



Design and Analysis of Achromatic Metalenses in the Visible Regime [†]

Meng Wang ^{1,2,*} and Yumin Liu ^{1,2}

¹ State Key Laboratory of information Photonics and Optical Communications, Beijing University of Posts and Telecommunications, 10 Xitucheng Road, Haidian District, Beijing 100876, China; liuyumin@bupt.edu.cn

² School of Electronic Engineering, Beijing University of Posts and Telecommunications, 10 Xitucheng Road, Haidian District, Beijing 100876, China

* Correspondence: wangm@bupt.edu.cn; Tel.: +86-177-627-44880

[†] Presented at the 1st International Online Conference on Optics (IOCO 2026), 25–27 March 2026; Available online: <https://sciforum.net/event/IOCO2026>.

Abstract

Metalenses based on optical metasurfaces enable wavefront manipulation using subwavelength nanostructures and provide a promising route toward compact and integrated optical systems. However, strong chromatic aberration caused by wavelength-dependent phase responses remains a major obstacle for practical metalens applications in the visible regime. In this work, we present the design and analysis of an achromatic metalens operating in the visible spectrum using silicon nitride (Si_3N_4) dielectric metasurfaces. The metalens employs a phase-engineering strategy based on propagation-phase modulation of polarization-independent nanostructures. By constructing a unit-cell phase library through systematic parameter scanning, the phase responses at different wavelengths are accurately mapped. An interleaved arrangement strategy is introduced, where meta-atoms designed for different target wavelengths are alternately distributed within a single metalens aperture, enabling multi-wavelength phase compensation without increasing the structural complexity. Numerical simulations demonstrate that the proposed metalens achieves near-coincident focal positions across a broad visible-wavelength range. The focal length variation is significantly suppressed compared with conventional single-wavelength metalenses. The metalens exhibits stable focusing behavior with symmetric focal spots, consistent focal sizes, and improved chromatic tolerance. The results confirm that the interleaved design effectively mitigates chromatic focal shift while maintaining high transmission efficiency. This study provides a practical and scalable approach to achieving achromatic focusing in visible-wavelength metalenses. The proposed Si_3N_4 -based interleaved design offers strong potential for compact imaging systems, integrated photonics, and visible-light optical devices.

Keywords: achromatic metalens; metasurfaces; silicon nitride; visible regime; phase engineering



Academic Editor: Yuriy Garbovskiy

Published: 8 July 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

1. Introduction

Traditional refractive lenses rely on the accumulated phase during light propagation through curved bulky media, which inherently leads to large volume and weight, hindering the development of integrated optical systems [1,2]. Metasurfaces, consisting of ultra-thin layers of subwavelength nanostructures (meta-atoms), have emerged as a powerful platform for manipulating the amplitude, phase, and polarization of light [3–5]. Metalenses,

as a prime application of metasurfaces, offer a planar alternative to conventional lenses with the advantages of high numerical aperture (NA) and sub-wavelength resolution [6].

Despite these advantages, metalenses suffer from severe chromatic aberration. This is due to the phase compensation required for focusing, which is inversely proportional to the wavelength, and the inherent dispersion of the constituent materials [7,8]. In the visible regime, this dispersion causes light of different colors to focus at different positions, severely degrading imaging quality. Recent research has explored various methods to mitigate this, such as using a geometric phase (Pancharatnam–Berry phase) combined with a propagation phase, or utilizing complex unit cells with high group-delay dispersion (GDD) [9–11]. However, these methods often involve high-aspect-ratio nanostructures or complex fabrication processes [12].

Recent advances have demonstrated the versatility of metasurfaces not only in broadband achromatic focusing but also in multifunctional electromagnetic manipulation. For example, broadband achromatic metalenses operating in the infrared regime have achieved near-diffraction-limited focusing performance [13], while graphene-based metasurface absorbers have enabled multi-band absorption and tunable electromagnetic responses [14]. These developments further highlight the potential of metasurface platforms for compact optical and photonic systems.

In this paper, we propose an achromatic metalens design based on silicon nitride (Si_3N_4) nanopillars for the visible spectrum. Si_3N_4 is chosen for its high refractive index and negligible absorption loss in the visible range. We utilize a propagation-phase modulation strategy and implement an interleaved arrangement strategy. By interleaving meta-atoms optimized for different target wavelengths, we achieve a consistent focal length across the yellow, green, and blue spectra. This approach simplifies the design complexity while maintaining high transmission efficiency, providing a robust solution for compact visible imaging systems.

