Controlling the sign of chromatic dispersion in diffractive optics with dielectric metasurfaces

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Diffraction gratings disperse light in a rainbow of colors with the opposite order than refractive prisms, a phenomenon known as negative dispersion. While refractive dispersion can be controlled via material refractive index, diffractive dispersion is fundamentally an interference effect dictated by geometry. Here we show that this fundamental property can be altered using dielectric metasurfaces, and we experimentally demonstrate diffractive gratings and focusing mirrors with positive, zero, and hyper-negative dispersion. These optical elements are implemented using a reflective metasurface composed of dielectric nano-posts that provide simultaneous control over phase and its wavelength derivative. In addition, as a first practical application, we demonstrate a focusing mirror that exhibits a five-fold reduction in chromatic dispersion, and thus an almost three-times increase in operation bandwidth compared with a regular diffractive element. This concept challenges the generally accepted dispersive properties of diffractive optical devices and extends their applications and functionalities.

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1. INTRODUCTION

Most optical materials have positive (normal) dispersion, which means that the refractive index decreases at longer wavelengths. As a consequence, blue light is deflected more than red light by dielectric prisms [Fig. 1(a)]. The reason diffraction gratings are said to have negative dispersion is that they disperse light similar to hypothetical refractive prisms made of a material with negative (anomalous) dispersion [Fig. 1(b)]. For diffractive devices, dispersion is not related to material properties, and it refers to the derivative of a certain device parameter with respect to wavelength. For example, the angular dispersion of a grating that deflects normally incident light by a positive angle θ is given by $d\theta/d\lambda = \tan(\theta)/\lambda$ (see [1] and Supplement 1, Section S2). Similarly, the wavelength dependence of the focal length ($f$) of a diffractive lens is given by $df/d\lambda = -f/\lambda$ [1,2]. Here we refer to diffractive devices that follow these fundamental chromatic dispersion relations as “regular.” Achieving new regimes of dispersion control in diffractive optics is important both at the fundamental level and for numerous practical applications. Several distinct regimes can be differentiated as follows. Diffractive devices are dispersionless when the derivative is zero [i.e., $d\theta/d\lambda = 0$, $df/d\lambda = 0$ shown schematically in Fig. 1(c)], have positive dispersion when the derivative has opposite sign compared with a regular diffractive device of the same kind (i.e., $d\theta/d\lambda < 0$, $df/d\lambda > 0$) as shown in Fig. 1(d), and are hyper-dispersive when the derivative has a larger absolute value than a regular device (i.e., $|d\theta/d\lambda| > |\tan(\theta)/\lambda|$, $|df/d\lambda| > |f/\lambda|$), as seen in Fig. 1(e). Here we show that these regimes can be achieved in diffractive devices based on optical metasurfaces.

Metasurfaces have attracted great interest in the recent years [3–12] because they enable precise control of optical wavefronts and are easy to fabricate with conventional microfabrication technology in a flat, thin, and lightweight form factor. Various conventional devices, such as gratings, lenses, holograms, and planar filter arrays [7–9,13–26], as well as novel devices [27,28] have been demonstrated using metasurfaces. These optical elements are composed of large numbers of scatterers, or meta-atoms placed on a two-dimensional lattice to locally shape optical wavefronts. Similar to other diffractive devices, metasurfaces that locally change the propagation direction (e.g., lenses, beam deflectors, holograms) have negative chromatic dispersion [1,2,9,29,30]. This is because most of these devices are divided in Fresnel zones whose boundaries are designed for a specific wavelength [30,31]. This chromatic dispersion is an important limiting factor in many applications, and its control is of great interest. Metasurfaces with zero and positive dispersion would be useful for making achromatic singlet and doublet lenses, and the larger-than-regular dispersion of hyper-dispersive metasurface gratings would enable high resolution spectrometers. We emphasize that the devices with zero chromatic dispersion discussed here are fundamentally different from the multiwavelength metasurface gratings and lenses recently reported [30–40]. Multiwavelength devices have
cept to demonstrate metasurface focusing mirrors with zero dispersion 
varying with respect to frequency ω (ϕ′ = dϕ/dω, which we refer to as chromatic phase dispersion or dispersion for brevity) makes it possible to dramatically alter the fundamental chromatic dispersion of diffractive components. This, in effect, is equivalent to simultaneously controlling the “effective refractive index” and “chromatic dispersion” of the meta-atoms. We have used this concept to demonstrate metasurface focusing mirrors with zero dispersion [41] in near IR. More recently, the same structure as the one used in Ref. [41] (with titanium dioxide replacing α-Si) was used to demonstrate achromatic reflecting mirrors in the visible [42].

