Non-local metasurfaces for spectrally decoupled wavefront manipulation and eye tracking

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Metasurface-based optical elements typically manipulate light waves by imparting space-variant changes in the amplitude and phase with a dense array of scattering nanostructures. The highly localized and low optical-quality-factor (Q) modes of nanostructures are beneficial for wavefront shaping as they afford quasi-local control over the electromagnetic fields. However, many emerging imaging, sensing, communication, display and nonlinear optics applications instead require flat, high-Q optical elements that provide substantial energy storage and a much higher degree of spectral control over the wavefront. Here, we demonstrate high-Q, non-local metasurfaces with atomically thin metasurface elements that offer notably enhanced light-matter interaction and fully decoupled optical functions at different wavelengths. We illustrate a possible use of such a flat optic in eye tracking for eyewear. Here, a metasurface patterned on a regular pair of eye glasses provides an unperturbed view of the world across the visible spectrum and redirects near-infrared light to a camera to allow imaging of the eye.

The emergence of new technologies can be a tremendous driver for innovation. We currently witness this with the rapid development of new handheld and wearable technologies. These technologies encompass a microcosm of electronic and optical devices that have to efficiently work together to perform a complex set of display, sensing, imaging, filtering, computation and illumination functions. The need for such devices to be lightweight, fashionable, and operate at high speed and low power has prompted some of the most thought-provoking design challenges. Nanostructured layers termed metasurfaces have presented many elegant, new solutions for the optical components by offering a compact form-factor, multi-functionality, very high-numerical apertures, minimal aberrations and control over the light field. Now, in the development of augmented and virtual reality (AR/VR) systems new functionalities are required for which even metasurface-based flat optics does not appear to have solutions. Functions that require very high spectral and angular control have proven particularly hard to achieve. These are not afforded by conventional metasurfaces that have largely relied on engineering of a local optical response, where single or small groups of closely spaced nanostructures are designed to imprint independent and spatially variant phases onto incident light waves. As the optical quality factor (Q) of subwavelength nanoscatte ranges tends to be low, they offer similar optical functions for light waves across broad ranges of wavelengths and incident angles. The realization of narrow-band responses in planar structures has typically been the domain of photonic crystals and guided-mode resonator (GMR) devices that display non-local responses involving optical modes that extend over many elements. Recent works on non-local metasurfaces have employed the concepts of GMRs and bound states in the continuum to realize high-Q flat optics capable of selectively manipulating light at certain wavelengths and incident angles at which non-local modes can be excited. One major limitation of these high-Q, non-local metasurfaces has been that their optical functions at different wavelengths are strongly tied together through their band structure and spectrally decoupled functions appear impossible to realize. In this work, we demonstrate that the introduction of spectrally dependent material absorption can fully decouple optical functions at different wavelengths. We start by showing how the need for this capability arose in an attempt to develop creative, new solutions for eye-tracking (ET) technology in wearables and AR devices.

ET has a myriad of applications in medicine, psychology and neuroscience, marketing research, sports and gaming. Optical ET techniques have successfully been commercialized and are integrated into regular and AR/VR eyewear (Supplementary Table 1). Figure 1a shows a photograph of a basic ET prototype that we constructed with a large-area (4 cm²), high-Q, non-local metasurface created on the eye-facing surface of a pair of glasses. A near-infrared light-emitting diode (NIR-LED) emitting at 870 nm illuminates an artificial eye and the metasurface redirects the scattered light from the eye toward a miniature camera that is attached to one of the arms. The metasurface should provide the person wearing the glasses with an unperturbed view of the outside world, while a high-speed camera can image and follow the eye’s motion. In an existing approach, two or more cameras are attached to the frame in such a way that they do not block the user’s view and allow capture of side-view images of the eye. To assess the gazing direction from side-view images unfortunately requires an undesirably large amount of computational processing power/time and the use of complex imaging algorithms. For this reason, it is ideal to acquire a front-view image with a single camera. This can also be accomplished with other compact optical elements (for example, gratings, miniature prisms, local metasurfaces and waveguides) placed directly in front of the eye, but these dispersive components inevitably produce unwanted rainbows. This is very distracting when used in environments with bright optical sources, such as the Sun. There are currently no compact ET systems that offer the required high transparency (>80%) across the visible, acceptable efficiencies (>10%) for redirecting near-IR photons for imaging purposes, and strong suppression of rainbows (>3 orders of magnitude).