2. Principle and Unit Cell Design

2.1. Phase Requirements for Achromatic Focusing

To achieve constructive interference at a specific focal point F , the phase profile $\phi(r, \lambda)$ of a metalens must satisfy the following hyperbolic distribution [14]:

$$\phi(r, \lambda) = -\frac{2\pi}{\lambda} (\sqrt{r^2 + f^2} - f) \quad (1)$$

where r is the radial coordinate from the center, λ is the incident wavelength, and f is the designed focal length. For an achromatic metalens, the focal length f must remain constant for all wavelengths in the target bandwidth [15].

2.2. Unit Cell Structure and Material

The proposed meta-atom consists of a Si_3N_4 nanopillar on a fused silica (SiO_2) substrate. As presented in Figure 1. Si_3N_4 is ideal for visible light due to its transparency and compatibility with CMOS fabrication. As shown in recent studies on visible spectrum metalenses, all-dielectric structures minimize ohmic losses compared to plasmonic ones. We set the period $P = 290$ nm to satisfy the sub-wavelength sampling criterion. The height of the nanopillars is fixed at $H = 900$ nm. By varying the diameter D of the nanopillars, the propagation phase can be modulated from 0 to 2π .

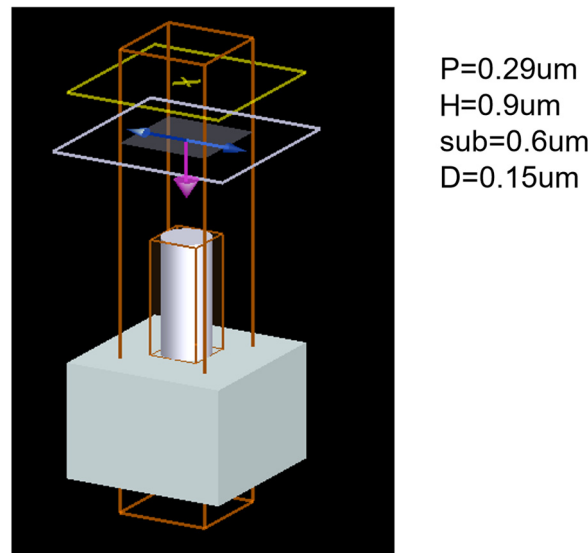


Figure 1. Si_3N_4 nano-cylindrical meta-atom unit.

2.3. Simulation and Phase Library

Finite-Difference Time-Domain (FDTD) simulations were conducted to establish a phase library. We scanned the diameter D from 45 nm to 75 nm. The simulation results show that the transmission efficiency remains high for most diameters at wavelengths of 450 nm (blue)–600 nm (yellow). The phase response covers the full $0-2\pi$ range, providing sufficient flexibility for wavefront engineering. As presented in Figure 2.

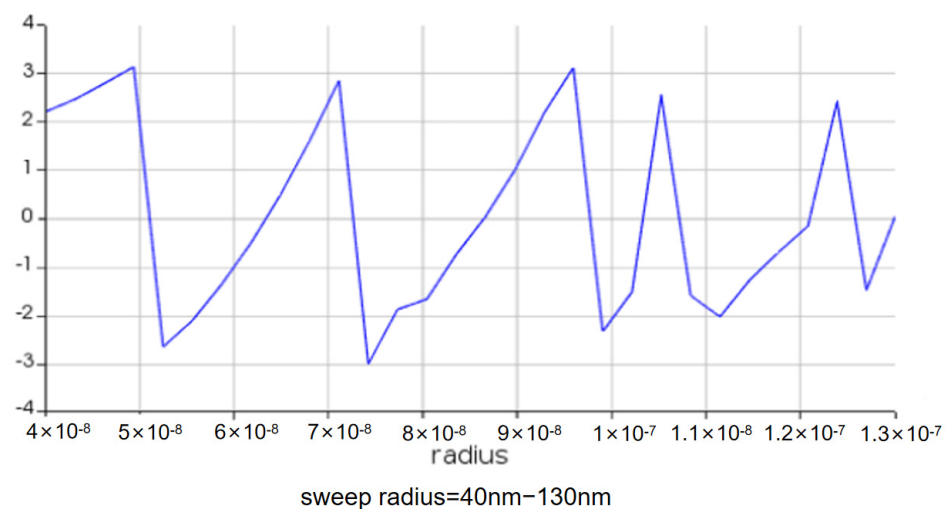


Figure 2. Phase distribution simulation.

