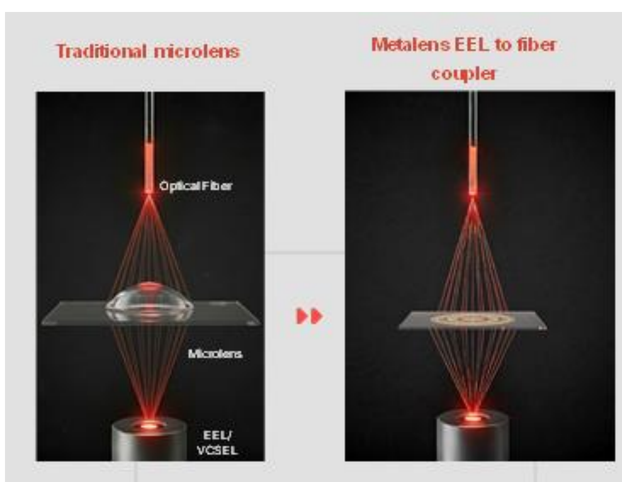
Metasurface Structures for Visible Wavelengths Now Possible with New Laser Writing System

By Chris Chinnock, Insight Media

Metasurface structures that can be used to manipulate light are already commercially available for IR and near-IR wavelengths. But extending this technology to visible wavelengths requires structure sizes on the order of 100 nm. Flat optics consisting of such small building blocks can eliminate traditional refractive optical elements providing the needed innovation in areas such as AR glasses, automotive head-up displays, pico-projectors, cameras, structured light, sensors, co-packed optics, and much more. Now, a new laser writing system is commercially available to enable the fabrication of small structures, suitable to compose visible spectral range metasurfaces.

Contents



What Are Metasurfaces?

A metasurface is composed of sub-wavelength nanostructures engineered to manipulate light in ways that natural materials cannot. Common shapes include:

- Nanopillars/Nanocolumns: Circular or square posts. These are used primarily for propagation phase control, where the diameter of the pillar determines how much the light is "delayed" (phase-shifted) as it passes through.
- Nanofins/Nanobricks: Rectangular blocks. Their asymmetric shape makes them highly sensitive to polarization. Rotating these bricks enables Pancharatnam-Berry (PB) phase control.

Metasurface structures act as local resonators or phase shifters. By varying their geometric properties across a surface, designers can control three fundamental attributes of light:

- Phase: Changing the width or rotation of the structures can bend light to a focus, creating a metalens, or generate complex holograms.
- Amplitude: Structures designed to resonate at specific frequencies can act as spectral filters that absorb or reflect specific colors.
- Polarization: Anisotropic structures such as nanobricks can change linear light to circular or filter out specific polarization angles.

These metasurface structures can function over a wide range of wavelengths, but their size is determined by the shortest operation wavelength. A simple rule of thumb is that the minimum feature size needed is 1/3 of the shortest wavelength requirement. For the visible spectrum (400 to 700nm), blue at 400 nm requires metasurface features less than 130 nm to operate.

Where Metasurfaces Can be Used

Metasurfaces can be used to replace conventional refractive or reflective optics to save space and/or reduce cost.

Capability	Primary Method	Application
Phase Control	Nanostructure rotation/geometry	Metalenses, Beam steering, Holography
Spectral Filtering	Resonant size/periodicity	Hyperspectral sensors, RGB color filters
Amplitude Control	Absorption/Scattering loss	Image processing, Grayscale holograms
Polarization	Anisotropic geometry	Polarimeters, Waveplates

For example, controlling the phase of light is needed to create a lens, to steer a light beam, or produce a phase hologram. Instead of designing curved surfaces, flat optics can be realized by designing the size height and spacing of truncated vertical waveguides, i.e. nanopillars. Creating a color filter for red, green or blue wavelength requires a different design that operates on a resonance principle to create the corresponding bandpass. Polarization control is achieved by arranging block-like elements in specific orientations.