It is clear that a new type of optical element needs to be created that is capable of performing different, independent operations on light waves at different frequencies and incident angles. In our...
example, all light waves in the visible (VIS) spectrum should be allowed to pass completely unimpeded, independent of the incident angle. However, in the NIR we aim to redirect light across a narrow band of wavelengths and a small range of angles to a camera for imaging. At least in principle, linear optical elements are well suited for the task of sorting out photons in overlapping beams by their fundamental characteristics (wavelength, polarization state or propagation direction). Physically, it is a matter of manipulating wave interference effects and the relevant mathematics comprised of simple additions and subtractions. However, in practice it can be extremely challenging to design a thin, ideally single-layer optical element that acts very differently on different types of waves. Only recently, have new physics concepts and inverse design for nanophotonics started to enable such tasks. Given the tremendous design flexibility for metasurfaces with millions of scattering nanostructures, this technology would appear promising. However, a clever arrangement of the nanostructures turns out to be insufficient to solve this challenge and we will argue that it is critical to achieve a high-Q, non-local response by engineering a long-range, coherent coupling between many designer elements in the metasurface.

To see the benefits of our metasurface design, we first consider the properties of a conventional grating consisting of 30-nm-thick Cr strips whose dimensions were optimized to redirect 10% of a normally incident NIR beam through the first diffracted order. The view through such a grating is plagued by the presence of intense rainbows (Fig. 1b) that are a direct consequence of the local scattering response of the Cr strips. Figure 1c,d show the same scene as viewed through two of the newly proposed high-Q, non-local GMR metasurfaces. They are made up of either 7-nm-thick or 3-nm-thick polycrystalline Si (pSi) strips placed on a Si$_3$N$_4$ dielectric waveguide (Fig. 1e). These structures effectively suppress the rainbows and nanometre-scale changes in the thickness of the grating elements strongly impact the intensity of the rainbows. To understand the difference in behaviour of regular Cr gratings and the high-Q GMR metasurface, it is of value to go back to the early modelling work on GMR structures by Hessel and Oliner. They analysed how the efficiency in/out of the waveguide and thus also the radiative losses strongly impact the intensity of the rainbows. To understand the difference in behaviour of regular Cr gratings and the high-Q GMR metasurface, it is of value to go back to the early modelling work on GMR structures by Hessel and Oliner. They analysed how the diffraction efficiency into the +1 diffracted order for the 30-nm-thick Cr grating and the optimized GMR metasurface under normally incident TE-polarized plane wave illumination. Each structure reaches ~10% efficiency at the target wavelength of 870 nm. The dashed blue curve shows the situation where the material absorption in the pSi is artificially set to zero. The horizontal dashed line indicates a 0.1% upper limit for visible light diffraction to avoid perceptible rainbows. The purple shaded region shows the absorption coefficient of pSi, $\alpha_{pSi}$.  