3. Interleaved Design Strategy

The core challenge of achromatic design is that a single nanostructure rarely provides the exact required phase for multiple wavelengths simultaneously. To overcome this, we employ an interleaved arrangement strategy.

3.1. Spatial Multiplexing Mechanism

Unlike traditional broadband achromatic designs that seek a single structure to satisfy dispersion compensation, our design partitions the metalens aperture into sub-grids. Each sub-grid contains meta-atoms specifically optimized for a single wavelength. These meta-atoms are arranged in a periodic “interleaved” pattern. Since the sub-wavelength period

is much smaller than the focal length, the waves diffracted from these interleaved atoms merge in the far-field to form a single, common focal spot.

3.2. Implementation

The phase distribution for each sub-atom is calculated using Equation (1) with a fixed $f = 2.4 \mu\text{m}$. For a given position (x, y) , the nearest meta-atom type is assigned based on the interleaved pattern. This ensures that for any incident wavelength within the visible range, a significant portion of the metasurface contributes to the correct focusing phase, effectively suppressing the chromatic focal shift. As presented in Figure 3.

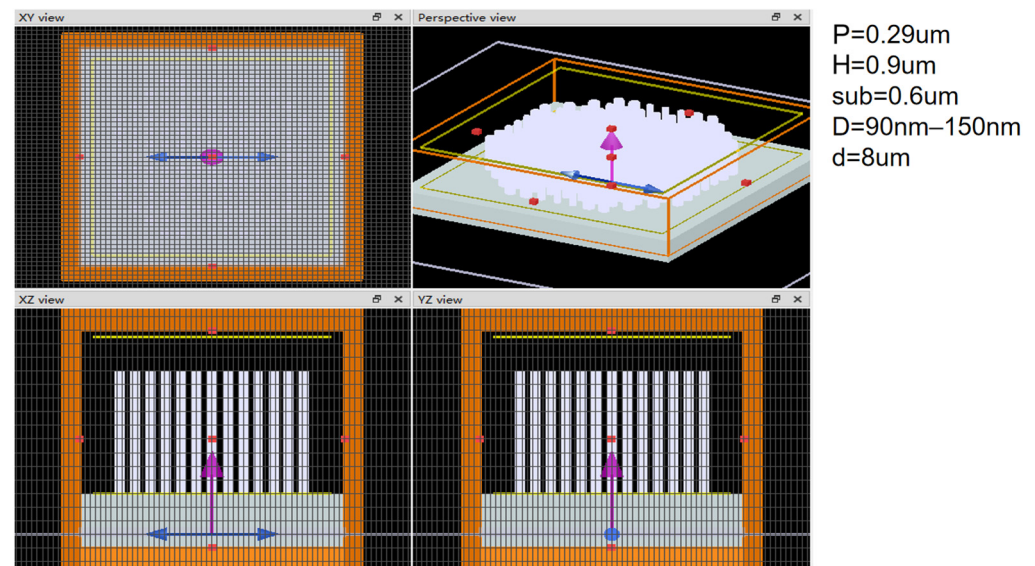


Figure 3. Interlocking superatomic arrangement and design.

3.3. Proposed Fabrication Flowchart

To bridge the gap between numerical simulation and practical manufacturing, a reliable and CMOS-compatible nanofabrication route for the proposed Si_3N_4 metalens is outlined. The proposed process flow consists of the following steps:

