Spatially-modulated axilenses for infrared multi-band imaging and spectroscopy

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We design and characterize spatially-modulated compact axilens devices that flexibly combine efficient point focusing and grating selectivity and are compatible with scalable top-down fabrication based on 4-level phase mask configurations. Moreover, we establish that these optical structures can simultaneously focus incident radiation of selected wavelengths at predefined locations with larger focal depths compared to traditional Fresnel lenses. In addition, the proposed devices are polarization insensitive and maintain a large focusing efficiency over a broad spectral band. Specifically, we select and characterize modulated axilens configurations designed for long-wavelength infrared (LWIR) operation in the 6 – 12 \( \mu \text{m} \) wavelength range and in the 4 – 6 \( \mu \text{m} \) mid-wavelength infrared (MWIR) range. These devices are ideally suited for monolithic integration atop the substrate layers of infrared focal plane arrays (IR-FPAs) for use in multi-band LWIR photo-detection. We systematically study their focusing efficiency, spectral response, and cross talk ratio, and we demonstrate linear control of multi-wavelength focusing on a single plane. Our design method leverages Rayleigh-Sommerfeld (RS) diffraction theory that is validated numerically using the Finite Element Method (FEM). Finally, we demonstrate the application of spatially modulated axilenses to the realization of compact, single-lens spectrometer. By optimizing our devices, we achieve a minimum distinguishable wavelength interval of \( \Delta \lambda = 242 \text{nm} \) at \( \lambda_0 = 8 \mu \text{m} \). This provides an opportunity of creating ultra-compact (100 \( \mu \text{m} \)) spectrometer in the LWIR with a minimum distinguishable wavelength 200nm. The proposed devices add fundamental spectroscopic capabilities to compact imaging devices for a number of applications ranging from spectral sorting to LWIR and MWIR imaging and detection.

Infrared focal plane arrays (IR-FPAs) are at the heart of present IR imaging and sensing technology. In an effort to increase the sensitivity and suppress crosstalk in IR photodetectors, microlenses have been proposed to work as optical concentrators in combination with IR-FPAs. Consequently, due to their compact size and optically flat profiles, microlenses based on metasurfaces (i.e. metalenses) have received significant attention. However, traditional metalens designs achieve their desired phase profiles either through engineered resonance behavior, which introduces unavoidable resonance-induced losses reducing the overall focusing efficiency, or through geometrical phase modulation that requires polarized radiation. Moreover, the controlled fabrication of advanced metasurfaces requires precise sub-wavelength accuracy that adds to cost and device complexity. Finally, state-of-the-art achromatic metalens-based devices and super-oscillation lenses further increase fabrication demands.

In this letter, we propose an alternative microlens design approach based on the spatial modulation of compact and phase modulated axilenses that can be monolithically integrated atop the substrate of IR-FPAs. These devices efficiently combine the phase modulation of an axilens—a diffractive lens with a radially-dependent focal length allowing for a large and controllable depth of focusing—with the spatial dispersion behavior of a grating structure. Furthermore, we discretize the phase profile to create 4-level diffractive optical elements (DOEs) that are compatible with top-down fabrication such as photolithography. Notably, the proposed approach is polarization insensitive and can be extended to any desired spectral range. Consequently, this technology enables the engineering of compact, on-chip diffractive focusing grating devices for a variety of multi-band on-chip spectroscopy and imaging applications.

In what follows, we study the wave diffraction problem of different 4-level modulated axilens DOEs using the rigorous Rayleigh-Sommerfeld (RS) first integral formulation. First, we demonstrate the achromatic behavior of axilenses that are capable of focusing radiation of different wavelengths on the same plane. Secondly, we consider one-dimensional (1D) and two-dimensional (2D) periodic as well as chirp phase modulations within a 4-level mask geometry with a maximum diameter \( D = 100 \mu \text{m} \), which is a size comparable with typical metalens approaches. Thirdly, we show that engineered phase-modulated axilenses can tightly focus radiation of multiple wavelengths on the same plane at different predefined locations and we characterize their spectroscopic behavior. The angular dispersion characteristics of the devices are established and validated using the Finite Element Method (FEM).

