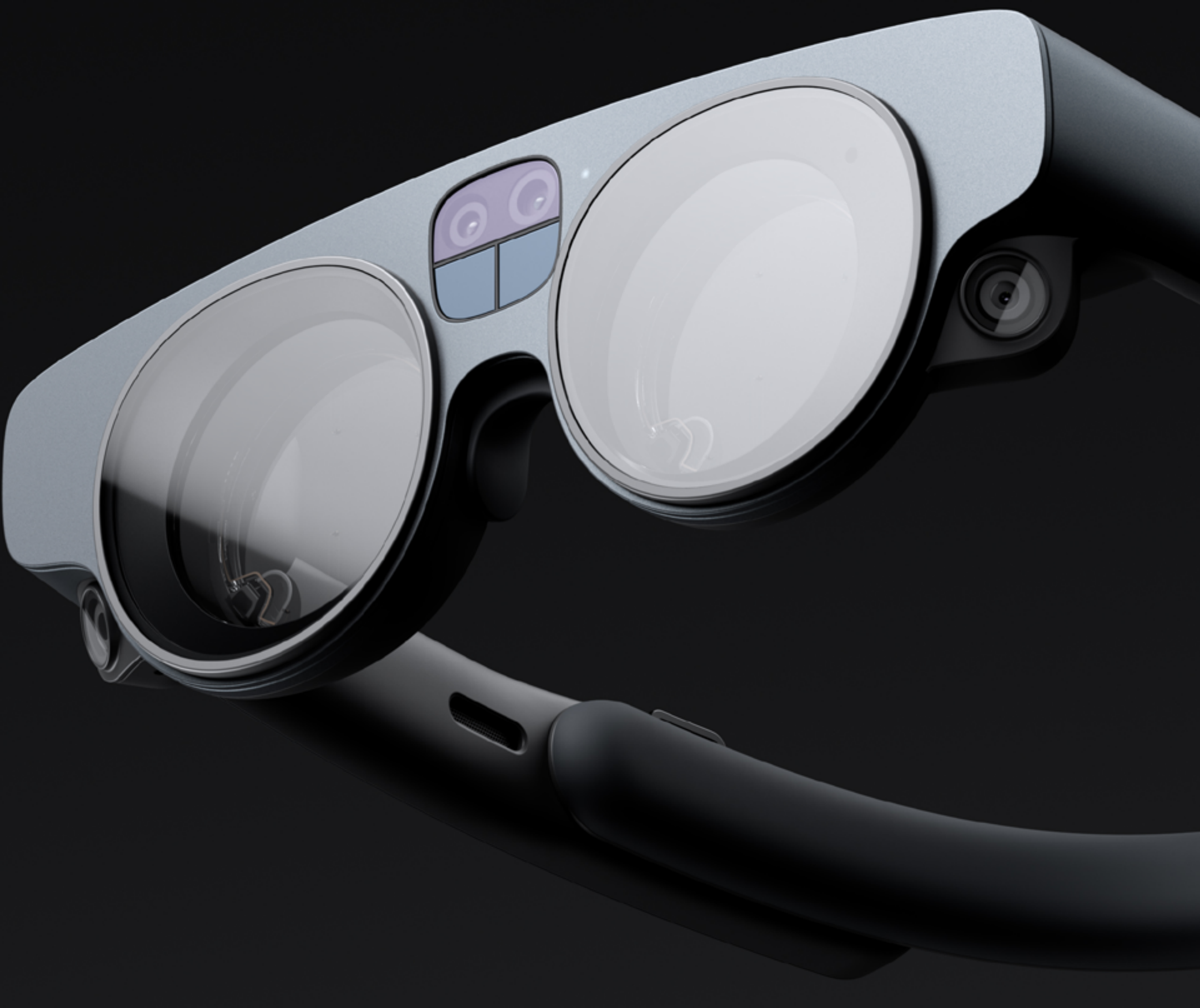
Magic Leap 2's Advanced AR Platform and Revolutionary Optics

White Paper
February 2022



Magic Leap

Introduction: Four Optics Breakthroughs to Power Enterprise AR

When it launches later this year, we believe Magic Leap 2 will be the most advanced enterprise platform for the most immersive augmented reality (AR) solutions. It brings a huge leap forward in optical performance, offering critical benefits to end-users, developers, and enterprises.