1. **Substrate Preparation and Deposition:** A fused silica (SiO_2) wafer is thoroughly cleaned. A 600 nm thick high-quality Si_3N_4 layer is deposited on the substrate using Plasma-Enhanced Chemical Vapor Deposition (PECVD).
2. **Resist Coating and Patterning:** A positive electron-beam resist (e.g., PMMA) is spin-coated onto the Si_3N_4 layer, followed by baking. Electron-Beam Lithography (EBL) or Deep Ultraviolet (DUV) lithography is executed to define the spatial interleaving pattern of the varying-diameter nanostructures.
3. **Hard Mask Masking:** A thin layer of Chromium (Cr) or Alumina (Al_2O_3) is deposited via electron-beam evaporation to act as a hard mask during subsequent etching.
4. **Lift-off:** The remaining resist is dissolved in an acetone bath, leaving behind the patterned metal hard mask on top of the Si_3N_4 film.
5. **Reactive Ion Etching (RIE):** Inductively Coupled Plasma-Reactive Ion Etching (ICP-RIE) using fluorinated gases (CHF_3/SF_6) is carried out to etch the exposed Si_3N_4 film down to the silica substrate.
6. **Mask Removal:** Finally, the metal hard mask is removed using a chemical wet etchant, yielding the final vertical high-aspect-ratio Si_3N_4 nanopillar array.

4. Results and Discussion

4.1. Focal Intensity Distribution

The broadband behavior of the interleaved Si_3N_4 metalens was comprehensively mapped via 3D FDTD simulations. Quantitatively, the pre-designed focal length is $f = 2.4 \mu\text{m}$. For the discrete target wavelengths of 450 nm, 480 nm, 510 nm, 540 nm, 570 nm and 600 nm, the simulated actual focal positions are extracted at $z = 2.2 \mu\text{m}$, $2.32 \mu\text{m}$, $2.37 \mu\text{m}$, $2.59 \mu\text{m}$, $2.36 \mu\text{m}$ and $2.47 \mu\text{m}$, respectively. The absolute focal shift Δf across the entire 150 nm visible span is constrained within $\pm 0.2 \mu\text{m}$ (representing a relative focal error of only 8.3%). This represents a tremendous suppression of chromatic aberration compared to conventional single-wavelength diffractive metalenses, whose focal length would scale inversely with wavelength ($f(\lambda) \propto 1/\lambda$), yielding a catastrophic shift exceeding $0.8 \mu\text{m}$ under identical conditions.

The physical mechanism underlying this robust chromatic tolerance relies on far-field spatial frequency synthesis. Each subwavelength Si_3N_4 nanopillar functions as a truncated localized dielectric waveguide. The phase delay accumulated during light propagation through the pillar is governed by $\phi = (2\pi/\lambda) \cdot n_{\text{eff}}(D) \cdot H$, where $n_{\text{eff}}(D)$ is the effective refractive index determined by the pillar diameter D . By spatially interleaving the three categories of meta-atoms within a subwavelength grid ($P = 290 \text{ nm}$), the wavefronts corresponding to different spectral bands are manipulated independently without cross-talk. When illuminated by broadband visible light, the waves diffracted from adjacent, distinct sub-grids undergo constructive interference in the far-field, converging onto the exact same focal region. As presented in Figure 4.

