Rectangular Metalenses:

Improved Fill Factor and Scalable Fabrication

A product and technology overview

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Introduction

Camera sensors are rectangular. The optics that focus light onto them have always been round. This geometric mismatch means conventional lenses must be oversized to fully illuminate the sensor, wasting space and adding bulk to every camera module. Metalenses—flat optical elements made from nanostructured surfaces—can now be fabricated in any shape, including rectangular, to match the sensor footprint exactly.

MetaOptics Technologies, headquartered in Singapore and listed on the Singapore Exchange (SGX Catalist) since September 2025, has developed rectangular metalenses that improve optical fill factor while reducing the size and weight of the integrated camera module. These second-generation flat lenses represent just one facet of a broader technology platform that spans three material systems, two complementary fabrication methods, AI-powered image processing, and electrically tunable optics.

This white paper provides an overview of the company's metalens technology: how the structures work, how they are made, what camera systems they enable, and where the technology is heading—from tunable autofocus modules to a planned metalens foundry in the United States.

How Metalenses Work

A metalens is composed of sub-wavelength nanostructures—typically nanopillars or nanofins—fabricated on a transparent substrate such as glass or quartz. These structures are smaller than the wavelength of light they manipulate, typically ranging from 100 to 400 nm in diameter depending on the target wavelength. By varying the geometry, spacing, and orientation of these structures across the surface, designers can precisely control the phase, amplitude, and polarization of transmitted light.

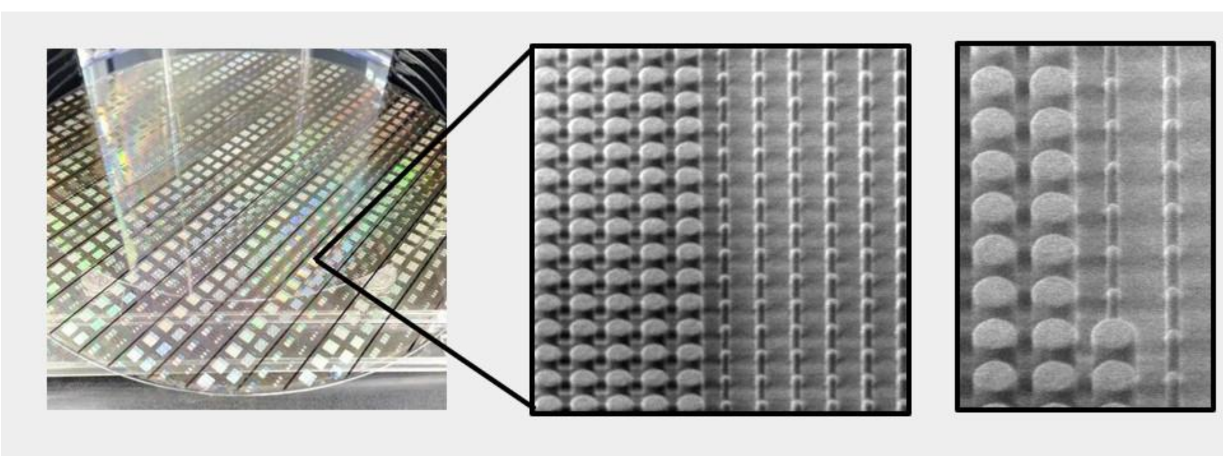

Figure 1: SEM images of rectangular metalens nanostructures. Left: fabricated metalens array on a glass wafer. Center and right: close-up views showing nanopillar structures with diameters from 120nm to 400 nm. (Source: MetaOptics Technologies)

The result is a flat optical element—often less than a micrometer thick—that can replicate the function of a conventional curved lens, a color filter, or a polarizer. Because the optical function is encoded in the surface pattern rather than in curved geometry, metalenses can be manufactured in any shape using standard semiconductor lithography processes on wafer-scale substrates.

A simple design rule determines the minimum feature size: approximately one-third of the shortest operating wavelength. For visible-light applications starting at 400 nm (blue), this means structures smaller than approximately 130 nm are required.