Fig. 1 | A high-Q GMR metasurface facilitates decoupled optical functions at different wavelengths and optical ET without rainbows. a, Image of our prototype ET glasses. We gratefully acknowledge Eunae Kim for creating the image and Andrew Brodhead from the Stanford News Service for the photo of Hoover Tower in this image. Light from a NIR-LED is scattered by the eye and redirected to a camera by a metasurface patterned on the glass. At the same time, the metasurface should offer a high transmission in the VIS region in order to allow an unperturbed view of the outside world (Hoover Tower at Stanford University). b, Photograph taken through a glass surface with a 200-nm-thick Si$_3$N$_4$ antireflection coating patterned with a 30-nm-thick Cr grating showing a weak rainbow. The GMR metasurface comprises a 100-nm-thick SiO$_2$, 7-nm-thick pSi grating, 200-nm-thick Si$_3$N$_4$ slab and glass substrate from top to bottom. The period and width of the pSi grating are 1 μm and 900 nm, respectively. c, Photograph taken through a GMR metasurface with a 3-nm-thick pSi grating showing a strongly suppressed rainbow and a high, colour-balanced transmission. d, Photograph taken through a GMR metasurface with a 7-nm-thick pSi grating showing a weak rainbow. The GMR metasurface comprises a 100-nm-thick SiO$_2$, 7-nm-thick pSi grating, 200-nm-thick Si$_3$N$_4$ slab and glass substrate from top to bottom. The period and width of the pSi grating are 1 μm and 580 nm, respectively. e, Schematic diagram illustrating how a high-Q GMR metasurface affords unimpeded transmission of light across the VIS and narrow-band redirection of NIR light at 870 nm into a +1 diffracted order. f, Simulated zeroth-order transmittance spectra of the Cr grating (Cr) and optimized GMR metasurface (w/abs.) under normally incident plane wave illumination. The dashed curve shows the situation where the material absorption in the pSi is artificially set to zero (wo/abs.). The polarization direction is in parallel to the grooves of the grating (TE). g, Simulated diffraction efficiency into the +1 diffracted-order transmission for the 30-nm-thick Cr grating and the optimized GMR metasurface under normally incident TE-polarized plane wave incidence. Both structures reach ~10% efficiency at the target wavelength of 870 nm. The dashed blue curve shows the situation where the material absorption, $\alpha$, in the pSi is artificially set to zero. The horizontal dashed line indicates a 0.1% upper limit for visible light diffraction to avoid perceptible rainbows. The purple shaded region shows the absorption coefficient of pSi, $\alpha_{pSi}$.  

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function as metasurface-based flat optics capable of steering light at a preselected wavelength of NIR light (in our example 870 nm) while allowing an unperturbed transmission across the visible without the appearance of rainbows.

The optical spectra in Fig. 1f,g quantitatively compare the distinct optical behaviour of the Cr grating (Fig. 1b) and optimized high-Q GMR metasurface (Fig. 1d). The Cr grating displays a low transmissivity across the visible, which is linked to strong absorption and scattering by the metal structures. We can see undesired diffraction across the entire visible range, consistent with Fig. 1b. This results from diffraction into second- and higher-order diffracted beams. In contrast, the 3-nm-thick GMR metasurface shows a very high transmissivity at normal incidence across the visible range (89% on average). This can be expected as the grating is at least two orders of magnitude thinner than the absorption depth in pSi. Moreover, with proper design the Si,N,
waveguide and silica cover can also serve as a high-performance, double-layer antireflection coating (Supplementary Information 2). The transmission spectrum for the GMR metasurface shows a sharp spectral feature near 870 nm that can be attributed to a GMR. This resonance provides a second, indirect pathway for the light through the structure. At the resonant wavelength, about 40% of the light is taken out of the incident beam and redirected into four first-order diffracted beams (+1 and −1 in the forward and backward directions). Whereas the scattering by a single metasurface/scattering element is weak, a high diffraction efficiency nonetheless results from constructive interference of many coherent scattering elements that work together on resonance to first couple and then redirect the light. The diffraction efficiency spectrum (Fig. 1g) shows peaks with an asymmetric lineshape that come about from the interference of the light radiating from the GMR and the directly transmitted light (that is the background). Based on the high diffraction efficiency seen at 870 nm, one would naturally expect to see high diffraction efficiencies in the visible range as well. However, the GMR resonances in the VIS (at 608 nm, 496 nm and 470 nm) display a very low diffraction efficiency (<0.07%), explaining the virtual absence of rainbows. The difference in behaviour in the VIS and NIR lies in the spectral absorption properties of the pSi metasurface elements, as explained next. The dashed curves in Fig. 11g show the transmission and diffraction efficiency for the case that the material absorption in pSi is artificially set to zero. They very nicely highlight how the material absorption in the ultrathin metasurface elements can control the flow of light through the device on resonance; in the presence/absence of material absorption, the diffracted orders can selectively be turned off/on without notably impacting the response off-resonance.