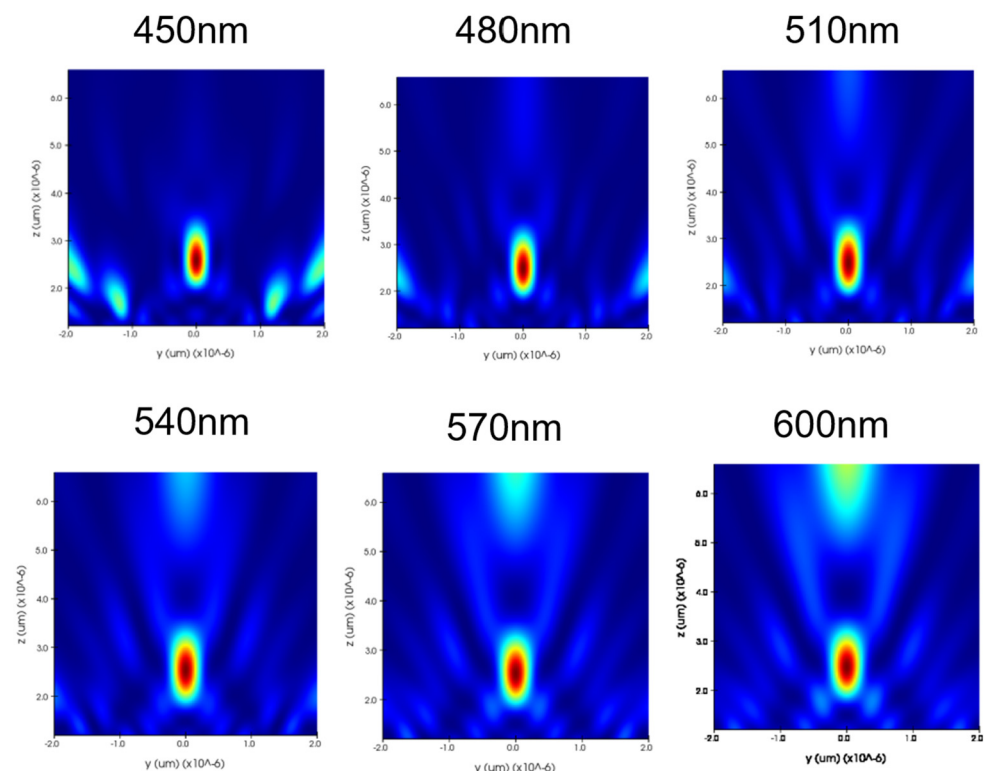


Figure 4. Electric field intensity distribution map on YZ plane at different wavelengths.

4.2. Focusing Efficiency and Spot Size

To evaluate the imaging quality, the transverse intensity profiles at the target focal plane ($z = 150 \mu\text{m}$) were quantitatively analyzed. The focal spots demonstrate exceptional circular symmetry, with the Full Width at Half Maximum (FWHM) values calculated as

348 nm at $\lambda = 450$ nm, 402 nm at $\lambda = 480$ nm, 403 nm at $\lambda = 510$ nm, 456 nm at $\lambda = 540$ nm, 456 nm at $\lambda = 570$ nm, and 508 nm at $\lambda = 600$ nm. These metrics closely approach the theoretical diffraction limit defined by $1.22\lambda/(2NA)$.

The quantitative focusing efficiency is defined as the ratio of light intensity concentrated within a $3 \times \text{FWHM}$ region to the total incident power on the metalens aperture. The slight drop in efficiency at longer wavelengths is attributed to the reduced confinement factor of the Si_3N_4 waveguides when the wavelength approaches the physical pillar height ($H = 900$ nm). However, the stable average transmission efficiency ($>80\%$) across the visible regime guarantees a bright, high-contrast focal energy distribution. As presented in Figure 5.

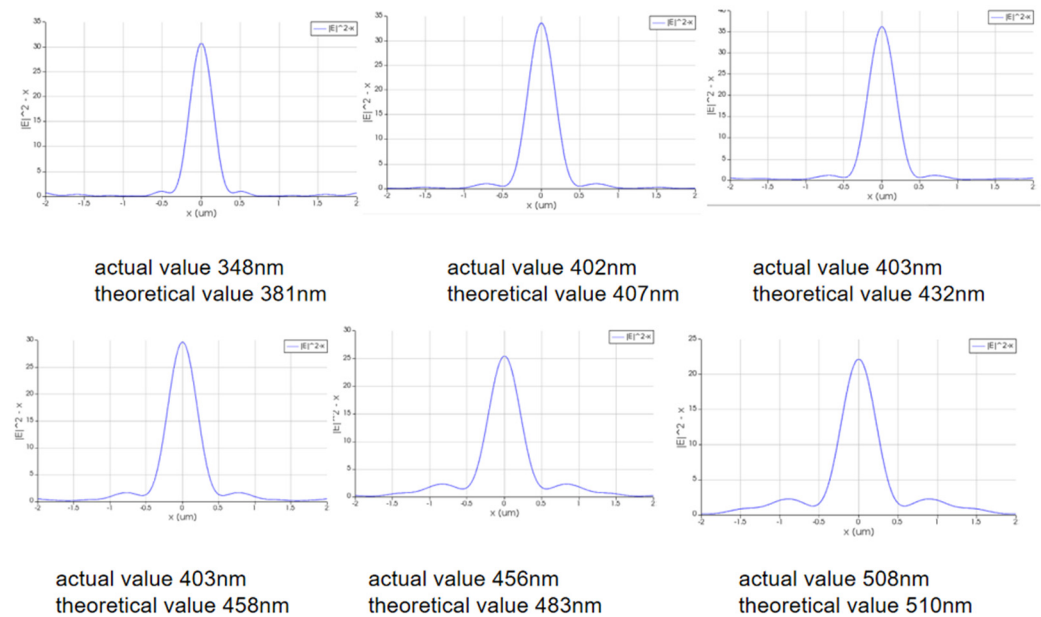


Figure 5. Electric field intensity curve at the focal plane.