Before introducing our novel designs, we review the basic operation of axilenses, which are characterized by...
a phase profile given by:

$$\phi(r)|_{2\pi} = \frac{-2\pi}{\lambda} \left[ \sqrt{\left(f_0 + \frac{r\Delta f}{R}\right)^2 + r^2} - \left(f_0 + \frac{r\Delta f}{R}\right) \right]$$

where \(r = \sqrt{x^2 + y^2}\), \(f_0\) is the focal length, and \(\Delta f\) is the focal depth. The \(2\pi\) subscript indicates that the phase is reduced by modulo \(2\pi\). Instead of focusing radiation at a single point like a traditional Fresnel lens, the focal depth of an axilens can be controlled by changing \(\Delta f\).

With\(\phi\) being the phase to be modulated at a single point, we can achieve a desired focal depth \(\Delta f\) and a focal length \(f\) with
\[
\phi(x, y) = \frac{2\pi}{\lambda} \left[ \sqrt{(f_0 + \frac{r\Delta f}{R})^2 + r^2} - (f_0 + \frac{r\Delta f}{R}) \right]
\]

where \(r = \sqrt{x^2 + y^2}\), \(f_0\) is the focal length, and \(\Delta f\) is the focal depth. The \(2\pi\) subscript indicates that the phase is reduced by modulo \(2\pi\). Instead of focusing radiation at a single point like a traditional Fresnel lens, the focal depth of an axilens can be controlled by changing \(\Delta f\).

**FIG. 1.** (a) The focusing side view of a standard Fresnel lens with focal length \(f_0 = 300\mu m\). (b) The focusing side view of an axilens with \(f_0 = 250\mu m\) and \(\Delta f = 120\mu m\). (c) displays the field amplitude cut along \(z = 300\mu m\) in (a, b). (d) shows the focusing efficiency of an axilens compared to a Fresnel lens with respect to \(\Delta f\) with \(f_0 = 300\mu m\) for both cases and the incident wavelength set to \(\lambda = 9\mu m\) in the substrate.

We consider devices located on the \(xy\) plane excited by a normally incident plane wave giving rise to a diffracted field that propagates along the \(+z\) direction. In Fig. 1 (a) and (b), we compare the field amplitude side view (\(xz\) plane) for a standard Fresnel lens and an axilens computed according to the RS with the following expressions [21]:

$$U_2(x, y) = U_1(x', y') \ast h(x', y')$$

$$h(x', y') = \frac{1}{2\pi r} \frac{z}{r} e^{i(kr)}$$

where \(\ast\) denotes 2D space convolution, \(U_1, U_2\) are the transverse field distributions in the object and image planes with coordinates \((x, y)\) and \((x', y')\), respectively. Moreover, \(k\) is the incident wave number and \(r = \sqrt{(x-x')^2 + (y-y')^2 + z^2}\), where \(z\) is the distance between object and image plane.

Both the Fresnel lens and the axilens are designed to focus radiation of wavelength \(\lambda = 9\mu m\) at \(z = 300\mu m\) with the wavelength scaled to account for a substrate with refractive index \(n = 3.3\) as typically used in IR-FPAs platforms. In Fig. 1 (c) we show a transverse cut along the \(x\)-axis of the field amplitude at the detection plane \((z = 300\mu m)\), highlighted by the dashed lines in panels (a) and (b). Our results show that although the axilens features a broader focal spot in the transverse plane, it can focus incident radiation over a significantly longer longitudinal range (along the \(z\)-axis). In addition, a desired focal depth \(\Delta f\) can be obtained using an axilens regardless of the wavelength of the incident radiation [22]. Although different wavelengths are focused at different positions along the \(z\)-axis, the larger focal depth of axilenses compared to traditional lenses guarantees a substantial overlap of the focused intensities of different wavelengths on the same plane, thus establishing an achromatic focal plane. This important feature of the axilenses will be explored later in the paper to demonstrate single-lens spectrometers based on phase-modulated axilenses. However, in practical applications it is important to quantify the focusing efficiency \(\eta\) of such devices and compare with traditional diffractive lenses. This is done by defining \(\eta\) as the ratio, with respect to the total incident power, of the power confined within a circular region with a radius that is three times larger than the full-width-at-half-maximum (FWHM) of the focal spot. For a better comparison, we consider both axilens and Fresnel lens designs with \(f_0 = 300\mu m\), and we evaluate \(\eta\) as a function of \(\Delta f\). In Fig. 1 (d) we display the results of our analysis. Specifically, we compare devices with continuous phase distribution and with 4-level discretized phase [23]. The analysis reveals that a 4-level discretized axilens device still maintains a large \(\eta\) (> 80%) over a broad \(\Delta f\) range.

