 700nm, corresponding to $\sim \lambda/1.2$. With $\Delta L=100$nm, giving $Q \sim 400$, 700nm separation is sufficient to suppress crosstalk. Evidence for this can be seen in Figure 4 showing that a metasurface with four different perturbation strengths, $\delta_W=7, 1, -1, -7$nm, imparts a linear phase gradient to a normally incident beam, deflecting it to an angle of 17.6°, or 52.3° after refracting at the sapphire/air interface. Efficient resonant beam steering seen in both the simulated diffraction spectra, Figure 4(b), and electric field wave pattern, Figure 4(c), agrees well with the measured diffraction spectra in Figure 1(c). Again, the use of $\delta_W=+1$ and -1nm, which is less than a 0.1% change in volume fraction, to produce a $\pi/2$ phase shift emphasizes the extreme phase sensitivity. In fact, the set of perturbations is so subtle that they are impossible to make out from the SEM image in Figure 1(a). If operating with smaller $\Delta L$, and so a higher Q-factor, coupling would need to be reduced by increasing the nanoantenna separation or otherwise decreasing the mode overlap, perhaps by improving the mode localization or using symmetry. However, the extreme structural response in Figure 3(b) already places the smaller phase steps at the boundary of our e-beam patterning resolution, meaning that higher tuning efficiency would add complications to the fabrication. It should also be mentioned that the relatively high index of the PMMA spacer, 1.49, and sapphire superstrate, 1.77, increases nearfield coupling by limiting the index contrast with silicon and
decreases the wave shaping resolution by shrinking the wavelength of diffracted light. Both issues can be easily addressed by updating the fabrication procedure.

The phase gradient explored in Figure 1 and Figure 4 is just one example of many possible wave transformations, all realizable with nanometer level tuning. To demonstrate that, unlike other high Q diffractive structures, our DGMR-based phase gradient metasurface platform is capable of universal wavefront shaping, next we target linear gradients with different slopes. To realize a continuous linear gradient with a periodic metasurface, the reflected phase must change by exactly $2\pi$ across each supercell of the metasurface. The phase slope is therefore decided simply by choosing how many nanoantennas, denoted by $m$, make up a supercell. According to the generalized Snell’s Law, for nanoantenna spacing $\Delta p$ and superstrate refractive index $n_r$, the deflection angle is given by $\theta_r = \arcsin(\lambda/n_r m \Delta p)$, when the metasurface is illuminated at normal incidence$^{50}$. As we ultimately detect the diffracted light in air, $n_r=1$. Figure 5 shows the measurements of three different metasurfaces with $m=4$, 5 and 6. A large resonant peak in the $+1^{st}$ diffraction order dominates in each case, indicating that the beam is being steered to angles 32.3°, 25° and 20.5°. This is supported by the Fourier images in the insets of Figures 5(a-c). The phase to perturbation mapping in Figure 3(b) was again used to choose the distribution of $\delta$ values for the three samples, shown in Figures 5(a-c). For phase steps between neighboring nanoantennas we initially targeted $2\pi/m$, but to correct for residual nearfield coupling, slight tweaks have been applied to improve the $+1^{st}$ diffraction efficiencies. High steering efficiencies of 43.8%, 58.0% and 38.2%, were observed for steering angles 32.3°, 25° and 20.5° in Figure (d), (e) and (f), respectively. And the extreme subtle structural variation of these three almost identical devices is negligible from SEM images (Figure S4).

As further evidence of the universality of our reflective high-Q meta-arrayed platform, beam-splitting is numerically and experimentally demonstrated in Figure 5 based on the same underlying design principles. The four nanoantennas with $\delta_W= 4, 4, -4, -4$ nm act as a binary phase grating, splitting the reflection into two equal and out-of-phase waves. Consistent with this description, destructive interference is seen to suppress the 0$^{th}$ order diffraction with the remaining signal shared evenly between +1$^{st}$ and -1$^{st}$ diffraction orders, in both simulated, Figure 6(b), and measured, Figure 6(c), diffraction spectra. High diffraction efficiency, defined here as the total proportion of the reflected light in the 1$^{st}$ order beams, is found in the simulation, 68.7%, and measurement, 56.7%. The diffraction spectra are also verified by the Fourier images taken with an IR camera in the inset of Figure 6(a), clearly showing two equal spots. The beam-splitter has the same periodicity and therefore diffraction angle 32.3° as the four element beam-steerer in Figure 1. This highlights that strikingly small changes to these nanostructures lead to totally different transfer functions.

**Discussion**
While our experiments represent much stronger resonant enhancement compared to previous generalized phase-front engineering schemes, these results are still far from optimal. The general design strategy offers extreme light-matter interaction strengths by pushing to much higher Q. Specifically, the practical Q factor in our proof-of-principle experiments is constrained by the increased refractive index of the substrate and spacer layers and the resolution of electron beam patterning. Therefore, the ultimate performance limits are still to be explored. It is important to point out that, the electron beam resolution only impacts the ability to reliably designate specific phase values in space and not Q. As highlighted by our recent theoretical study\textsuperscript{41}, Q factors at least two orders of magnitude larger than we report here could be achieved with a more sophisticated design and fabrication procedure, without sacrificing the subwavelength nanoantenna spacing and corresponding precise phase shaping.