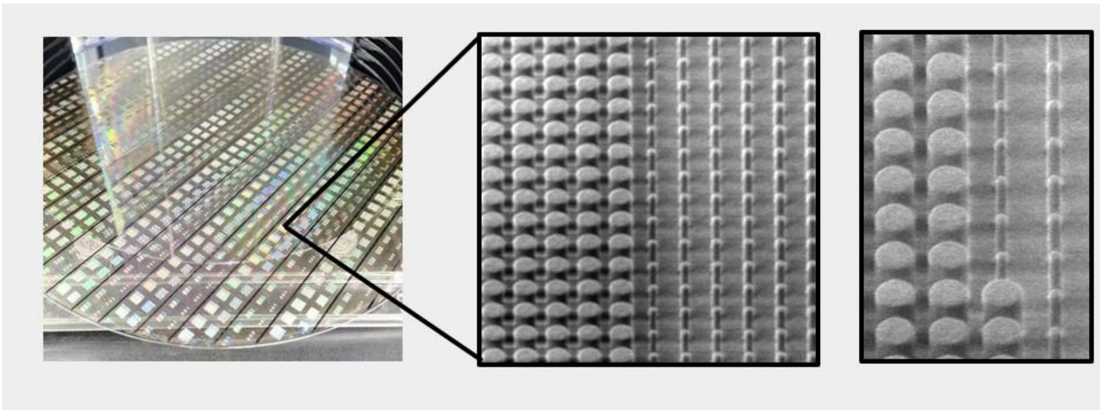


Figure 1: SEM Images of Metasurface Structures (source: Metaoptics Technologies)

Current State of Commercialization

Metasurfaces have been successfully commercialized for two important markets: Light Detection and Ranging (LiDAR) and 3D surface profiling. However, these applications use infrared light which only requires nanostructures down to about 200 nm size. Applications in the visible spectral range demand significantly smaller features.

LiDAR metasurfaces collect and shape a beam of light from arrays of infrared VCSELs. Infrared-based 3D surface profiling is used in phones or laptops for facial recognition and in cars for driver monitoring systems. Yet a great many devices rely on visible-light optical systems that could benefit from the cost, size, and weight reductions that metaoptics can offer.

How to Fabricate Metasurface Structures

While metasufaces can be of arbitrary size, current technology is best suited for small aperture applications below 5 mm. These nanometer-scale structures are fabricated with high-refractive-index materials like silicon nitride Si_3N_4 or, titanium dioxide TiO_2 on glass or silicon substrates. For nanostructures with sizes of 100 nm and below, several fabrication techniques are available. These include deep ultraviolet (DUV) photolithography, nano-imprint lithography (NIL), and electron-beam lithography (EBL).

EBL and NIL are typically performed on 8” substrates, while DUV lithography can accommodate wafer sizes up to 12”. EBL requires a vacuum environment and is inherently slow, making it suitable for prototyping but impractical for volume production. Fabricating structures at the 100 nm scale with NIL presents persistent yield and fidelity problems. The NIL process requires pressing a master mold — typically created using EBL — into photoresist to transfer the pattern. When the mold is separated after each imprint, resist inevitably adheres to its surface, distorting the delicate nanostructure geometry. At the critical dimensions required for visible-wavelength metasurfaces, even minor deformation compromises optical performance: maintaining near-vertical sidewall profiles on sub-150 nm pillars is extremely difficult with a contact-based transfer process. Compounding this, each imprint cycle progressively degrades the mold through mechanical wear and resist contamination, reducing pattern fidelity with every use and necessitating frequent, costly mold replacements.

A newly developed DUV direct-write laser tool now offers an alternative. It can create structures with 100 nm feature sizes on glass or quartz substrates at lower cost and higher throughput than the methods described above. Because it operates on transparent substrates, almost the full spectrum of light can pass through the finished device. The tool can produce visible light metalens in the 450nm - 650nm range, sensor or LiDAR structures in the NIR/IR 740nm - 940nm range, or co-packaged optical (CPO) communication devices in the 1245 - 1310nm range. It could even be used to create the master for NIL processing.