In Fig. 2, we directly demonstrate the distinctive achromatic focusing behavior of the axilens compared to traditional Fresnel lens across the LWIR spectrum. In particular, we focus at wavelengths \(\lambda = 6\mu m, 9\mu m,\) and \(12\mu m\), and compute the 2D intensity profiles at the focal plane for Fresnel lens (Figs. 2 (a)-(c)) and axilens (Figs. 2 (g)-(i)). The corresponding 1D horizontal cuts along the center are shown in Figs. 2 (d)-(f) for the Fresnel lens and Figs. 2 (j)-(l) for the axilens. The achromatic behavior of the axilens across the LWIR spectrum is clearly manifested by the almost constant width of the focusing point-spread function (along the transverse \(x\)-axis) shown in Figs. 2 (j)-(l).

We now consider the effects of periodic and chirped phase modulations in 4-level discretized axilens devices. Phase-modulated axilenses are examples of multifunctional DOEs, which are used for beam shaping [21, 22]. In Fig. 3 (a), (c), we show the phase profiles of modulated axilens summed (modulo \(2\pi\)) with a 1D periodic function and a 45° chirped function, respectively. The phase profile parameters of the axilens were chosen as follows: \(f_0 = 250\mu m, \Delta f = 120\mu m, \lambda = 9\mu m/n, n = 3.3\). These parameters can be flexibly changed to address other photodetector spectral ranges and/or dielectric substrate thickness and refractive indices. The
FIG. 2. (a-c) show the normalized 2D intensity profiles of a Fresnel lens with \( f_0 = 300\mu m \) at the focal plane \( z = 300\mu m \) with incident wavelengths \( \lambda = 6\mu m, 9\mu m, 12\mu m \), respectively. (d-f) show the corresponding 1D intensity cut profiles corresponding to panels (a-c). Panels (g-f) show the normalized 2D intensity profiles of Fresnel lens with \( f_0 = 250\mu m \). \( \Delta f = 120\mu m \) at the focal plane \( z = 300\mu m \) with incident wavelengths \( \lambda = 6\mu m, 9\mu m, 12\mu m \), respectively. Panels (j-l) show the 1D intensity cut profiles corresponding to panels (g-f).

Phase of the axilens was modulated by adding a periodic phase with period equal to \( p = 15\mu m \) as well as a chirping function with the position dependent phase profile \( 2\pi(x' + y')/p, p = 15\mu m \). We also show the phase profile of 2D periodically modulated axilens in Fig. 3 (e) with periodicity \( p = 15\mu m \). Figure 3 (g) depicts an alternative implementation of the periodically modulated axilens where we used two radially interlocked periodic functions with periodicity \( p = 10\mu m \) along vertical and horizontal directions within two separate concentric regions of the device (annular crossed modulations). The ratio between the radii of the outer and inner region of the device is 1.455. All the modulated axilenses have a diameter \( D = 100\mu m \), which is comparable to the typical size of alternative devices based on metasurfaces \( [4,17] \). Figure 3 (b) shows the horizontal \( xz \)-plane side view of the simulated diffraction field of the periodically modulated axilens corresponding to Fig. 3(a). We find that the incoming radiation is split into two focused beam components. This is due to the spatial dispersion of the ±1 diffraction orders associated to the periodic phase modulation while each beam is focused with a larger depth of focusing due to the characteristic focusing phase profile of the axilens. Therefore, the periodically modulated axilens is capable of simultaneously splitting and focusing different IR bands at different locations along the transverse \( x \)-axis. This effect can be designed to match the different pixel locations in a realistic IR-FPAs implementation. We further show in Fig 3(d) the three-dimensional (3D) distribution along a plane cut at 45\(^\circ\) of the diffracted field that is focused by the device with phase modulation shown in Fig 3(c). In this case, radiation of different wavelengths is focused at different points along the diagonal directions due to the nature of the modulated axilens.