In summary, we have experimentally established the first platform capable of high Q wavefront engineering with subwavelength resolution by phase gradient metasurfaces made from DGMR nanoantennas. The novelty of our approach is that each nanoantenna, composed here of a column of nano-block pairs, supports an independent magnetic-DGMR. We demonstrated both the evidence for and benefit of this independence by introducing and controlling diffraction via local redshifts induced by subtle structural changes to individual elements. Increasing the Q factor of a resonant phase modulator decreases the perturbation needed to reach a given phase value because of the decrease in resonant linewidth. As shown numerically, the Q factor of our magnetic-DGMR can, in principle, be made arbitrarily large, by making the difference between neighboring nano-blocks within a nanoantenna arbitrarily small. Even though we opted for a modest Q factor of ~ 400, significant phase gradients were seen when nano-block widths were altered by just a few nanometers across a metasurface. We exploited this extreme sensitivity to build an efficient narrow-band beam steering metasurface with nanoantenna volume fractions varying by no more than 2.6%. To demonstrate the universality of the metasurface platform we have introduced, which is a simple consequence of realizing subwavelength pixels with full 2\pi-phase access, we fabricated beam steering metasurfaces with different supercell periods and therefore different steering angles, as well as a binary phase grating which acts as a diffractive beamsplitter. However, other functions, such as lensing, should be easy to implement. By replacing the structural phase tuning with a dynamic refractive index bias, whether thermo-optic, electro-optic, or mechano-optic, high Q meta-reflect-arrays will also enable the realization of fast, efficient, and high-resolution spatial light modulators. Beyond increasing sensitivity to a bias, nonlinear effects, such as harmonic generation, four-wave-mixing, or the Kerr effect, would benefit even more directly from the extreme performance of the devices we have presented as they scale at least quadratically with the DGMR Q factor. Our work, therefore, brings low-power nonlinear wave shaping into view.

**Materials And Methods**

1. **Fabrication of DGMR nanoantenna**
The metasurfaces were fabricated using standard electron beam lithographic (EBL) procedures. First, 600nm, single crystal silicon-on-sapphire substrates (University Wafer) were cleaned via sonication in acetone and isopropyl alcohol. This substrate was further baked at 180 °C before spin coated with hydrogen silsesquioxane (HSQ) negative tone resist (XR-1541-06, Corning). Then the resist was baked at 80 °C for 45 min. To reduce charging, a charge dissipation layer (e-spacer, Showa Denko) was spin coated over the HSQ resist and baked again at 80 °C for 5 min. The metasurface patterns were defined by a 100 keV electron beam in an EBL system (JEOL JBX-6300FS). Patterns were developed for 120 seconds in a 25% solution of tetramethylammonium hydroxide. Reactive ion etching with Cl2, HBr, and O2 chemistries were utilized to transfer the pattern to the silicon layer (Lam TCP 9400). The HSQ resist was removed using 2% hydrofluoric acid in water and the samples were then cleaned using a piranha solution (9:1 H2SO4:H2O2) heated to 120 °C. Then the etched Si metasurfaces were spincoated with PMMA (A8) and post-baked at 180 °C for 15mins. The thermal evaporated Ag was performed in vacuum coater (Edwards 306) with a crystal balance for the desired thickness of 100nm.

2. Optical characterization for diffraction efficiency

The reflected diffraction spectra were measured by a home-built Fourier plane microscope, including an IR detector, an IR alignment camera, and a tunable laser (ECDL), 1460nm to 1570nm, (TOPTICA CTL 1500) as shown in the schematic in Figure S5. To access high deflection angles, a high numerical aperture (NA=0.79) aspheric lens is used as an objective lens, collimating the reflected diffraction orders from samples placed at the focal plane. A translatable detection stage was then used to image each diffraction order, one at a time, to the IR detector via a series of relay lenses. To illuminate the 200x200μm samples through the aspheric lens, the laser was focused via a 50/50 beam-splitter, close to the back focal plane of the asphere, producing a defocused spot roughly the same size as the samples. To focus and align the metasurfaces to the laser as well as ensuring normal incident illumination, samples were mounted on a rotation stage attached to a kinematic XYZ translational stage (Thorlabs Inc.).

Declarations

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Conflict of interests

There is not any conflict of interest in this work.

Author contributions

L.L. fabricated the reflective-meta-arrays, conducted the optical measurements, and performed all other characterization; J.H. and S.D. fabricated the Si metasurfaces. L.L. and M.L. wrote the manuscript. M.L. came up with the idea and supervised the whole project along with J.A.D. All authors contributed to preparation of the manuscript.