2. THEORY

Here we argue that simultaneously controlling the phase imparted by the meta-atoms composing the metasurface (ϕ) and its derivative with respect to frequency ω (ϕ′ = dϕ/dω, which we refer to as chromatic phase dispersion or dispersion for brevity) makes it possible to dramatically alter the fundamental chromatic dispersion of diffractive components. This, in effect, is equivalent to simultaneously controlling the “effective refractive index” and “chromatic dispersion” of the meta-atoms. We have used this concept to demonstrate metasurface focusing mirrors with zero dispersion [41] in near IR. More recently, the same structure as the one used in Ref. [41] (with titanium dioxide replacing α-Si) was used to demonstrate achromatic reflecting mirrors in the visible [42]. Using the concept introduced in [41], here we experimentally show metasurface gratings and focusing mirrors that have positive, zero, and hyper-chromatic dispersions.

We also demonstrate an achromatic focusing mirror with a highly diminished focal length chromatic dispersion, resulting in an almost three-times increase in its operation bandwidth.

First, we consider the case of devices with zero chromatic dispersion. In general for truly frequency independent operation, a device should impart a constant delay for different frequencies (i.e., demonstrate a true time delay behavior), similar to a refractive device made of a non-dispersive material [1]. Therefore, the phase profile will be proportional to the frequency:

\[ \phi(x, y; \omega) = \omega T(x, y), \]  

where \( \omega = 2\pi c/\lambda \) is the angular frequency (\( \lambda \), wavelength; \( c \), speed of light) and \( T(x, y) \) determines the function of the device (for instance, \( T(x, y) = -x \sin \theta_0/\lambda \) for a grating that deflects light by angle \( \theta_0 \); \( T(x, y) = -\sqrt{x^2 + y^2 + f^2}/c \) for a spherical-aberration-free lens with a focal distance \( f \)). Since the phase profile is a linear function of \( \omega \), it can be realized using a meta-surface composed of meta-atoms that control the phase \( \phi(x, y; \omega_0) = T(x, y) \omega_0 \) and its dispersion \( \phi' = d\phi(x, y; \omega)/d\omega = T(x, y) \). The bandwidth of dispersionless operation corresponds to the frequency interval over which the phase locally imposed by the meta-atoms is linear with frequency \( \omega \). For gratings or lenses, a large device size results in a large \( |T(x, y)| \), which means that the meta-atoms should impart a large phase dispersion. Since the phase values at the center wavelength \( \omega_0 = 2\pi c/\lambda_0 \) can be wrapped into the 0–2\( \pi \) interval, the meta-atoms only need to cover a rectangular region in the phase-dispersion plane bounded by \( \phi = 0 \) and 2\( \pi \) lines, and \( \phi' = 0 \) and \( \phi'_{\max} \) lines, where \( \phi'_{\max} \) is the maximum required dispersion that is related to the device size (see Supplement 1, Section S5, and Fig. S2). The required phase-dispersion coverage means that, to implement devices with various phase profiles, for each specific value of the phase, we need various meta-atoms providing that specific phase but with different dispersion values.

Considering the simple case of a flat dispersionless lens (or focusing mirror) with radius \( R \), we can get some intuition to the relations found for phase and dispersion. Dispersionless operation over a certain bandwidth \( \Delta \omega \) means that the device should be able to focus a transform limited pulse with bandwidth \( \Delta \omega \) and carrier frequency \( \omega_0 \) to a single spot located at focal length \( f \) [Fig. 2(a)]. To implement this device, part of the pulse hitting the lens at a distance \( r \) from its center needs to experience a pulse delay (i.e., group delay \( t_g = d\phi/d\omega \)) smaller by \( (\sqrt{r^2 + f^2} - f)/c \) than part of the pulse hitting the lens at its center. This ensures that parts of the pulse hitting the lens at different locations arrive at the focus at the same time. Also, the carrier delay (i.e., phase delay \( t_p = \phi(\omega_0)/\omega_0 \) should...
Fig. 2. Required phase and group delays and simulation results of dispersion-engineered metasurfaces based on hypothetical meta-atoms. (a) Schematics of focusing of a light pulse to the focal distance of a flat lens. The $E$ versus $t$ graphs show schematically the portions of the pulse passing through the center and at a point a distance $r$ away from the lens and when arriving at focus. The portions passing through different parts of the lens should acquire equal group delays and should arrive at the focal point in phase for dispersionless operation. (b) Required values of group delay for grating with various types of chromatic dispersion. The dashed line shows the required phase delay for all devices, which also coincides with the required group delay for the dispersionless gratings. The gratings are $90 \mu$m wide and have a deflection angle of $10$ deg in their center wavelength of $1520$ nm. (c) Required values of group delay for spherical focusing mirrors with various types of chromatic dispersion. The dashed line shows the required phase delay for all devices. The mirrors are $240 \mu$m in diameter and have a focal distance of $650 \mu$m at their center wavelength of $1520$ nm. (d) Simulated deflection angles for gratings with regular, zero, positive, and hyper-dispersions. The gratings are $150 \mu$m wide and have a $10$ deg deflection angle at $1520$ nm. (e) Simulated focal distances for metasurface focusing mirrors with different types of dispersion. The mirrors are $500 \mu$m in diameter and have a focal distance of $850 \mu$m at $1520$ nm. All gratings and focusing mirrors are designed using hypothetical meta-atoms that provide independent control over phase and dispersion (see Supplement 1, Section S1 for details). (f) Intensity in the axial plane for the focusing mirrors with regular negative, (g) zero, (h) positive, and (i) hyper-dispersions plotted at three wavelengths (see Fig. S3 for other wavelengths).