Controlling the flow of light through a non-local metasurface

The flow of light through the GMR metasurface is controlled by the relative magnitudes of the scattering and absorption efficiencies of the metasurface elements. These can be engineered through a choice of the material and geometry for these elements. For our metasurface, we obtain very different behaviour in the VIS and NIR by using pSi elements. The absorption depth of pSi changes by several orders of magnitude between these spectral ranges (Fig. 1g). Figure 2a illustrates the power flow for incident planewaves in the VIS and NIR. In both spectral ranges, light can couple to the GMR by picking up the second-order grating momentum (which equals 4π/p), where p is the grating period (Supplementary Information 3). The dispersion diagram in Fig. 2b shows this process for 870-nm transverse electric (TE) polarized light. Subsequent radiative decay from the GMR into the first diffracted order then produces the desired steered beam for imaging. The decoupling by the 3-nm-thick grating is very weak and this enables a resonance with a high Q of 8,700 at a wavelength λ = 870 nm. This Q is radiation limited as the pSi shows weak material absorption at this wavelength. As such, the light is trapped inside the Si,N,
waveguide for many optical cycles (equals to Q/2π) and a strong buildup of the internal electric fields (E) in the GMR (|E|2/|E,inc|2 ≈ 2,500) is observed, where E,inc is the incident electric fields. In turn, the large internal fields enable high diffraction efficiencies of 11.1% for the first-order reflected beams. This is consistent with temporal coupled mode theory (CMT) (Supplementary Information 4). The diffraction is clearly noticeable from the chequerboard pattern of nodes in the electric field intensity profile shown in Fig. 2c. In contrast, in the visible part of the spectrum the pSi material absorption is significantly stronger. As a result, the quality factor is absorption-dominated and the field buildup in the GMR results in a strongly enhanced light absorption. In this wavelength range, the energy in the GMR dissipates before it decouples to free space. Physically, the enhanced absorption results from a long interaction length with the absorbing pSi grating elements as the light is guided along the nitride waveguide. This results in a low first-order diffraction efficiency (<0.1%), as confirmed by CMT and a power flow analysis (Supplementary Information 4). For the directly transmitted light there is no noticeable energy storage and we find that the essentially single-pass transmission through the 3-nm-thick pSi grating provides a very high (close to 90%) transmittance, consistent with Fig. 1f. This shows we can fully deactivate the diffractive optical functions in the visible spectrum simply by introducing some material absorption in the atomically thin metasurface elements. At this point it is worth restressing that the Cr strips in the conventional grating only support low-Q, local scattering resonances. Such resonances do not afford the significant field buildup that is required to achieve independent control over the power flow paths in the VIS and NIR.

There are several trade-offs in the metasurface design. Thicker Si gratings elements can more effectively scatter than absorb light and can thus offer more intense first-order diffracted beams. Figure 2d shows the simulated dependence of the diffraction efficiency for the TE-polarized GMR near 870 nm into the first-order reflected beam used for ET. Here, we take a representative refractive index of Si (equal to 3.7+0.005i) in this spectral regime4. Despite the very weak material absorption of Si at this wavelength, the absorption ends up dominating the total quality factor (1/Q = 1/Q,inc + 1/Q,abs) for very thin strips (~1 nm) as a result of the large optical path length inside the GMR. The peak diffraction efficiency then increases as a function of the grating height and saturates as the scattering by the strips starts dominating the absorption. This transition is further analysed in Supplementary Information 6. At a 2 nm grating height, the diffraction efficiency already exceeds 4%. Figure 2e summarizes the diffraction efficiency into the unwanted, first-order transmitted beam for the TE-polarized GMR in the visible (near 605 nm). In this spectral region, the Si is significantly more absorptive (n = 4.0 + 0.1i) and the peak diffraction efficiency is decreased by two orders of magnitude as compared to the NIR. The peak diffraction efficiency falls below 0.1% for grating heights smaller than 4 nm, which we therefore set as the maximally acceptable grating height. Combined, these requirements locate the optimum grating height around 3 nm. Finally, such a grating height is also thin enough to fulfil the >80% transmittance requirement (see Fig. 2f).