To create it, our engineering team had to solve four of the toughest challenges in AR optics. The innovations of Magic Leap 2 were built upon the lessons of Magic Leap 1, customers’ feedback, and the problems limiting AR devices and applications.

This led us to the four major optics advances on Magic Leap 2:

- Breakthrough architecture doubles field of view in a smaller device.
  Magic Leap 2’s proprietary optics architecture enables more immersive AR experiences in half the device volume, with excellent image quality.
- Dynamic dimming brings AR into bright conditions.
  Our unique dynamic dimming solution enables Magic Leap 2 to work across a huge range of ambient light conditions, from outdoors to operating rooms.
- Unique solutions enable comfortable viewing and extended wear with a simplified optical system.
  Novel solutions minimize common sources of eye strain for comfortable viewing of near and far virtual objects in a single focal plane.
- Unmatched manufacturing ensures precision at scale and enables high performance from a diffractive eyepiece.
  Our in-house manufacturing capabilities produce Magic Leap 2’s advanced optics at scale with incredible quality, high efficiency, and a path for future advances.

This white paper explores each of these advances: the challenges we faced, how we solved them, and the potential real-world applications and benefits. We also include a Technical Appendix that goes into greater detail on the science behind each solution.

These breakthroughs promise to elevate every enterprise AR solution, while empowering developers to push even further. We designed Magic Leap 2 as not only a powerful AR platform, but a tool that workers and enterprises can use every day, integrating the most immersive solutions into their work.

We’re extremely proud of Magic Leap 2—and we’re excited to see how businesses, developers, and the ecosystem make use of those advances to build the future of enterprise AR.

Kevin Curtis
VP of Optical Engineering
Magic Leap

Breakthrough Architecture Doubles Field of View in a Smaller Device

Challenge: Twice the FOV, Half the Size

Expanding the Field of View (FOV) was a design priority for Magic Leap 2. Customers told us FOV was critical to their use cases, especially for cooperative work. But we also wanted to decrease the size of the projector by a factor of 2x—leading to a major optics challenge.

Through years of rigorous research, our optics team concluded that the currently available projector options (uLED arrays, laser-scan-based systems, LCoS panels) were not sufficient. These projectors were either too large, consumed too much power, or led to a Pandora's box of image artifacts.

Adapting the eyepiece for a larger FOV also presented a design hurdle. If we simply enlarged Magic Leap 1's eyepiece, its surface area would have to increase by over 50%—or, as big as a hand, making it too big for practical use.

Our Solution: Advances in Projector and Eyepiece Design

Our team invented a new projector architecture and eyepiece design (rendered below) to solve these challenges:

- New projector architecture:
  We invented a new projector architecture that solved the issues with all other LCoS based projectors, which enabled larger FOV with much smaller size and higher efficiency (described in Technical Appendix).

- New eyepiece design:
  Using modeling software developed at Magic Leap, we designed new 2D pupil expansion, double sided, and spatial varying grating thicknesses to achieve a 70 degree FOV eyepiece with high efficiency, large eye-box, and exceptional uniformity.

Magic Leap 2 architecture and its benefits

- 2x Field of View, ½ the volume
- 12x more efficient
- 20-2,000 nits of brightness, with dynamic dimming
- Roadmap to higher FOV, smaller form factor

*Compared to Magic Leap 1.