also be adjusted so that all parts of the pulse interfere constructively at the focus. Thus, to implement this phase delay and group delay behavior, the lens needs to be composed of elements, ideally with sub-wavelength size, that can provide the required phase delay and group delay at different locations. For a focusing mirror, these elements can take the form of sub-wavelength one-sided resonators, where the group delay is related to the quality factor $Q$ of the resonator (see Supplement 1, Section S7), and the phase delay depends on the resonance frequency. We note that larger group delays are required for lenses with larger radius, which means that elements with higher quality factors are needed. If the resonators are single mode, the $Q$ imposes an upper bound on the maximum bandwidth $\Delta \omega$ of the pulse that needs to be focused. The operation bandwidth can be expanded by using one-sided resonators with multiple resonances that partially overlap. As we will show later in the paper, these resonators can be implemented using silicon nano-posts backed by a reflective mirror.

To realize metasurface devices with non-zero dispersion of a certain parameter $\xi(\omega)$, phase profiles of the following form are needed:

$$\phi(x, y, \omega) = \omega T(x, y, \xi(\omega)).$$  

(2)

For instance, the parameter $\xi(\omega)$ can be the deflection angle of a diffraction grating $\theta(\omega)$ or the focal length of a diffractive lens $f(\omega)$. As we show in Supplement 1, Section S4, to independently control the parameter $\xi(\omega)$ and its chromatic dispersion $\partial \xi/\partial \omega$ at $\omega = \omega_0$, we need to control the phase dispersion at this frequency in addition to the phase. The required dispersion for a certain parameter value $\xi_0 = \xi(\omega_0)$, and a certain dispersion $\partial \xi/\partial \omega|_{\omega=\omega_0}$, is given by

$$\frac{\partial \phi(x, y; \omega)}{\partial \omega} \bigg|_{\omega=\omega_0} = T(x, y, \xi_0) + \partial \xi/\partial \omega|_{\omega=\omega_0} \frac{\partial T(x, y, \xi)}{\partial \xi} \bigg|_{\xi=\xi_0}.$$

This dispersion relation is valid over a bandwidth where a linear approximation of $\xi(\omega)$ is valid. One can also use Fermat’s principle to get similar results to Eq. (3) for the local phase gradient and its frequency derivative (see Supplement 1, Section S6).

We note that discussing these types of devices in terms of phase $\phi(\omega)$ and phase dispersion $\partial \phi/\partial \omega$, which we mainly use in this paper, is equivalent to using the terminology of phase delay ($T = \phi(\omega_0)/\omega_0$) and group delay ($\tau = \partial \phi/\partial \omega$). The zero dispersion case discussed above corresponds to a case where the phase and group delays are equal. Figures 2(b) and 2(c) show the required phase and group delays for blazed gratings and focusing mirrors with various types of dispersion, demonstrating the equality of phase and group delays in the dispersionless case.
In microwave photonics, the idea of using sets of separate optical cavities for independent control of the phase delay of the optical carrier and group delay of the modulated RF signal has previously been proposed [43] to achieve dispersionless beam steering and resemble a true time delay system over a narrow bandwidth. For all other types of chromatic dispersion, the phase and group delays are drastically different, as shown in Figs. 2(b) and 2(c).