References


**Figures**

**Figure 1**

Design and characterization of high-Q reflective wave shaping with DGMR phase gradient metasurfaces. (a) Schematic operation of assembled reflective high-Q DGMR beam-steerer. (b) Scanning Electron Microscope (SEM) image of high-Q DGMR metasurfaces with four nanoantennas per unit cell with $L_A=450$ nm, $L_B=350$ nm, $W_1=247$ nm, $W_2=241$ nm, $W_3=239$ nm, and $W_4=233$ nm. (c) Measured normally incident diffraction spectra, $0^{\text{th}}$ order (black), $+1^{\text{st}}$ order diffraction (red) and $-1^{\text{st}}$ order diffraction (blue), from metasurfaces shown in (b). Inset illustrates the normally incident beam, polarization direction, and diffraction configuration of steering angle $\theta=+32.3^\circ$ on resonance with matching the color of the spectra.
Figure 2

Engineering high-Q dipolar-guided-mode-resonances in silicon nanoantennas. (a) Nanoantenna made from array of identical nano-blocks along with simulated guided mode standing wave which is perfectly bound, Q is infinite. (b) Simulated Q-factor of DGMR in silicon nanoantenna shown in (a) after breaking translational symmetry, plotted as a function of symmetry breaking parameter $\Delta L$. (c) Cross-sectional view of simulated resonant dipole radiation ($H_y$-field) from nanoantennas with $\Delta L=10$nm (red) and
$\Delta L=100\text{nm}$ (blue), demonstrating the decrease in leakage strength responsible for the diverging Q-factor that occurs with decreasing symmetry breaking. (d) Simulated transmittance/reflectance (solid/dashed) spectra from periodic arrays of DGMR nanoantennas modelled in (b-d), with a 700 nm array spacing. $\Delta L=10\text{nm}$ (red) and $\Delta L=100\text{nm}$ (blue).

Figure 3

Highly sensitive reflective phase tuning from mirror backed DGMR nanoantennas. (a) Simulated (black) and measured (light blue) reflectance spectrum $|r(\lambda)|^2$ with corresponding simulated reflection phase (blue) from periodic DGMR nanoantenna array placed above reflective silver plane. Left inset shows the cross-sectional view of the reflective high-Q DGMR meta-arrays. $H=1.20\mu m$ and $\Delta L=100\text{nm}$ for simulated and measured structures. Right inset shows the near-field intensity enhancement at the resonant wavelength of 1495.5nm. (b) Simulated reflectance (black) and reflection phase (blue) from silver-backed DGMR nanoantenna array with varying perturbation, $\delta_w$, added to nano-block B width, at wavelength of 1495.5nm.
Figure 4

Numerical demonstration of narrow-band beam-steering. (a) Selecting four distinct perturbation parameters, $\delta_w$ (-7, -1, 1 and 7nm), from periodic simulation in Figure 3b to provide linear phase gradient spanning 0-2$\pi$, and so approximately $\pi/2$ discretization between each nanoantenna. (b) Simulated diffraction spectra from phase gradient metasurface with perturbations selected from (a) labelled by diffraction order. (c) Simulated magnetic field distribution ($H_y$) with $\lambda$=1495.5 nm, showing beam-steering.
Figure 5

Experimental demonstration of universal narrowband wave-shaping with high-Q metasurface beam-steerers targeting different deflection angles. (a-c) $m$ distinct perturbation parameters, $\delta_W$, selected from periodic simulation in Figure 3b to provide linear phase gradients spanning $0-2\pi$, and so approximately $2\pi/m$ discretization between each nanoantenna. Number of elements per super-cell $m = 4$ (a), 5 (b), and 6 (c), producing steering angles $32.2^\circ$, $25.3^\circ$, and $20.9^\circ$, respectively. Insets show measured Fourier images of corresponding metasurface diffraction on resonance clearly revealing a tuned deflection angle. (d-f) Measured diffraction spectra from metasurfaces based on perturbation distributions given in (a)-(c) with steering angle of (d) $32.2^\circ$, (e) $25.3^\circ$, and (f) $20.9^\circ$. Insets illustrate the normal incident beam and diffraction configuration on resonance with matching color of the spectra.
Figure 6

Experimental and numerical demonstration of reflective beam splitting with high-Q binary-phase DGMR metasurface. (a) Two perturbations selected to give approximately π phase difference between pairs of nanoantennas, δW = -4, -4, 4, and 4nm. Inset shows measured Fourier image of metasurface diffraction on resonance clearly revealing two equally split diffraction spots. (b) Numerical and (d) experimental diffraction spectra with excellent agreement and strong, balanced +1st/-1st order diffraction, with inset illustrating the normal incident beam and diffraction configuration on resonance with matching color of the spectra. (d) Simulated magnetic field (H_y) distribution corresponding to beam splitter on resonance at 1495.5nm.

Supplementary Files

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