Fabrication: Three Material Platforms, Two Lithography Paths

Producing metalenses that operate across the visible spectrum demands nanostructures with feature sizes at or below 130 nm—fabricated from transparent, high-refractive-index materials on glass substrates. MetaOptics Technologies works with three material platforms, each suited to different wavelength ranges and performance requirements, and employs two complementary lithography methods to cover the full journey from first prototype to volume production.

Material Platforms

Amorphous silicon (a-Si) offers the highest refractive index of the three platforms ($n \approx 3.5$ at near-infrared wavelengths) and is deposited by plasma-enhanced chemical vapor deposition (PECVD) in a straightforward, well-characterized process. Typical pillar heights range from 300 to 800 nm. However, because a-Si absorbs visible light, its use is limited to wavelengths above approximately 700 nm. This makes it the material of choice for NIR applications such as LiDAR, 3D sensing, and co-packaged optics for data-center interconnects.

Silicon nitride (Si_3N_4) provides a moderate refractive index ($n \approx 2.0$) with excellent transparency across both the visible and near-infrared spectrum. It represents the most mature platform for metalens fabrication, with well-established deposition processes and thoroughly characterized optical properties. Current fabrication achieves critical dimensions (CDs) of 120 to 220 nm, with ongoing development targeting the full 100 to 265 nm range needed for complete visible-spectrum coverage. Pillar heights are typically around 650 nm.

Titanium dioxide (TiO_2) combines a higher refractive index ($n \approx 2.6$ at 532 nm) with high transparency in the visible range. The higher index allows more efficient phase manipulation for a given pillar geometry, resulting in better focusing efficiency and sharper imaging performance. MetaOptics' latest second-generation rectangular metalenses use TiO_2 with a target CD of 100 nm and pillar heights of 650 to 800 nm. The move from SiN to TiO_2 for the color camera lenses has yielded measurable improvements in both focusing efficiency and image sharpness, with transmissivity reaching more than 90%. Why is that? The higher index of titanium dioxide allows the circular pillars to be smaller and have a reduced period to achieve the same critical dimensions. This helps with focusing efficiency with less losses to the system MTF – and hence, increased sharpness.

Two Lithography Paths

For prototyping and rapid design iteration, MetaOptics uses its proprietary Direct Laser Writer (DLW)—a deep-UV (266 nm) direct-write tool that achieves a 90 nm linewidth and 150 nm minimum pillar diameter on 4-inch glass substrates. The DLW uses a super-oscillatory metalens to create a sub-diffraction-limited focal spot, enabling fabrication of visible-wavelength metasurface features without requiring the vacuum environment or long cycle times of electron-beam lithography (EBL). A typical 4-inch wafer can be patterned in days, compared to weeks with EBL, at a fraction of the cost. For more on this tool, please download the white paper: Metasurface Structures for Visible Wavelengths Using Direct Laser Writing Tool

MetaOptics is currently working with a leading semiconductor equipment manufacturer to develop a 12-inch version of this direct-write tool. The larger substrate format will significantly increase prototyping throughput and bridge the gap toward production volumes. This partnership pairs MetaOptics' proprietary super-oscillatory optics and deep-UV laser expertise with the equipment company's 12-inch wafer-handling and process-integration capabilities.

Figure 2: MetaOptics Technologies Executive Chairman, Mark Thng with 12" glass wafer with fabricated rectangular metalenses

For volume production, MetaOptics uses a 12-inch deep-UV (DUV) photolithography system. Standard DUV lithography—the same process used to manufacture semiconductor devices at scale—is well understood, highly repeatable, and capable of sub-100 nm feature resolution on 12-inch glass wafers. While the photomask represents a one-time investment, subsequent wafers can be produced at a small fraction of the prototyping cost. A single 12-inch wafer yields substantially more metalens devices than a 4-inch substrate, and the process is compatible with all three material platforms.

This dual approach—DLW for fast prototyping and design validation, DUV foundry for production—provides customers with a complete pathway from concept to volume manufacturing, with consistent performance across both fabrication methods.