Assuming hypothetical meta-atoms that provide independent control of phase and dispersion up to a dispersion of $-150 \text{ Rad}/\mu\text{m}$ (to adhere to the commonly used convention, we report the dispersion in terms of wavelength) at the center wavelength of 1520 nm, we have designed and simulated four gratings with different chromatic dispersions (see Supplement 1, Section S1 for details). The simulated deflection angles as functions of wavelength are plotted in Fig. 2(d). All gratings are 150 µm wide and have a deflection angle of 10 deg at their center wavelength of 1520 nm. The positive dispersion grating exhibits a dispersion equal in absolute value to the negative dispersion of a regular grating with the same deflection angle but with an opposite sign. The hyper-dispersive design is three times more dispersive than the regular grating, and the dispersionless beam deflector shows almost no change in its deflection angle. Besides gratings, we have also designed focusing mirrors exhibiting regular, zero, positive, and hyper-dispersions. The focusing mirrors have a diameter of 500 µm and a focal distance of 850 µm at 1520 nm. Hypothetical meta-atoms with a maximum dispersion of $-200 \text{ Rad}/\mu\text{m}$ are required to implement these focusing mirror designs. The simulated focal distances of the four designs are plotted in Fig. 2(e). The axial plane intensity distributions at three wavelengths are plotted in Figs. 2(f)–2(i) (for intensity plots at other wavelengths, see Fig. S3). To relate to our previous discussion of dispersionless focusing mirrors depicted in Fig. 2(a), a focusing mirror with a diameter of 500 µm and a focal distance of 850 µm would require meta-atoms with group delay of $\sim 24\lambda_0/c$ (corresponding to a $\sim 36.5\mu\text{m}$ propagation in free space, or a $\sim 10.7\mu\text{m}$ propagation in bulk silicon), with $\lambda_0 = 1520$ nm. To implement this device, we used hypothetical meta-atoms with maximum dispersion of $\sim 100\text{ Rad}/\mu\text{m}$, which corresponds to a group delay of $\sim 24\lambda_0/c$. The hypothetical meta-atoms exhibit this almost linear dispersion over the operation bandwidth of 1450 to 1590 nm.

3. METASURFACE DESIGN

An example of meta-atoms capable of providing $0\text{–}2\pi$ phase coverage and different dispersions is shown in Fig. 3(a). The meta-atoms, composed of a square cross-section amorphous silicon ($\alpha$-Si) nano-post on a low refractive index silicon dioxide ($\text{SiO}_2$) spacer layer on an aluminum reflector, play the role of the multi-mode one-sided resonators mentioned in Section 2 [Fig. 2(a)]. They are located on a periodic square lattice [Fig. 3(a), middle]. The simulated dispersion versus phase plot for the meta-atoms at the wavelength of $\lambda_0 = 1520$ nm is depicted in Fig. 3(b) and shows a partial coverage up to the dispersion value of $\sim -100 \text{ Rad}/\mu\text{m}$. The nano-posts exhibit several resonances, which enable high dispersion values over the 1450 nm to 1590 nm wavelength range. The meta-atoms are 725 nm tall, the $\text{SiO}_2$ layer is 325 nm thick, the lattice constant is 740 nm, and the nano-post side length is varied from 74 to 666 nm at 1.5 nm steps. Simulated reflection amplitude and phase for the periodic lattice are plotted in Figs. 3(c) and 3(d), respectively.

The reflection amplitude over the bandwidth of interest is close to 1 for all nano-post side lengths. The operation of the nano-post meta-atoms is best intuitively understood as truncated multi-mode waveguides with many resonances in the bandwidth of interest [28,44]. By going through the nano-post twice, light can obtain larger phase shifts compared with the transmissive operation mode of the metasurface (i.e., without the metallic reflector). The metallic reflector keeps the reflection amplitude high for all sizes, which makes the use of high quality factor resonances possible. As discussed in Section 2, high quality factor resonances are necessary for achieving large dispersion values, because, as we have shown in Supplement 1, Section S7, dispersion is given by $\phi' \approx -Q/\lambda_0$, where $Q$ is the quality factor of the resonance.