Direct Laser Writing Tool Key Innovation

A Singapore-based company called Metaoptics Technologies has now commercialized the first Direct Laser Writing tools capable of achieving around 100 nm feature size. It uses deep UV laser light (266nm) as the light source and a specially-developed metasurface optic to create a light "needle" that is smaller than the diffraction limit.

The diffraction limit is a fundamental consequence of the wave nature of light passing through a finite aperture. This limit is defined by 0.61*wavelength/ numerical aperture (NA) of the system. For a system with an NA of 1 and a laser wavelength of 266nm, the diffraction limited spot size is around 160 nm. So how can you create a spot size smaller than the diffraction limit? The answer is: with super oscillation metasurfaces, sometimes called super critical lenses.

Metaoptics Technologies designed the flat lens in their Direct Laser Write tool using a principle called super-oscillation. The idea is to design a pattern of nano structures that creates a static pattern of constructure and destructive interference at the focal plane. They are designed to have constructive interference at the focal center where a narrow peak is formed with destructive interference further from this peak. The concept is analogous to a noise cancelling microphone.

Using this approach, Metaoptics Technologies could create a stable spot size with a full width half maximum (FWHM) that is 0.37λ/NA (100nm). Figure 2 shows how the focus rings look very different in a super-oscillatory design compared to a Fresnel design.

However, the super-oscillatory spot is always accompanied by a halo of high intensity surrounding it at some distance. This is not an artifact or imperfection — it is a mathematical necessity. The energy that is squeezed out of the central spot must go somewhere.

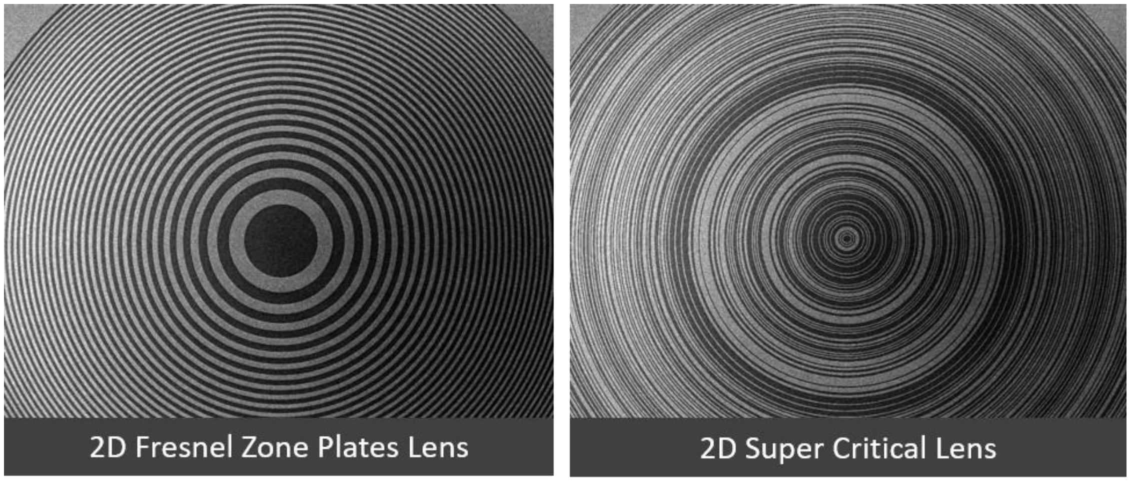


Figure 2: Fresnel Zone Plates are Diffraction Limited Whereas Super Critical (Super-Oscillatory) Lenses are Not (source: Metaoptics Technologies)