Camera Systems: From Monochrome to Full-Color RGB

The ability to shape metalenses into non-circular geometries has immediate practical value in camera systems, where image sensors are universally rectangular or square. MetaOptics Technologies has demonstrated this advantage across two generations of color camera designs and a wide-field-of-view monochrome NIR system. Each platform is supported by AI-enhanced image processing that compensates for the inherent optical constraints of flat lenses.

Gen 1: Round RGB Metalenses

The first-generation color camera uses three separate circular metalenses—red, green, and blue—each optimized for a narrow spectral band and positioned above a monochrome image sensor. Narrowband color filters below each metalens ensures spectral purity. The three spatially separated color channels are then computationally recombined to produce a full-color image.

Figure 3: Left: Gen 1 round RGB metalens triplet on glass — three circular metalenses (red, green, blue) on a single substrate. Right: Gen 1 RGB camera development kit with integrated metalens optics, sensor, and AI processing. (Source: MetaOptics Technologies)

This architecture demonstrated the fundamental viability of metalens-based color imaging. However, the circular lens geometry means each color channel illuminates only a portion of the sensor area, and creating a full-color image requires algorithmic registration and interpolation across the three displaced channel images.

MetaOptics has developed AI-based image-processing algorithms—integrated into its MOTviewer software platform—that counteract the wavelength-dependent aberrations inherent in metalens optics. A deep-learning-based deconvolution module reverses chromatic blur, coma, and astigmatism in a single inference pass, delivering sharper images with improved contrast across the full field of view. This technology was developed in collaboration with our Singapore National Institute for its effectiveness in real-time video processing on live camera hardware.

The Gen 1 RGB camera development kit is commercially available and can be purchased from the website Shopify platform. It includes the metalens RGB optics, narrowband color filters, a monochrome image sensor, an onboard processor running MetaOptics' AI algorithms, and a USB-C interface for connection to any PC.

Gen 2: Rectangular RGB Metalenses

The second-generation design replaces the round metalenses with rectangular ones, spanning the full area of the image sensor in contrast to the round lenses of Gen 1. The three color-channels —red, green, and blue— combined now illuminate the complete sensor surface, significantly improving the optical fill factor and light collection efficiency.

Figure 4: Left: Gen 2 uses three rectangular metalenses which cover the full sensor. Right: Gen 2 rectangular metalens camera module. (Source: MetaOptics Technologies)

Computational processing combines the three color-channels into a final full-color image. In a conventional Bayer-pattern camera, each sensor pixel records only one color, and the missing two channels must be mathematically interpolated from neighbouring pixels—a process (demosaicing) that introduces color fringing, moiré, and interpolation blur. The metalens approach fundamentally avoids this limitation: each rectangular metalens captures the full field of view image and projects its wavelength band onto separated sensor areas, so every color channel is a complete, directly measured component image rather than a reconstruction from sparse samples. In addition, because the MetaOptics approach separates the wavelengths with steep spectral cut-offs, each channel achieves high spectral purity with minimal crosstalk—unlike conventional organic dye filters, which exhibit significant spectral overlap between adjacent color bands. The result is true per-pixel color data with native spatial precision and zero interpolation artifacts—a critical advantage for machine vision, medical imaging, and other applications where measurement fidelity matters. The rectangular form factor also simplifies mechanical integration, as the optics now match the sensor outline with no wasted packaging space.