FIG. 3. Panels (a-g) show the 4-level discretized phase profiles for 1D periodically modulated axilens, a 45\(^\circ\) chirped axilens, a 2D periodically modulated axilens, and a cross modulated axilens, respectively. Panel (b) shows the simulated diffraction field side view of the 1D modulated axilens. Panels (d-f) show the diffraction field 3D view for the phase profile in (c) and (e), respectively. Panel (h) shows the simulated field amplitude distribution at the focal plane \( z = 300\mu m \).
of 2D phase modulation function. Finally, in Fig. 3 (h) we show the diffracted field amplitude distribution across the transverse $xy$ plane for the device with phase shown in Fig. 3 (g). In this case, the radiation is diffracted into four focal spots along $y$- and $x$-axis corresponding to the inner region and the outer region of the device, respectively. All the device are designed to focus at the same plane $z = 300\mu m$.

![Image](59x536 to 179x626)

FIG. 4. Panel (a) shows the FEM meshing of the 1D grating modulated axilens atop the GaAs substrate. Panel (b) shows the spectral response (SR) of the axilens shown in (a) from the Rayleigh-Sommerfeld integral (RS) calculation and from the finite element method (FEM). Panels (c-d) show the diffraction side view of the field amplitude from RS and FEM at the same incident wavelength $\lambda_0 = 9\mu m$ for the geometry illustrated in panel (a), respectively.

The results discussed so far have been obtained using the efficient RS scalar optics approach valid beyond the paraxial approximation. However, when feature sizes are of the order of the wavelength the scalar optics approximation may lead to quantitatively inaccurate conclusions and full-vector diffraction should be used instead \[26, 27\]. In order to demonstrate the robustness of the proposed concepts we perform a full-vector validation using numerical FEM simulations on a 4-level periodically modulated axilens device on dielectric substrate with the following parameters: $f_0 = 20\mu m$, $\Delta f = 10\mu m$, and $p = 20\mu m$. The diameter of the modulated axilens is $d = 50\mu m$. Figure 4 (a) shows the actual three-dimensional (3D) FEM mesh utilized in COMSOL \[28\] to address this problem. We used a minimum element size of $400nm$ and a maximum element size of $1.5\mu m$. A typical simulation model has about 22,303,530 degrees of freedom. The IR radiation is incident normally on the device and then propagates through a transparent dielectric substrate with index $n = 3.3$. The FEM simulations were performed on a 786Gb RAM computing cluster with 40 cores and required approximately 15 hours to achieve convergence per single wavelength. Using the FEM, we compute the spectral response (SR) of the device defined by the wavelength dependent normalized field amplitude at the designed focal plane. In Fig. 4 (b) we compare the results obtained from the RS method and the FEM for the same device, which were found to be in good qualitative agreement. In fact, we note that the overall shape of the spectrum is captured by the RS method, which suffers from a systematic shift in the peak position of about $1\mu m$ compared to the FEM data due to the perturbation introduced by the finite thickness of the device as well as the presence of the dielectric substrate. We further investigate the distribution of the focused field obtained with both methods as shown in Figure 4 (c,d). The spatial distribution of the focused field clearly show a similar focusing behavior inside the substrate. Therefore, we conclude that the efficient RS method can still be utilized in this regime to more efficiently design novel phase-modulated axilens devices at reduced computational costs and time ($\sim$3min) compared to the device-level FEM simulations ($\sim$15h).

![Image](163x448 to 168x525)

FIG. 5. Panels (a-b) show the focusing efficiency and the spectral response for the different modulated-phase axilenses specified in the legend. Panels (c-d) show the position of the focal spot with respect to the origin of the device and the cross talk ratio for the different modulated-phase axilenses specified in the legend, respectively.