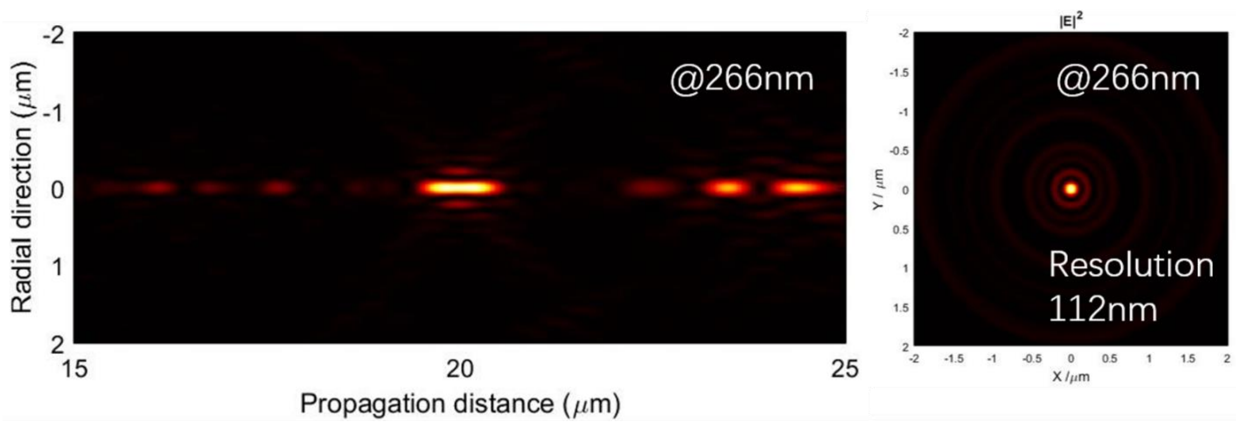


Figure 3: x-z plane and x-y plane profiles at 266nm (source: Metaoptics Technologies)

Figure 3 shows the simulated intensity profiles at the x-z plane at the wavelength 266 nm which indicates about a one-micron depth-of-field. This makes the tool highly suitable for fabricating high profile structures with very steep sidewalls. The simulated profile in the x-y plane shows a point spread function with a small side-lobe halo, suggesting a resolution of 112 nm.

The design of this super-oscillation metasurface has been carefully engineered by Metaoptics as the design requires some key trade-offs in the design space to balance the spot size, halo intensity, and the depth of focus.

Direct Laser Writing Tool System

Figure 4 shows the configuration of the DLW tool from Metaoptics Technologies. This tool is designed to fabricate nanostructures on glass or quartz opening opportunities that have not yet been commercially viable. The glass/quartz substrate size is limited to 4 inches as it is important to prove this tool in metasurface fabrication and pilot production. Metaoptics Technologies has plans to develop a new tool to handle 12” round glass substrates once mass production partners are ready. In addition, work is already underway to enable the tool to be used with silicon substrates in the future.