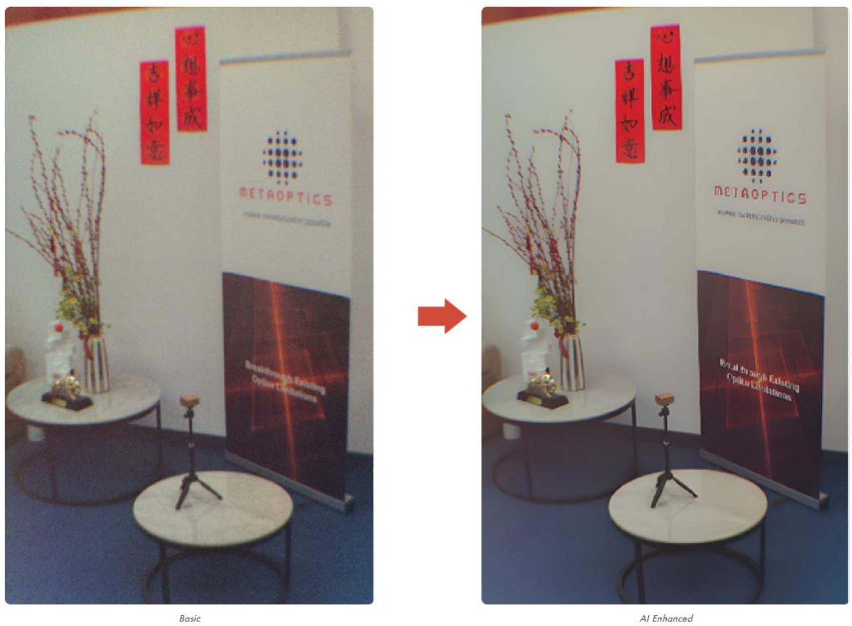

Figure 5: Image quality after channel overlay and other basic processing versus additional AI processing. Left: base processing showing a high-quality rectangular metalens color image. Right: after AI processing, with substantially improved clarity and detail. (Source: MetaOptics Technologies)

Currently, the Gen 2 rectangular metalenses are fabricated in Si_3N_4 with fabrication in TiO_2 in development for debut at CES 2027. TiO_2 will take advantage of its higher refractive index and better efficiency compared to the Si_3N_4-based Gen 1 design. The same AI-based processing pipeline—color reconstruction, sharpening, and brightness enhancement—is applied to the Gen 2 output, transforming the raw sensor data into publication-quality color images. Si_3N_4 rectangular metalenses are also available for purchase now on the Shopify page.

Wide Field-of-View Monochrome NIR Imaging

For single-wavelength applications—industrial inspection, gesture recognition, 3D sensing—a single metalens provides the complete optical system without color-channel complexity. MetaOptics has also developed a wide field-of-view FoV (179 degrees) monochromatic near-infrared (NIR) metalens operating at 740nm, fabricated in amorphous silicon (a-Si). The high refractive index of a-Si at NIR wavelengths allows efficient light focusing with relatively relaxed fabrication tolerances, making this an ideal platform for high-volume industrial applications.

Figure 6: Left: Wide field-of-view NIR metalens on glass substrate, designed for 740 nm operation. Right: NIR camera development kit housing the wide-FoV metalens with integrated sensor and processing. (Source: MetaOptics Technologies)