Using the dispersion-phase parameters provided by this metasurface, we designed four gratings operating in various dispersion regimes. The gratings are $\sim 90 \mu\text{m}$ wide and have a 10 deg deflection angle at 1520 nm. They are designed to operate in the 1450–1590 nm wavelength range and have regular negative.
zero, positive, and hyper (3-times-larger negative) dispersion. Since the phase of the meta-atoms does not follow a linear frequency dependence over this wavelength interval [Fig. 3(d), top right], we calculate the desired phase profile of the devices at 8 wavelengths in the range (1450–1590 nm at 20 nm steps) and form an 8 x 1 complex reflection coefficient vector at each point on the metasurface. Using Figs. 3(c) and 3(d), a similar complex reflection coefficient vector is calculated for each meta-atom. Then, at each lattice site of the metasurface, we place a meta-atom whose reflection vector has the shortest weighted Euclidean distance to the desired reflection vector at that site. The weights allow for emphasizing different parts of the operation bandwidth and can be chosen based on the optical spectrum of interest or other considerations. Here, we used an inverted Gaussian weight \( \exp((\lambda - \lambda_0)^2 / 2\sigma^2) \), \( \sigma = 300 \text{ nm} \), which values wavelengths farther away from the center wavelength of \( \lambda_0 = 1520 \text{ nm} \). The same design method is used for the other devices discussed in the paper. The designed devices were fabricated using standard semiconductor fabrication techniques as described in Supplement 1, Section S1. Figures 3(e) and 3(f) show scanning electron micrographs of the nano-posts, and some of the devices fabricated using the proposed reflective meta-atoms. Figure S5 shows the chosen post side lengths and the required as well as the achieved phase and group delays for the gratings with different dispersions. Required phases and the values provided by the chosen nano-posts are plotted at three wavelengths for each grating in Fig. S6.

4. EXPERIMENTAL RESULTS

Figures 4(a) and 4(b) show the simulated and measured deflection angles for gratings, respectively. The measured values are calculated by finding the center of mass of the deflected beam 3 mm away from the grating surface (see Supplement 1, Section S1, and Fig. S8 for more details). As expected, the zero dispersion grating shows an apochromatic behavior resulting in a reduced dispersion, the positive grating shows positive dispersion in the ~1490–1550 nm bandwidth, and the hyper-dispersive one shows an enhanced dispersion in the measurement bandwidth. This can also be viewed from the grating momentum point of view: a regular grating has a constant momentum set by its period, resulting in a constant transverse wave-vector. In contrast, the momentum of the hyper-dispersive grating increases with wavelength, while that of the zero and positive gratings decreases with it. This means that the effective period of the non-regular gratings changes with wavelength, resulting in the desired chromatic dispersion. Figures 4(c)–4(h) show good agreement between simulated intensities of these gratings versus wavelength and transverse wave-vector (see Supplement 1, Section S1 for details) and the measured beam deflection (black stars). The change in the grating pitch with wavelength is more clear in Fig. S6, where the required and achieved phases are plotted for three wavelengths. The green line is the theoretical expectation of the maximum intensity trajectory. Measured deflection efficiencies of the gratings, defined as the power deflected by the gratings to the desired order, divided by the power reflected from a plain aluminum reflector (see Supplement 1, Section S1, and Fig. S8 for more details), are plotted in Figs. 4(c) and 4(d) for TE and TM illuminations, respectively. A similar difference in the efficiency of the gratings for TE and TM illuminations has also been observed in previous works [16,28].

As another example for diffractive devices with controlled chromatic dispersion, four spherical-aberration-free focusing mirrors with different chromatic dispersions were designed, fabricated, and measured using the same reflective dielectric meta-atoms. The mirrors are 240 μm in diameter and are designed to have a focal distance of 650 μm at 1520 nm. Figure S7 shows the chosen post side lengths and the required as well as the achieved phase and group delays for the focusing mirrors with different dispersions. Figures 5(a) and 5(b) show simulated and measured focal distances for the four focusing mirrors (see Figs. S9, S10, and S11 for detailed simulation and measurement results). The positive dispersion mirror is designed with dispersion twice as large as a regular mirror with the same focal distance, and the hyper-dispersive mirror has a negative dispersion 3 1/2 times larger than...
a regular one. The zero dispersion mirror shows a significantly reduced dispersion, while the hyper-dispersive one shows a highly enhanced dispersion. The positive mirror shows the expected dispersion in the ∼1470 to 1560 nm range.

As an application of diffractive devices with dispersion control, we demonstrate a spherical-aberration-free focusing mirror with increased operation bandwidth. For brevity, we call this device dispersionless mirror. Since the absolute focal distance change is proportional to the focal distance itself, a relatively long focal distance is helpful for unambiguously observing the change in the device dispersion. Also, a higher NA value is preferred because it results in a shorter depth of focus, thus making the measurements easier. Having these considerations in mind, we have chosen a diameter of 500 μm and a focal distance of 850 μm (NA ≈ 0.28) for the mirror, requiring a maximum dispersion of $\phi_{\text{max}} \approx -98 \text{ Rad}/\mu\text{m}$, which is achievable with the proposed reflective meta-atoms. We designed two dispersionless mirrors with two $\sigma$ values of 300 and 50 nm. For comparison, we also designed a regular metasurface mirror for operation at $\lambda_0 = 1520$ nm and with the same diameter and focal distance as the dispersionless mirrors. The simulated focal distance deviations (from the designed 850 μm) for the regular and dispersionless ($\sigma = 300$ nm) mirrors are plotted in Fig. 5(c), showing a considerable reduction in chromatic dispersion for the dispersionless mirror. Detailed simulation results for these mirrors are plotted in Fig. S12.