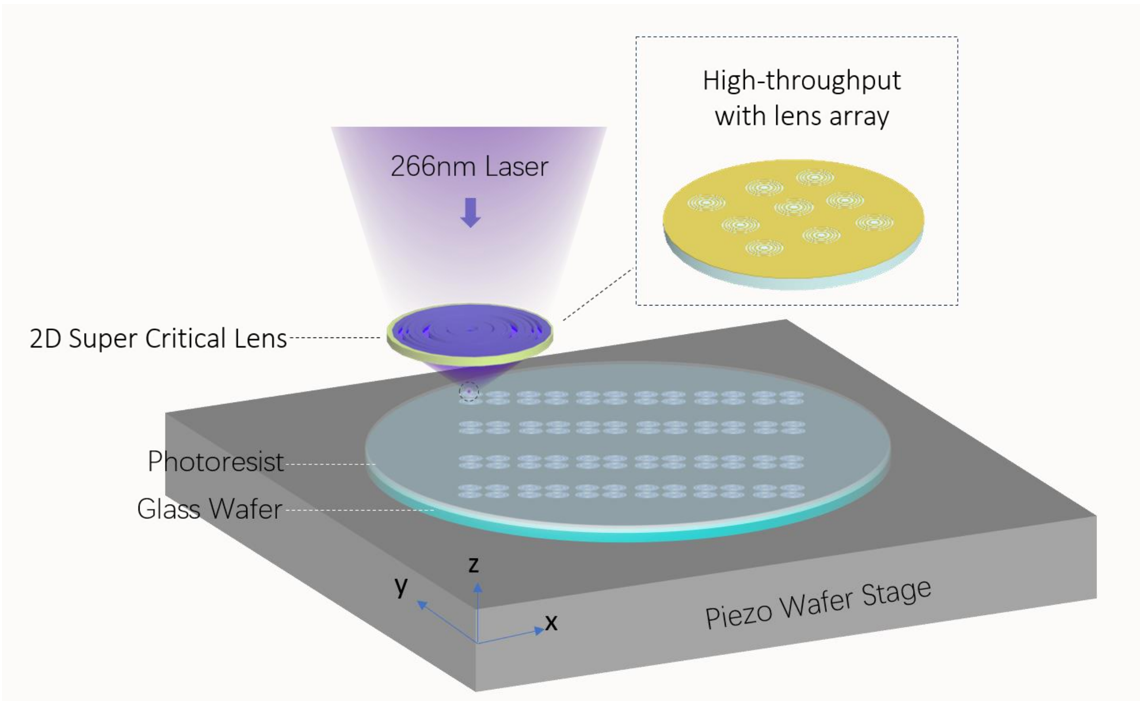


Figure 4: Direct Laser Writing System Configuration (source: Metaoptics Technologies)

Writing Specifications:

Minimum Critical Dimensions (CD) For Circular Pillars: **120 - 150nm**

Minimum Linewidth: **90nm**

Laser Source: **266nm**

Maximum Writing Speed: **100mm/s**

Maximum Exposure Area: **135mm x 85mm**

Autofocus Compensation Range: **±100nm**

Minimum Surface Roughness: **≤20nm**

Repeatability in X / Y / Z: **±2 / ±2 / ±3 nm**

Substrate Size: **Min 1cm x 1cm or Ø1cm, Max 4″ x 4″ or Ø4″**

Figure 5: Writing Specifications for Metaoptics Technologies Direct Laser Writer Tool

Key writing specifications are shown in Figure 5 with the commercially available system depicted in Figure 6. Note that for single lines, the tool can achieve a 90 nm spot size, but when constructing circular pillars, the minimum size is 120 nm – perfectly acceptable to cover the full visible range of the human eye.

Figure 6: Metaoptics Technologies Direct Laser Writer

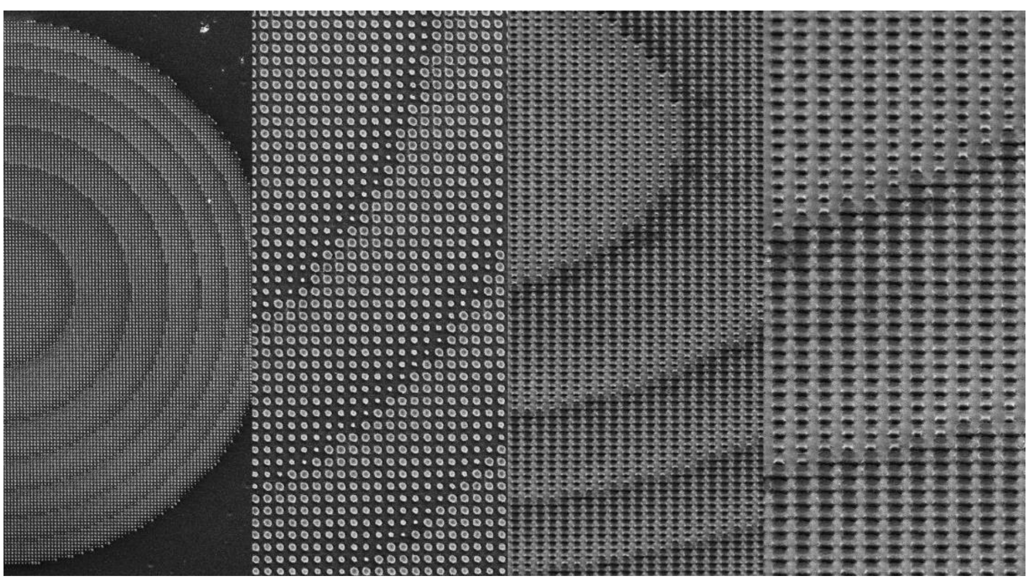


Figure 7: SEM images of Metalenses with pillar diameters from 200 nm to 400nm and center to center distance of 600nm, fabricated by DUV DLW for Co-Packaged Optics (source: Metaoptics Technologies)

Metaoptics Technologies offers two types of super-oscillatory metalenses in their DLW tool. For the smallest spot size of 100nm, a single super oscillatory lens is used. This mode is best for creating straight line-based structures and can even be used to create conventional silicon-based photolithography masks, offering a cost-saving options to foundries.