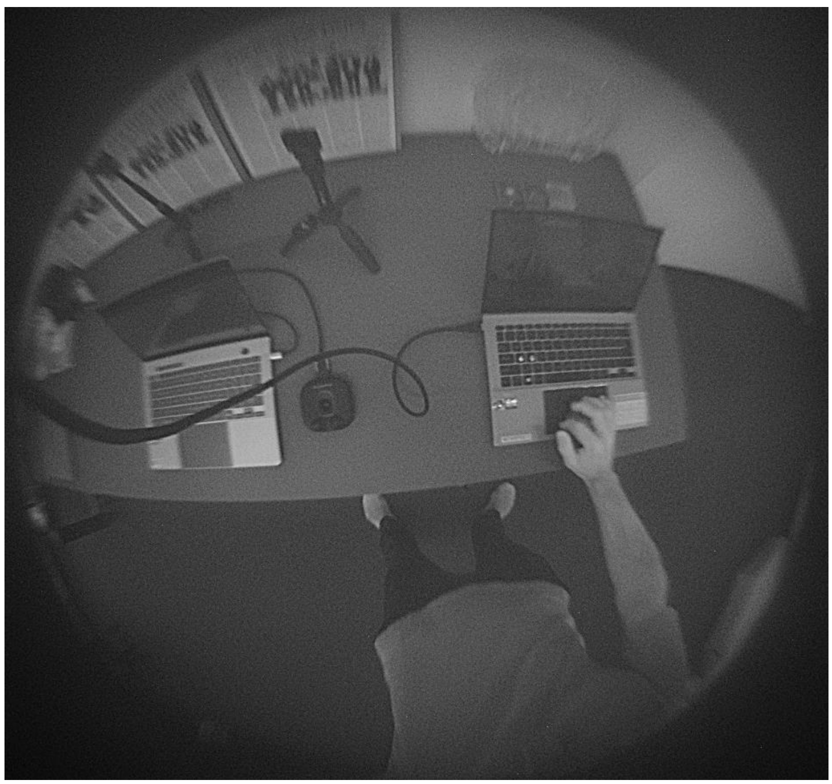

Figure 7: A wide-FoV NIR metalens demonstration image showing the field coverage and imaging quality of the 740 nm module. (Source: MetaOptics Technologies)

The wide-FoV NIR lens achieves coverage well beyond what is typical for conventional optics at this form factor, enabling compact sensing modules for applications such as proximity detection, eye tracking in AR/VR headsets, and structured-light depth mapping. Because NIR illumination is invisible to the human eye, these modules can operate unobtrusively in consumer devices. AR eye tracking is a particularly compelling application as a small, unobtrusive solution is desired. However, even with a small sensor, conventional optics create a much larger package. A metalens solution can shrink this package considerably.

Non-Contact Fingerprint Sensing

A particularly promising near-term application is non-contact fingerprint recognition. Under-display fingerprint sensors in smartphones must focus precisely at very short working distances through the display stack, and the ability to dynamically adjust focal length is critical for reliable recognition across varying finger positions. A metalens-based tunable module—with an aperture of approximately 2 mm and a total thickness under 2 mm—can provide the required focal adjustment range while maintaining the ultra-thin profile that smartphone designs demand.

The solid-state, vibration-free operation also makes the technology attractive for other compact sensing applications: gesture recognition in AR/VR headsets, depth sensing, adaptive autofocus for miniature cameras, and biomedical imaging instruments where mechanical autofocus would be impractical.

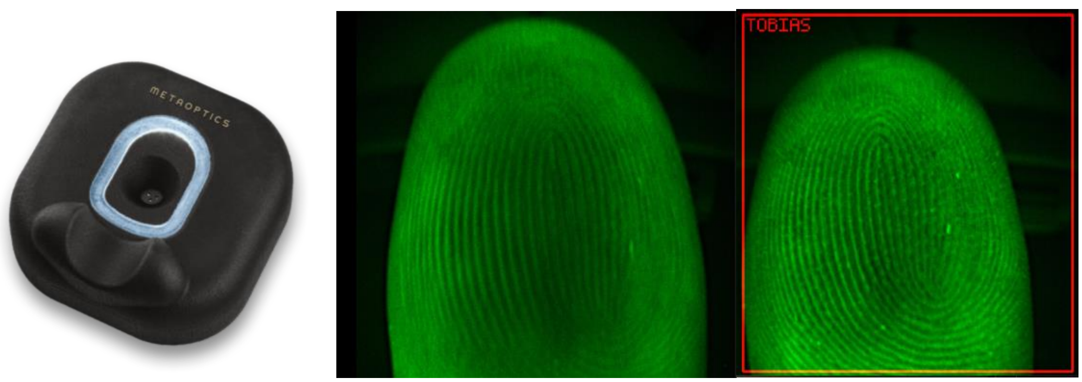

Figure 8: Non-contact fingerprint sensing with a metalens module. Left: fingerprint sensing module. Middle: raw fingerprint image. Right: after recognition processing, with the subject identified. (Source: MetaOptics Technologies)

As described next, MetaOptics is pursuing this technology through research collaborations with leading institutions and targets a working demonstration module during CES 2027.

Tunable Metalens: Electrically Adjustable Focus

One compelling direction for metalens technology is the creation of electrically tunable optical elements—lenses whose focal length can be adjusted without any moving parts.