Figures 5(d)–5(g) summarize the measurement results for the dispersionless and regular mirrors (see Supplement 1, Section S1, and Fig. S8 for measurement details and setup). As Figs. 5(d) and 5(g) show, the focal distance of the regular mirror changes almost

![Simulation and measurement results for mirrors with different dispersion regimes.](image-url)
linearly with wavelength. The dispersionless mirror, however, shows a highly diminished chromatic dispersion. Besides, as seen from the focal plane intensity measurements, while the dispersionless mirrors are in focus in the 850 μm plane throughout the measured bandwidth, the regular mirror is in focus only from 1500 to 1550 nm (see Figs. S13 and S14 for complete measurement results, and the Strehl ratios). Focusing efficiencies, defined as the ratio of the optical power focused by the mirrors to the power incident on them, were measured at different wavelengths for the regular and dispersionless mirrors (see Supplement 1, Section S1 for details). The measured efficiencies were normalized to the efficiency of the regular metasurface mirror at its center wavelength of 1520 nm (which is estimated to be ~80%-90% based on Fig. 3, measured grating efficiencies, and our previous works [16]). The normalized efficiency of the dispersionless mirror is between 50% and 60% in the whole wavelength range and shows no significant reduction in contrast to the regular metasurface mirror.

5. DISCUSSION AND CONCLUSION

The reduction in efficiency compared with a mirror designed only for the center wavelength (i.e., the regular mirror) is caused by two main factors. First, the required region of the phase-dispersion plane is not completely covered by the reflective nanopost meta-atoms. Second, the meta-atom phase does not change linearly with respect to frequency in the relatively large bandwidth of 140 nm, as would be ideal for a dispersionless metasurface. Both of these factors result in deviation of the phase profiles of the demonstrated dispersionless mirrors from the ideal ones. Furthermore, dispersionless metasurfaces use meta-atoms supporting resonances with high quality factors, thus leading to higher sensitivity of these devices to fabrication errors compared with the regular metasurfaces.

Equation (3) is basically a Taylor expansion of Eq. (2) kept to the first order. As a result, this equation is accurate only over the range of linearity of the phase given in Eq. (2). To increase the validity bandwidth, one can generalize the method to keep higher order terms of the series. Another method to address this issue is the Euclidean distance minimization method that was used in the design process of the devices presented here.

In conclusion, we demonstrated that independent control over phase and dispersion of meta-atoms can be used to engineer the chromatic dispersion of diffractive metasurface devices over continuous wavelength regions. This is in effect similar to controlling the “material dispersion” of meta-atoms to compensate for, overcompensate for, or increase the structural dispersion of diffractive devices. In addition, we developed a reflective dielectric metasurface platform that provides this independent control. Using this platform, we experimentally demonstrated gratings and focusing mirrors exhibiting positive, negative, zero, and enhanced dispersions. We also corrected the chromatic aberrations of a focusing mirror resulting in a ~3 times bandwidth increase (based on an Strehl ratio >0.6, see Fig. S14). In addition, the introduced concept of metasurface design based on dispersion-phase parameters of the meta-atoms is general and can also be used for developing transmissive dispersion-engineered metasurface devices.

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See Supplement 1 for supporting content.