For small circular pillar structures, the laser operates in pulse mode to increase writing speed. Circular pillars as small as 150 nm have been demonstrated. For larger circular pillars, the laser operates in a spiral mode.

For IR-based co-packages optics, the critical dimensions are much larger - around 200 nm for the metasurface features. In this case, the single super-oscillatory lens can be replaced with a 32 element super-oscillatory lens array. This allows the DLW tool to simultaneously write 32 co-packaged optics lenses – each with a diameter of 0.127 mm and containing 40,000 circular pillars - in a single hour (Figure 7).

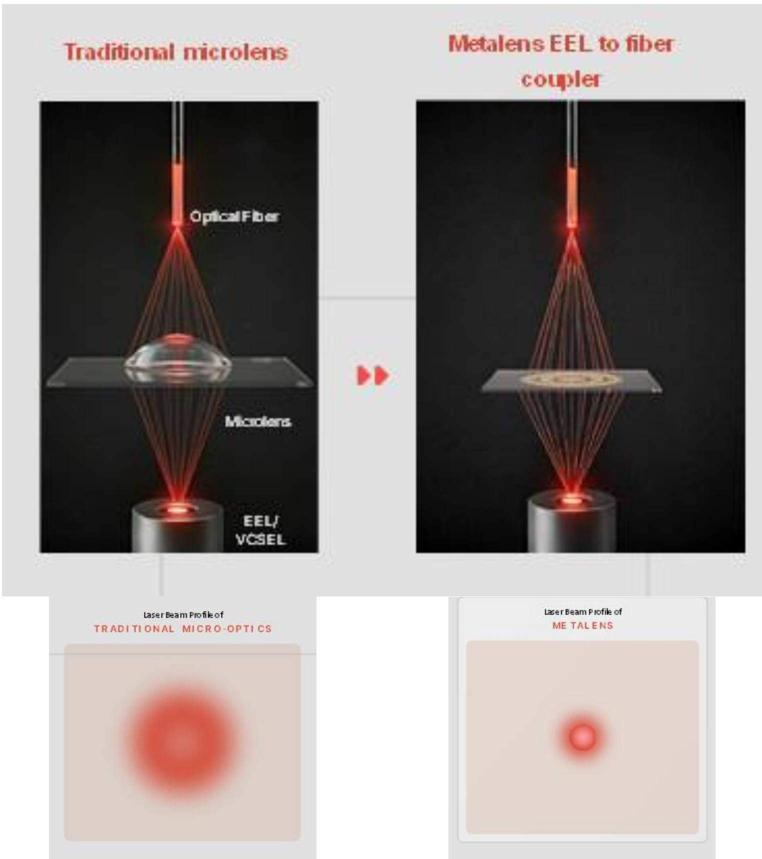


Figure 8: Geometric vs. Metalens Lens for Fiber Coupling (source: Metaoptics Technologies)

Co-packaged optics are critical for coupling light into fiberoptics. Metalenses can now replace conventional geometric lens arrays to save space and potentially reduce cost as well (Figure 8).

Process Steps

To fabricate metasurface structures with the Direct Laser Write tool, the first step is to coat the entire glass or quartz wafer with a uniform layer of Silicon Nitride Si_3N_4 or Titanium Dioxide TiO_2. Next a specially formulated UV curable photoresist layer is spin coated onto the substrate. The DLW tool then exposes the photoresist on the metasurface structure pattern, followed by the development of the photoresist to remove the unexposed material. This exposed area is then etched (dry or wet) to reveal the metasurface features. A final cleaning step removes the exposed photoresist above the features.