MetaOptics Technologies is developing a tunable metalens module that combines two polarization-insensitive metalenses with a thin liquid crystal (LC) cell sandwiched between them. Applying a voltage across the LC layer changes its effective refractive index, which in turn shifts the combined focal length of the optical stack. The module will operate at smartphone-compatible voltages and contains no mechanical actuators — eliminating the bulk, fragility, and power consumption of conventional voice-coil autofocus mechanisms.

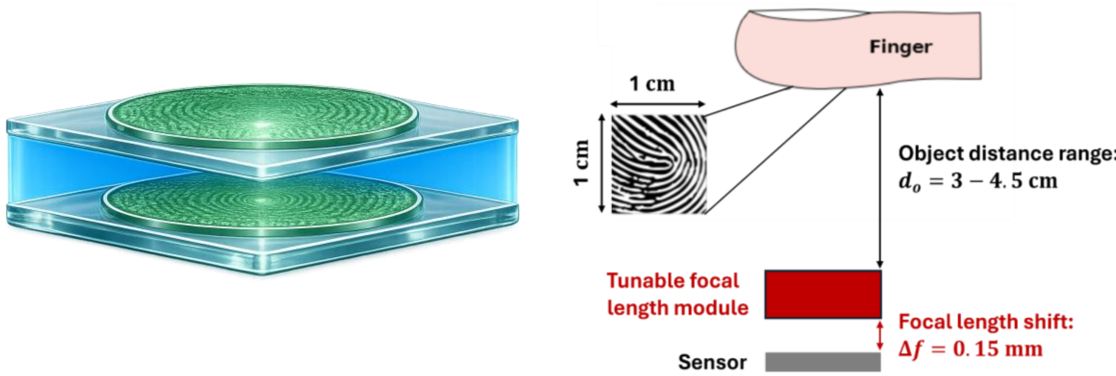

Figure 9: Tunable metalens camera module concept and application. Left: Concept rendering of a tunable metalens module. Two metalenses (green) with a liquid crystal cell (blue layer). Applying voltage shifts the effective focal length with no moving parts. Right: schematic of the target dimensions for fingerprint recognition application (Source: MetaOptics Technologies).

The total module thickness is below 4 mm, with the optical core under 2 mm — significantly thinner than voice-coil autofocus assemblies that typically require 4–6 mm. With no moving parts, the tunable metalens offers faster focusing (low-millisecond LC switching), lower power consumption, and complete immunity to vibration and shock. The metalens fabrication uses the same 12-inch DUV lithography process described earlier, ensuring scalable, low-cost manufacturing. Beyond smartphone autofocus and fingerprint sensing, the technology targets machine vision, medical and endoscopic imaging, LiDAR depth sensing, and touchless display interfaces.

From Singapore to the World: Building a Metalens Foundry

MetaOptics Technologies was listed on the Singapore Exchange (SGX) Catalist Board in September 2025—a milestone that provides the company with the capital base and market visibility to scale its technology globally. Since the listing, the company has undertaken a strategic reorganization to reflect its evolution from a prototyping-stage enterprise into a product-focused technology company.

The restructured organization, reflected on the company's updated website (www.metaoptics.sg), centers on four integrated capabilities: Metalens capital equipment, Metalens Foundry, Metalens Products and MetaOptics AI. This structure allows MetaOptics to serve customers across the full value chain—from initial optical design through production-ready modules.

As part of its long-term manufacturing strategy, MetaOptics is planning to establish a metalens foundry in the United States. This facility will bring 12-inch wafer metalens fabrication to American soil, providing domestic production capacity for US and global customers operating in automotive, consumer electronics, and telecommunications markets where supply-chain security is increasingly important.

The US foundry initiative builds on the company's existing collaboration with a major semiconductor equipment manufacturer to develop 12-inch direct-write and DUV lithography capabilities specifically optimized for metasurface fabrication. MetaOptics already maintains a US presence through MetaOptics Inc. in San Francisco, California, which serves as the operational base for its growing North American customer and partner network.

The combination of a proven design platform, established fabrication partnerships in Asia, an expanding US manufacturing footprint, and a growing portfolio of AI-enhanced camera and sensor products positions MetaOptics Technologies as a key enabler of the transition from conventional optics to flat, mass-producible metalens technology.

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