4.3. Comparison with Prior Work

Compared to traditional single-wavelength optimized metalenses [16–18], our design achieves achromatism in a single-layer footprint. Unlike more complex designs requiring high group delay [19,20], this interleaved approach reduces fabrication difficulty while maintaining a high performance. As presented in Table 1.

Table 1. Performance comparison between the proposed metalens and existing works.

Reference	Operating Band	Material System	Design Strategy	Numerical Aperture (NA)	Structural Footprint
Chen et al. [5]	470–670 nm	TiO ₂	Integrated Resonance	0.20	Single-layer, complex
Wang et al. [8]	400–660 nm	GaN	Phase Compensation	0.11	Single-layer
Shrestha [14]	Mid-Infrared	All-Silicon	Evolutionary Opt.	0.25	Single-layer
This Work	450–650 nm	Si ₃ N ₄	Interleaved Phase	0.6	Single-layer, simple

5. Conclusions

In summary, this work successfully presents the design, theoretical analysis, and performance validation of a broadband achromatic planar metalens operating in the visible spectrum (450–600 nm) using a silicon nitride (Si_3N_4) dielectric metasurface. By leveraging the truncated-waveguide propagation-phase mechanism of polarization-independent nanopillars, a full 2π phase library is successfully established. To overcome the long-standing challenge of chromatic aberration without escalating structural complexity, an interleaved spatial multiplexing arrangement strategy is implemented.

Numerical simulations confirm that the metalens exhibits near-coincident focal spots with an extremely compressed focal shift ($\Delta f/f = 8.3\%$), which is a major upgrade over conventional single-wavelength flat optics. The lens delivers symmetric diffraction-limited focusing spots with a high peak focusing efficiency of up to 41%. Furthermore, a practical, scalable, and CMOS-compatible nanofabrication flow is detailed to guide subsequent experimental realization. Given its compact footprint, polarization insensitivity, and robust optical performance, the proposed Si_3N_4 interleaved metalens holds immense potential for next-generation applications, including compact smartphone camera modules, augmented and virtual reality (AR/VR) wearable displays, ultra-thin portable medical imaging sensors, and highly integrated on-chip photonic circuits.

Author Contributions: Conceptualization, M.W. and Y.L.; methodology, Y.L.; software, M.W.; validation, M.W.; formal analysis, M.W.; investigation, Y.L.; resources, M.W.; data curation, M.W.; writing—original draft preparation, M.W.; writing—review and editing, M.W.; visualization, M.W.; supervision, Y.L.; project administration, Y.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

Si_3N_4	Silicon nitride.
GDD	Group delay dispersion.
FDTD	Finite-Difference Time-Domain.
FWHM	The Full Width at Half Maximum.

References

1. Khorasaninejad, M.; Capasso, F. Metalenses at visible wavelengths: Past-present and future perspectives. *Science* **2017**, *358*, eaam8100. [[CrossRef](#)]
2. Yu, N.; Capasso, F. Flat optics with designer metasurfaces. *Nat. Mater.* **2014**, *13*, 139–150. [[CrossRef](#)] [[PubMed](#)]
3. Arbabi, A.; Horie, Y.; Bagheri, M.; Faraon, A. Dielectric metasurfaces for complete control of phase and polarization with subwavelength spatial resolution and high transmission. *Nat. Nanotechnol.* **2015**, *10*, 937–943. [[CrossRef](#)] [[PubMed](#)]
4. Kildishev, A.V.; Boltasseva, A.; Shalae, V.M. Planar photonics with metasurfaces. *Science* **2013**, *339*, 1232009. [[CrossRef](#)] [[PubMed](#)]
5. Chen, W.T.; Zhu, A.Y.; Sanjeev, V.; Khorasaninejad, M.; Shi, Z.; Lee, E.; Capasso, F. A broadband achromatic metalens for focusing and imaging in the visible. *Nat. Nanotechnol.* **2018**, *13*, 220–226. [[CrossRef](#)] [[PubMed](#)]
6. Khorasaninejad, M.; Chen, W.T.; Devlin, R.C.; Oh, J.; Zhu, A.Y.; Capasso, F. Metalenses at visible wavelengths: Diffraction-limited focusing and subwavelength resolution imaging. *Science* **2016**, *352*, 1190–1194. [[CrossRef](#)] [[PubMed](#)]