Characterization of the fabricated non-local metasurface

The analysis above indicates that we need atomic-scale control over the Si grating thickness across the 4 cm2 area of the metasurface. The scanning electron microscopy (SEM) image in Fig. 3a shows how we can achieve such high accuracy by adopting standard photolithography and Si-compatible processing (Supplementary Information 7). A pSi deposition followed by a slow thermal Si oxidation process enables subnanometre control over the pSi layer height (Supplementary Information 8). The cross-section of the grating pattern shows a 30-nm-deep over-etching of the pSi layer into the Si,N,
slab (Fig. 3b). The over-etching increases the
cross-polarized transmission measurements remove the direct, non-resonant transmission channel for the metasurface and clearly show the sharp resonance peaks from the GMRs (Fig. 3c). The measured quality factor ($Q = 540$) is lower than in the simulation ($Q = 1400$), which we attribute to the increased radiative decay rate by fabrication imperfections.

Using a home-built angle-resolved confocal spectroscopy setup, we characterize the optical dispersion (Fig. 3d) as well as the power efficiency of the resonant diffraction (Fig. 3e) by the high-Q GMR metasurface (Supplementary Information 10). Figure 3e shows the measured peak diffraction efficiency spectra for both TE and transverse magnetic (TM) polarizations. The measured data agree well with those of the corresponding simulations (Supplementary Information 5). We find that the TE GMR at 864 nm delivers a 12.8% diffraction efficiency. The slightly larger peak diffraction efficiency compared to the simulation (11.1%) is attributed to a small deviation in the width of the pSi grating elements from the original design. This mode provides an excellent platform to redirect normally incident NIR light from the eyes into the desired direction.

**Fig. 2 | Spectrally selective resonant diffraction mechanism of a GMR metasurface.**

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**Supplementary Information 9**

Radiative decay rate compared to that for the non-over-etched case. Cross-polarized transmission measurements remove the direct, non-resonant transmission channel for the metasurface and clearly show the sharp resonance peaks from the GMRs (Fig. 3c). The measured quality factor ($Q = 540$) is lower than in the simulation ($Q = 1400$), which we attribute to the increased radiative decay rate by fabrication imperfections.

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over a 60° angle, where the ET camera is positioned. The diffraction in the visible spectrum is suppressed to 0.07% on average while maintaining a high degree of zeroth-order transmission (>85%). It is worth noting that the ability to diffract light at long wavelength and let it pass unperturbed at short wavelengths goes against one of the most basic traits of conventional, periodic gratings.

**Optical ET prototype**

As a final step, we demonstrate the possible use of the proposed metasurface in a basic, prototype ET system. Figure 4a shows a front view of the prototype ET glasses where the location of the metasurface is outlined. This front view of the eye is also seen by the camera after a redirection by the metasurface. We develop a basic ray-tracing approach to describe the image formation by the metasurface, for which the details are discussed in Supplementary Information 11. It is used to transform a collection of points in the object space to the horizontal image resolution of the high-Q GMR metasurface limits the range of angles that can effectively couple to the guided mode and thus can be used for imaging. A detailed analysis (Supplementary Information 13) shows that the image resolution is limited by the numerical aperture (NA) of the system and is given as $d = \lambda / 2NA = \lambda / (2n_g z)$, where $\lambda$ and $n_g$ are the wavelength and group index of the relevant guided mode. Plugging in the experimentally obtained values of $\lambda_r$ (equal to 864 nm), $Q$ (540) and $n_g$ (2.04) we find an image resolution of ~40 μm. We chose our imaging optics to closely match this action enables us to track large lateral motions of the pupil and spatially resolve features of the eye, no matter how far the eye is located from the metasurface (Supplementary Information 12).