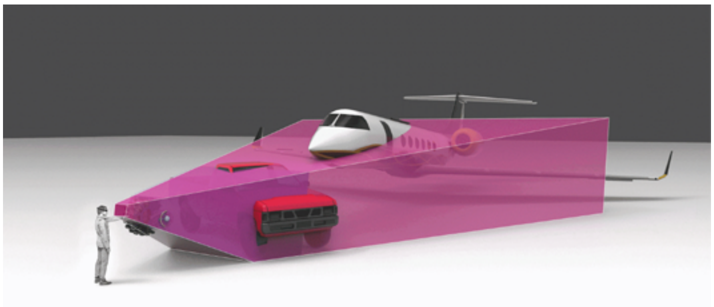
Why It Matters: More Immersive AR Solutions

Magic Leap 2's advanced architecture enables more immersive AR solutions. It offers twice the FOV (44.6 x 53.6 x 66º) in a smaller form factor, with 2x image quality, 2-3x color uniformity, and 100x reduction in front rainbows.[1]

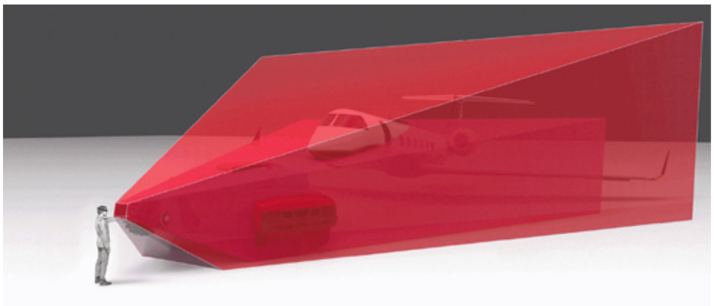
The larger FOV, especially its larger vertical direction, provides direct benefits to enterprises and end-users. Some potential examples:

- Two or more colleagues can comfortably view and collaborate on virtual content from different viewing angles.
- A doctor can visualize a full person for health applications.
- An engineer can see and modify a full-scale Computer Aided Design (CAD) model.
- A contractor, architect, or property developer can walk through a building site and see plumbing, electrical, and other construction elements.
- An analyst can visualize data at room-scale.

Looking ahead, we have already partially validated this roadmap with Magic Leap 3 projectors and bionicles that offer larger FOV and 50% smaller volume for projector and integrated stack. This architecture could ultimately achieve 80+ degree FOV in <1000mm3 projector.



FOV: Magic Leap 1



FOV: Magic Leap 2

[1] Versus Magic Leap 1.

Dynamic Dimming Brings AR Into Bright Conditions

The Challenge: Solid Digital Content Almost Anywhere, Even Outdoors

We wanted Magic Leap 2 to work across a huge range of ambient light conditions – including bright areas like outdoors or operating rooms. But virtual content gets washed out in these environments, which has limited where and how workers can use AR devices.

While Magic Leap 2 can reach up to 2,000 nits of brightness, this still isn't enough to compete with direct sunlight. And making the display even brighter would have required consuming more power, in a bigger form factor.

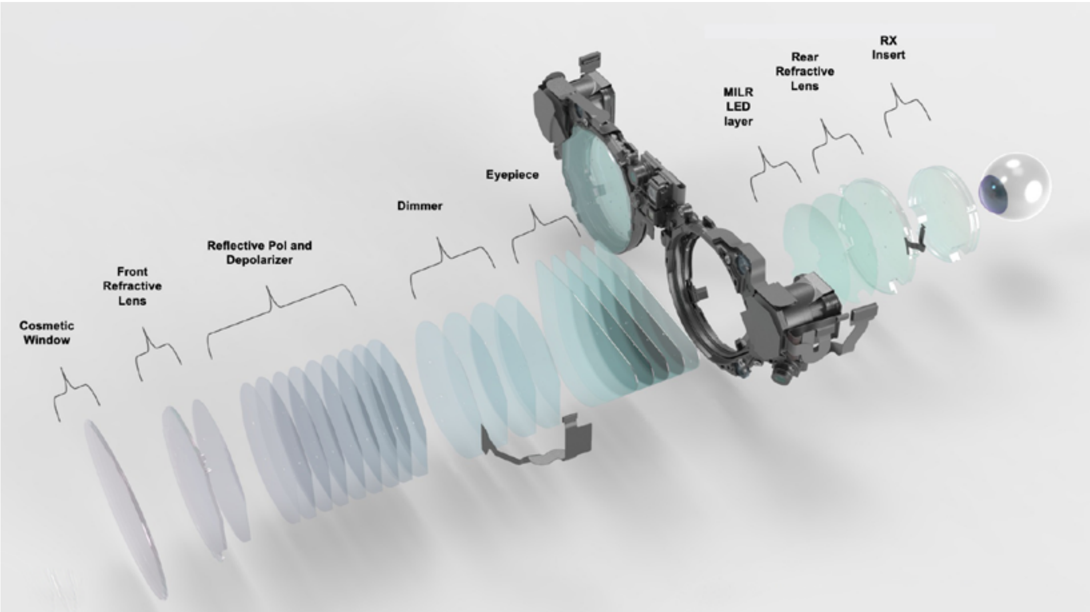
Our Solution: Dynamic Dimming Capabilities