REFERENCES

1. M. Born and E. Wolf, Principles of Optics: Electromagnetic Theory of Propagation, Interference and Diffraction of Light (Cambridge University, 1999).
2. D. C. O’Shea, T. J. Sulecki, A. D. Kathman, and D. W. Prather, Diffractive Optics: Design, Fabrication, and Test (SPIE, 2004).
3. A. V. Kildishev, A. Boltasseva, and V. M. Shalaev, “Planar photonics with metasurfaces,” Science 339, 1232009 (2013).
4. N. Yu and F. Capasso, “Flat optics with designer metasurfaces,” Nat. Mater. 13, 139–150 (2014).
5. A. F. Koenderink, A. Alú, and A. Polman, “Nanophotonics: shrinking light-based technology,” Science 348, 516–521 (2015).
6. S. Jahani and Z. Jacob, “All-dielectric metamaterials,” Nat. Nanotechnol. 11, 23–36 (2016).
7. P. Lalanne, S. Astilean, P. Chavel, E. Cambril, and H. Launois, “Blazed binary subwavelength gratings with efficiencies larger than those of conventional échelette gratings,” Opt. Lett. 23, 1081–1083 (1998).
8. P. Lalanne, S. Astilean, P. Chavel, E. Cambril, and H. Launois, “Design and fabrication of blazed binary diffractive elements with sampling periods smaller than the structural cutoff,” J. Opt. Soc. Am. A 16, 1143–1156 (1999).
9. D. Fattal, J. Li, Z. Peng, M. Fiorentino, and R. G. Beausoleil, “Flat dielectric grating reflectors with focusing abilities,” Nat. Photonics 4, 466–470 (2010).
10. X. Yin, Z. Ye, J. Rho, Y. Wang, and X. Zhang, “Photic spin hall effect at metasurfaces,” Science 339, 1405–1407 (2013).
11. J. Lee, M. Tymchenko, C. Arygropoulos, P.-Y. Chen, F. Lu, F. Demmerle, G. Boehm, M.-C. Amann, A. Alu, and M. A. Belkin, “ Giant nonlinear response from plasmonic metasurfaces coupled to intersubband transitions,” Nature 511, 65–69 (2014).
12. A. Silva, F. Monticone, G. Castaldi, V. Galdi, A. Alù, and N. Engheta, “Performing mathematical operations with metamaterials,” Science 343, 160–163 (2014).
13. X. Ni, S. Ishii, A. V. Kildishev, and V. M. Shalaev, “Ultra-thin, planar, babinet-inverted plasmonic metamolecules,” Light: Sci. Appl. 2, e72 (2013).
14. S. Vo, D. Fattal, W. V. Sorin, P. Zhen, T. Tho, M. Fiorentino, and R. G. Beausoleil, “Sub-wavelength grating lenses with a twist,” IEEE Photon. Technol. Lett. 26, 1375–1378 (2014).
15. D. Lin, P. Fan, E. Hasman, and M. L. Brongersma, “Dielectric gradient metasurface optical elements,” Science 345, 298–302 (2014).
16. A. Arbabi, Y. Horie, A. J. Ball, M. Bagheri, and A. Faraon, “Subwavelength-thick lenses with high numerical apertures and large efficiency based on high-contrast transmittarys,” Nat. Commun. 6, 7069 (2015).
17. Y. F. Yu, A. Y. Zhu, R. Paniagua-Dominguez, Y. H. Fu, B. Luk’yanchuk, and A. I. Kuznetsov, “High-transmission dielectric metasurface with 2π phase control at visible wavelengths,” Laser Photonics Rev. 9, 412–418 (2015).
18. A. Arbabi, R. M. Briggs, Y. Horie, M. Bagheri, and A. Faraon, “Efficient dielectric metasurface collimating lenses for mid-infrared quantum cascade lasers,” Opt. Express 23, 33310–33317 (2015).
19. M. Decker, I. Staude, M. Falkner, J. Dominguez, D. N. Neshev, I. Brener, T. Pertsch, and Y. S. Kivshar, “High-efficiency dielectric Huygens’ surfaces,” Adv. Opt. Mater. 3, 813–820 (2015).

20. Q. Wang, E. T. F. Rogers, B. Gholipour, C.-M. Wang, G. Yuan, J. Teng, and N. I. Zheludev, “Optically reconfigurable metasurfaces and photonic devices based on phase change materials,” Nat. Photonics 10, 60–65 (2016).

21. S. M. Kamali, E. Arbabi, A. Arbabi, Y. Horie, and A. Faraon, “Highly tunable elastic dielectric metasurface lenses,” Laser Photon. Rev. 10, 1062 (2016).

22. Y. Horie, A. Arbabi, E. Arbabi, S. M. Kamali, Y. Horie, S. Han, and A. Faraon, “Miniature optical planar camera based on a wide-angle metasurface doublet corrected for monochromatic aberrations,” Nat. Commun. 7, 13682 (2016).

23. A. Arbabi, E. Arbabi, S. M. Kamali, Y. Horie, S. Han, and A. Faraon, “Miniature optical planar camera based on a wide-angle metasurface doublet corrected for monochromatic aberrations,” Nat. Commun. 7, 13682 (2016).

24. M. Khorasaninejad, W. T. Chen, R. C. Devlin, J. Oh, A. Y. Zhu, and F. Capasso, “Metamirrors at visible wavelengths: diffraction-limited focusing and subwavelength resolution imaging,” Science 352, 1190–1194 (2016).