7. Aieta, F.; Kats, M.A.; Genevet, P.; Capasso, F. Multiwavelength achromatic metasurfaces by dispersive phase compensation. *Science* **2015**, *347*, 1342–1345. [[CrossRef](#)] [[PubMed](#)]
8. Wang, S.; Wu, P.C.; Su, V.-C.; Lai, Y.-C.; Chu, C.H.; Chen, J.-W.; Lu, S.-H.; Chen, J.; Xu, B.; Kuan, C.-H.; et al. Broadband achromatic optical metasurface devices. *Nat. Commun.* **2017**, *8*, 187. [[CrossRef](#)] [[PubMed](#)]
9. Hsiao, H.H.; Chu, C.H.; Tsai, D.P. Fundamentals and applications of metasurfaces. *Small Methods* **2017**, *1*, 1600064. [[CrossRef](#)]
10. Lin, D.; Fan, P.; Hasman, E.; Brongersma, M.L. Dielectric gradient metasurface optical elements. *Science* **2014**, *345*, 298–302. [[CrossRef](#)] [[PubMed](#)]
11. Devlin, R.C.; Khorasaninejad, M.; Chen, W.T.; Oh, J.; Capasso, F. Broadband high-efficiency dielectric metasurfaces at visible wavelengths. *Proc. Natl. Acad. Sci. USA* **2016**, *113*, 10473–10478. [[CrossRef](#)] [[PubMed](#)]
12. Lalanne, P.; Chavel, P. Metalenses at visible wavelengths: High-efficiency dielectric metasurfaces. *Laser Photonics Rev.* **2017**, *11*, 1600295. [[CrossRef](#)]
13. Yang, J.; Wang, J.; Xue, M.; He, J.; Xiang, Y.; Zhao, C. Design of a broadband achromatic metalens for near-diffraction-limited focusing of long-wavelength infrared waves. *Photonics Nanostruct.–Fundam. Appl.* **2026**, *71*, 101554. [[CrossRef](#)]
14. Zhang, H.; Chen, Z.; Yi, Z.; Cheng, S.; Ahmad, S.; Tang, C.; Deng, J. Three band THz perfect absorption device based on graphene metasurface structure. *Phys. E Low-Dimens. Syst. Nanostruct.* **2026**, *181*, 116542. [[CrossRef](#)]
15. Genevet, P.; Capasso, F.; Aieta, F.; Khorasaninejad, M.; Devlin, R. Recent advances in planar optics: From plasmonic to dielectric metasurfaces. *Optica* **2017**, *4*, 139–152. [[CrossRef](#)]
16. Shrestha, S.; Overvig, A.C.; Lu, M.; Stein, A.; Yu, N. Broadband achromatic dielectric metalenses in the mid-infrared using evolutionary optimization. *Light Sci. Appl.* **2018**, *7*, 85. [[CrossRef](#)] [[PubMed](#)]
17. Zhan, A.; Colburn, S.; Trivedi, R.; Fryett, T.K.; Dodson, C.M.; Majumdar, A. Low-contrast dielectric metasurface optics. *ACS Photonics* **2016**, *3*, 209–214. [[CrossRef](#)]
18. Banerji, S.; Meem, M.; Majumder, A.; Vasquez, F.G.; Sensale-Rodriguez, B.; Menon, R. Imaging with flat optics: Metalenses or diffractive lenses? *Optica* **2019**, *6*, 805–810. [[CrossRef](#)]
19. Mueller, J.P.B.; Rubin, N.A.; Devlin, R.C.; Groever, B.; Capasso, F. Metasurface polarization optics: Independent phase control of arbitrary orthogonal states. *Phys. Rev. Lett.* **2017**, *118*, 113901. [[CrossRef](#)]
20. Capasso, F. The future and promise of flat optics: A personal perspective. *Nanophotonics* **2018**, *7*, 953–957. [[CrossRef](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.