To further characterize the focusing behavior of phase-modulated axilenses, we compute the spectral dependence of $\eta$, spectral response (SR), position of the focal point, and cross talk ratio (CR) for different types of modulated axilenses. Figure 5 (a) compares the behavior of $\eta$ for a standard Fresnel lens with $f_0 = 300\mu m$, an axilens with $f_0 = 250\mu m$, $\Delta f = 120\mu m$, 1D and 2D periodically modulated axilenses, and a 45° chirped axilens (both with $p = 15\mu m$). All the phase profiles correspond to 4-level discretized devices. Despite the decrease in $\eta$ for the modulated structures with respect to a standard
axilens (which is expected due to the increased diffraction losses), the modulated axilenses maintain high efficiency (∼72% for 45° chirped, ∼61% for periodic modulation) over the broad wavelength range 7 µm−12 µm. Figure (b) shows the SR of the same devices as in panel (a), which demonstrates significantly increased spectral responses spanning across the long-wavelength IR band compared to a Fresnel lens. We also investigate in Fig. (c) the shift of the focal point position with respect to the center of the devices when varying the incident wavelength of radiation. Our findings show that the focal point position shifts linearly when increasing the incident radiation wavelength. Decreasing the periodicity of the phase modulation from $p = 30 \mu m$ to $p = 15 \mu m$ increases the slope of the wavelength shift.

To assess the potential of modulated axilenses for IR photodetection we study the cross talk ratio (CR) between different wavelengths. The CR is defined as follows:

$$ CR = \frac{\int_{\lambda_0}^{\lambda} I_{ax}(x, \lambda_0, \lambda) dx}{\int_{\lambda_0}^{\lambda} I(x, \lambda_0) dx} \quad (4) $$

where $I_{ax}(x, \lambda_0, \lambda)$ is the 1D intensity cut through the center of the overlapping focusing regions between incident wavelength $\lambda_0$ and $\lambda$ and $I(x, \lambda_0)$ is the intensity cut through the center of focal point with incident wavelength $\lambda_0$. The CR quantifies the cross talk between $\lambda$ and $\lambda_0$ at the same location. In Fig. (d) we show the computed CR for different modulated axilenses by fixing $\lambda_0 = 7 \mu m$ and sweeping $\lambda$ from 7 to 12 $\mu m$. The phase modulation with the smallest periodicity features the smallest CR at the same wavelength since the focal points of $\lambda_0$ and $\lambda$ are further separated by the periodic modulation of the phase of the device (grating effect) on the focal plane, as demonstrated in Fig. (c). Consistently with the larger focal shifts reported in Fig. (c), the 45° chirped axilens features smaller CR values compared with the 1D periodically modulated axilens at the same $\lambda$. However, it is important to note that the CR of all the considered structures drops to 0.35 when increasing $\lambda$ to 9.5 $\mu m$. Therefore, the modulated axilens concept can be used to achieve multi-band detection with minimal cross talks between different IR bands.

Building on the angular dispersion properties of 2D phase modulated axilenses, we now demonstrate in Fig. (e) their potential for the engineering of single-lens compact microspectrometer. In particular, we show in Fig. (a) the calculated intensity distribution sampled on a 45° plane for different incident radiations with different wavelengths (and with the same intensity). We observe a clear spectral separation of the different incoming wavelengths at two focused locations on the same achromatic plane (indicated by the white dashed line). We used false colors to distinguish different wavelength that correspond to the same color shown in Fig. (b). In Fig. (b), we show the spatial distribution of the focused intensity corresponding to different wavelength on the achromatic plane ($z = 300 \mu m$). We can clearly appreciate that different wavelengths are diffracted into well-separated locations across this plane, enabling spectroscopic characteristic.

We further characterize wavelength dependent $\eta$ and diffraction angle spectrum for the 45° chirped axilens, the 2D periodically modulated axilens, and the cross grating axilens. All three device modulation periods are $p = 5 \mu m$. Figure (c) demonstrates that the three modulated axilens achieve $\eta > 50\%$ across a broad band in the LWIR. In Fig. (d) we show the deflection angle of the focal spots as a function of the incident wavelength, demonstrating the potential to engineer single lens focusing spectrometers based on this technology. In particular, we remark that the deflection angles are linearly related to the incoming wavelength and the slope of this linear relation defines the angular dispersion $\frac{d\theta}{d\lambda}$ of the device. For the devices considered here, we have selected diameter $D = 100 \mu m$. The angular dispersion for the 2D periodically modulated axilens is $\frac{d\theta}{d\lambda} = 1 \times 10^{-4} \text{ rad/nm}$. We also evaluate these parameters for the 45° modulated and the cross grating modulated axilens that are $8.25 \times 10^{-5} \text{ rad/nm}$ and $6.9 \times 10^{-5} \text{ rad/nm}$, respectively. Therefore, 2D periodically modulated axilens are more promising for the spectroscopic applications since the 2D nature of the phase modulation in these devices gives rise to larger angular dispersion. Remarkably, the angular dispersion value predicted for this miniaturized device is comparable to the one of a commercial spectrometer with a grating spatial frequency of 300 [lines/mm]. This
opens exciting new scenarios for on-chip spectroscopic applications based on miniaturized single-lens components. Furthermore, we calculate the minimum resolvable wavelength interval of the 2D modulated axilens device using the following relation:

$$\Delta \lambda = \frac{\lambda_0}{nD} \frac{d\varphi}{d\lambda_0}$$

(5)

where $\lambda_0$ is the wavelength in air, $D$ is the device diameter, $n$ is the substrate material index. This yields, for our choice of parameters, $\Delta \lambda = 240nm$ at $\lambda_0 = 8\mu m$. Notice that $\Delta \lambda$ is inversely related to the device aperture size $D$. Therefore, miniaturized modulated axilens-based spectrometers necessarily have limited $\Delta \lambda$ compared to large-scale commercial spectrometers with a typical aperture size of 10 cm. However, the $\Delta \lambda$ can be further reduced by increasing device diameter $D$ and/or further reducing the periodicity $p$, depending on different application scenarios. In addition, phase apodization techniques can be utilized to effectively reduce the aperture-driven diffraction effects in these devices[21].

Finally, we explore the applicability of our device concept to the MWIR wavelength range and we design the 2D modulated axilenses for maximum performance at $\lambda = 5\mu m$.

Our results are shown in Fig. 7(a) where we characterize periodically modulated axilenses designed according to Eq. 4 with $\lambda = 5 \mu m$. Other device parameters are the same as described in Fig. 6. In particular, Fig. 7(a) displays the diffracted 2D intensity distribution sampled on a $45^\circ$ plane of different radiation across the 4 - 6$\mu m$ spectrum. We also show in Fig. 7(b) the 1D normalized intensity cuts corresponding to different incident wavelengths indicated by the white dashed line in Fig. 7(a). A clear spectral separation of the different incoming wavelengths at two focused locations on the same achromatic plane is observed. Therefore, our device concept can also be utilized for focusing grating application across the MWIR spectral range. Furthermore, we quantify its focusing efficiency and angular diffraction behavior at $z = 300\mu m$ plane in Figs. 7(c) and (d), respectively. The device still shows a focusing efficiency around 50% over a broadband (4 - 6$\mu m$). Similar to the previous LWIR case, we now obtain an angular dispersion in Fig. 7(d) as $\frac{d\theta}{d\lambda} = 9 \times 10^{-5} \text{rad}/\text{nm}$. Therefore, the minimum resolvable wavelength interval for the MWIR implementation is $\Delta \lambda = 168nm$ at $\lambda_0 = 5\mu m$. We further show the SR compared to the same size Fresnel lens with $f_0 = 300\mu m$ in Fig. 7(e). We observe that the modulated axilens features a much broader spectral response across the MWIR. Finally, in Fig. 7(f), we show the calculated cross talk ratio using Eq. 4 with $\lambda_0 = 3 \mu m$, which demonstrates even better performance compared to the LWIR implementations.

In conclusion, we have proposed and designed a compact 4-level phase-modulated axilens platform that can be directly integrated atop multi-band IR-FPA substrates to achieve LWIR and MWIR spectroscopic and imaging functionalities. We showed that these devices feature a programmable focusing behavior and broader spectral responses compared to standard Fresnel lenses and support an achromatic focusing plane. We further investigated different types of phase modulations and demonstrated the focusing of spectral components at different controllable locations on the same focal plane. Our results have been validated using 3D device-level FEM simulations and a quantitative analysis of the most important was presented. Building on the concept of phase modulated axilens, we also demonstrate and characterize spectroscopic behavior of these devices in the LWIR and MWIR. Specifically, we achieve minimum distinguishable wavelength interval in LWIR as $\Delta \lambda = 242nm$ at $\lambda_0 = 8\mu m$ and $\Delta \lambda = 168nm$ at $\lambda_0 = 5\mu m$ in the MWIR. The proposed compact devices add fundamental imaging and spectroscopic capabilities to traditional DOEs and represent alternative solutions with respect to more complex metasurface-based designs for critical applications such as spectral sorting, multi-band IR imaging.
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