25. Y. Horie, A. Arbabi, S. Han, and A. Faraon, “High resolution on-chip optical filter array based on double subwavelength grating reflectors,” Opt. Express 23, 29848–29854 (2015).

26. Y. Horie, A. Arbabi, E. Arbabi, S. M. Kamali, and A. Faraon, “Wide-bandwidth and high resolution planar filter array based on DBR-metasurface–DBR structures,” Opt. Express 24, 11677–11682 (2016).

27. A. Arbabi, Y. Horie, M. Bagheri, and A. Faraon, “Dielectric metasurfaces for complete control of phase and polarization with subwavelength spatial resolution and high transmission,” Nat. Nanotechnol. 10, 937–943 (2015).

28. S. M. Kamali, A. Arbabi, E. Arbabi, Y. Horie, and A. Faraon, “Decoupling optical function and geometrical form using conformal flexible dielectric metasurfaces,” Nat. Commun. 7, 11618 (2016).

29. C. Sauvan, P. Lalanne, and M.-S. L. Lee, “Broadband blazed with artificial dielectrics,” Opt. Lett. 29, 1593–1595 (2004).

30. E. Arbabi, A. Arbabi, S. M. Kamali, Y. Horie, and A. Faraon, “Multimodal wavelength polarization-insensitive lenses based on dielectric metasurfaces with meta-molecules,” Optica 3, 628–633 (2016).

31. D. Faklis and G. M. Morris, “Spectral properties of multioriented diffractive lenses,” Appl. Opt. 34, 2462–2468 (1995).

32. O. Eisenbach, O. Avayu, R. Ditcovski, and T. Ellenbogen, “Metasurfaces based dual wavelength diffractive lenses,” Opt. Express 23, 3928–3936 (2015).

33. F. Aieta, M. A. Kats, P. Genevet, and F. Capasso, “Multiwavelength achromatic metasurfaces by dispersive phase compensation,” Science 347, 1342–1345 (2015).

34. M. Khorasaninejad, F. Aieta, P. Kanhaiya, M. A. Kats, P. Genevet, D. Rousso, and F. Capasso, “Achromatic metasurface lens at telecommunication wavelengths,” Nano Lett. 15, 5358–5362 (2015).

35. B. Wang, F. Dong, Q.-T. Li, D. Yang, C. Sun, J. Chen, Z. Song, L. Xu, W. Chu, Y.-F. Xiao, Q. Gong, and Y. Li, “Visible-frequency dielectric metasurfaces for multicycleachromatic and highly dispersive holograms,” Nano Lett. 16, 5235–5240 (2016).

36. E. Arbabi, A. Arbabi, S. M. Kamali, Y. Horie, and A. Faraon, “High efficiency double-wavelength dielectric metasurface lenses with dichroic birefringent meta-atoms,” Opt. Express 24, 18468–18477 (2016).

37. W. Zhao, B. Liu, H. Jiang, J. Song, Y. Pei, and Y. Jiang, “Full-color hologram using spatial multiplexing of dielectric metasurface,” Opt. Lett. 41, 147–150 (2016).

38. Z.-L. Deng, S. Zhang, and G. P. Wang, “Wide-angled off-axis achromatic metasurfaces for visible light,” Opt. Express 24, 23118–23128 (2016).

39. E. Arbabi, A. Arbabi, S. M. Kamali, Y. Horie, and A. Faraon, “Multimodal wavelength metasurfaces through spatial multiplexing,” Sci. Rep. 6, 32803 (2016).

40. D. Lin, A. L. Holsteen, E. Maguid, G. Wetzstein, P. G. Kik, E. Hasman, and M. L. Brongersma, “Photonic multitasking interleaved Si nanoantenna phased array,” Nano Lett. 16, 7671–7676 (2016).

41. E. Arbabi, A. Arbabi, S. M. Kamali, Y. Horie, and A. Faraon, “Dispersionless metasurfaces using dispersive meta-atoms,” in Conference on Lasers and Electro-Optics (CLEO) (2016), pp. 1–2.

42. M. Khorasaninejad, Z. Shi, Y. A. Zhu, W. T. Chen, V. Sanjeev, A. Zaidi, and M. L. Brongersma, “Photic photonic multitasking interleaved Si nanoantenna phased array,” Nano Lett. 16, 7671–7676 (2016).

43. P. Lalanne, “Metasurfaces,” Optica 3, 628–633 (2016).

44. P. Lalanne, “Metasurfaces,” Optica 3, 628–633 (2016).