Possible concerns with imaging through a diffractive order are the achievable image resolution and the impact of image distortion45,46 along the z direction. The high-Q of the GMR metasurface limits the range of angles that can effectively couple to the guided mode and thus can be used for imaging. As shown in Fig. 4d, our experimental investigation of the ET resolution target confirms our ability to easily resolve 0.63-mm-sized horizontal and vertical bars. This image resolution is also sufficient to image the key features of the eye, even at the large rotation angles shown in Fig. 4d. Our experimental investigation of the ET
The presented aspects of non-local metasurfaces also nicely complement the development of non-local, low-contrast, display and nonlinear optics that complement those of conventional, low-Q metasurfaces. Since only the resonant wavelengths are manipulated, the metasurface and allow different, uncoupled functions at different wavelengths. Light at a preselected resonance wavelength can be stored in the high-Q metasurface at the cost of increased rain-bow artifacts. The bandwidth and the polarization of the source should be matched to the GMR resonance (1.6 nm) to increase the efficiency of 53% of the incident planewave redirected into the diffracted channel used for imaging (Supplementary Information 16).

Conclusions
In this work, we have shown how high-Q, non-local metasurfaces can be created that offer independent functions across different wavelength bands. Light at a preselected resonance wavelength can be stored in the high-Q GMR metasurface to notably boost the internal fields $|E|^2 / |E_{inc}|^2 \approx 2,500$ and light–matter interaction before it is released into a desired direction. A judicious choice for the absorbing materials used to create the metasurface building blocks can facilitate effective control over the flow of light through the metasurface and allow different, uncoupled functions at different wavelengths. Since only the resonant wavelengths are manipulated, these structures can conveniently be stacked (Supplementary Information 17). We expect these non-local metasurfaces to open many new functions for optical imaging, sensing, communication, display and nonlinear optics that complement those of conventional, low-Q metasurfaces. The presented aspects of non-local metasurfaces also nicely complement the development of non-local metasurfaces for dynamic wavefront shaping and analogue optical computing.

Online content
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Methods
Fabrication. We deposit Si₃N₄ and pSi films by low pressure chemical vapour deposition (LPCVD). The thickness and the optical constants of the deposited Si₃N₄ and pSi films are characterized by ellipsometry (Woollam, M2000 Spectroscopic Ellipsometer). We make the grating patterns by optical lithography (ASML, PAS 5500/60 I-line Stepper) and reactive ion etching (Oxford, PlasmaPro 80). The capping layer is spin-coated by 4% HSQ (XR-1541-004) and cured at 400 °C for 12 hours.

Characterization. We use a supercontinuum source (NKT Photonics, SuperK EXTREME) as the broadband light illumination for the cross-polarized transmission and the diffraction efficiency measurements. The collected optical signals are analysed using a spectrometer (SpectraPro, Acton 2300i) with a cooled CCD (Princeton Instruments, Pixis 1024). We use a rigorous coupled-wave analysis (RCWA) method for the numerical simulations, which are carried out using free released Matlab codes developed in Z. Zhang's group at Georgia Tech.

Data availability
The data that support the plots within this paper and other findings of this study are available from the corresponding author upon reasonable request.

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Author contributions
J.-H.S. and M.L.B. conceived the research plan. J.-H.S., J.v.d.G. and S.J.K. fabricated the samples and performed all optical measurements. J.-H.S., J.v.d.G. and M.L.B. performed the data analysis and calculations. All authors contributed to writing the manuscript.

Competing interests
J.-H.S. and M.L.B. have a granted US patent on the topic of this paper (JH Song, ML Brongersma—US patent 10,890,772,2021). The other authors declare no competing interests.

Additional information
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