Key Value Propositions

This is believed to be the first commercially available direct laser writing tool capable of creating metasurface features of this size. With a high precision, 6-axis piezo-driven stage, consistent fabrication of metasurface structures (Repeatability in X / Y / Z: ±2 / ±2 / ±3 nm) over the 4-inch square or round glass/quartz substrate are now possible in hours rather than days or weeks with alternative methods. Rapid prototyping and quick-turn services of 7-10 days are possible with this new tool, compared to months with alternative technologies.

The tool can operate in a non-vacuum environment – a significant advantage over alternative fabrication tools for features in this size range.

Markets for this Tool

MetaOptics DLW tool fills a gap in the market for tools that can fabricate structures between 100 and 300 nm. It also offers a competitive advantage vs. alternative methods that are much slower and more costly. This is summarized in Figure 9.

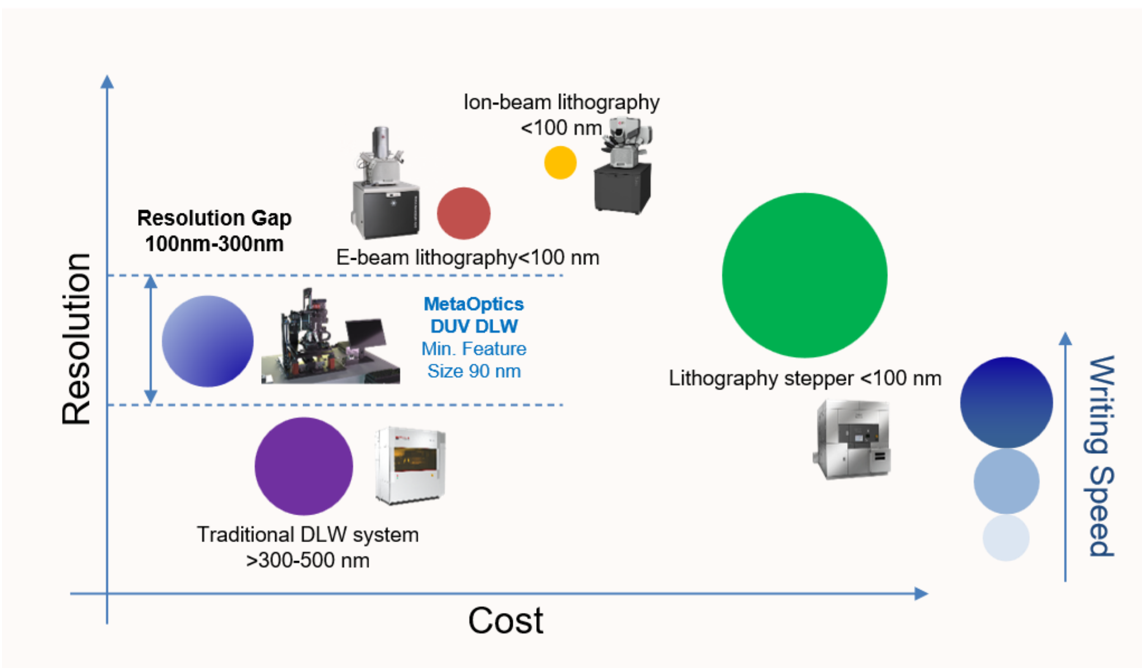


Figure 9: Resolution vs. Cost - The resolution gap between 100 nm-300 nm filled by MetaOptics DUV DLW (source: Metaoptics Technologies)

There are many small aperture applications with visible light where a metasurface flat optic can replace a conventional refractive optical element. Some include:

- Miniature cameras in smartphones, drones, robots, etc.
- IR 3D sensing for cars, phone, laptops, etc.
- Gesture recognition
- Eye tracking devices
- Laser light collimation, filtering or steering
- AR glasses projection engines
- AR glasses waveguides
- Endoscopes and medical imaging devices
- Miniaturized fluorescence microscopes
- Co-packaged optics for chip-to-chip or system-to-system communication
- Photonics on chip optical modules
- Navigation and positioning instruments
- Industrial inspection equipment
- Scientific and research instrumentation
- Fiberoptic coupling
- Barcode and industrial scanners
- Optical encoders
- Security and surveillance pinhole cameras

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