We turned to a unique solution: dynamic dimming capabilities. Magic Leap 2 is the first general purpose AR device to feature dimmers integrated into the optical stack. This enables two types of dimming capabilities:

- Global dimming:
  Magic Leap 2 can dim the entire environment to ensure clear, solid, and vibrant digital content in bright areas. The dimmer can automatically adjust based on the brightness in the room and the brightness of the projector; we're also exploring how to give end-users control of this capability.

- Segmented dimming:
  Magic Leap 2 enables applications to locally dim just the part of the display with virtual content. The segmented dimmer results in excellent virtual image quality, as background light is eliminated. The segmented dimmer also enables the rendering of black, which is impossible without a dimmer. This feature also allows for minimum amount of virtual light leakage into the real world.

Magic Leap 2 optical stack



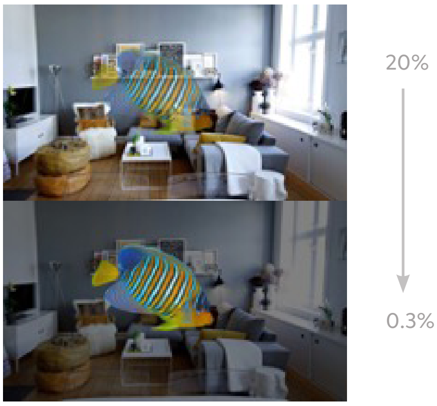
Why It Matters: Use AR Across a Range of Light Conditions

Dynamic dimming improves the user experience on Magic Leap 2 and enables it to work in more environments. This could include use cases like:

- Enabling workers to see solid virtual content outside, like construction sites or outdoor facilities.
- Bringing immersive AR solutions into brightly lit operating rooms, where it can help with surgery and related health needs.
- Providing a better experience for people next to windows, in brightly lit conference rooms, or bright industrial spaces.
- Ensuring easy text and image legibility for stationary blocks of content, such as menus, interfaces, and instructions.

Segmented Dimming

Global Dimming



Unique Solutions Enable Comfortable Viewing & Extended Wear with a Simplified Optical System

The Challenge:
Minimize Visual Discomfort for Near & Far Viewing

When viewing virtual content, a number of problems can cause visual discomfort. Vergence-accommodation conflict occurs when your visual system senses that your eyes' focus and rotation don't match. Incorrect render perspective occurs when the AR device misperceives the location of your eyes and renders incorrectly. Bionicle misalignment occurs when the virtual image in your right eye doesn't match your left eye.

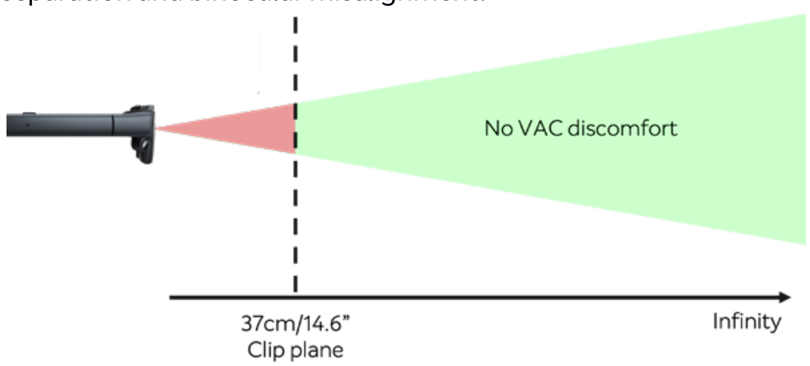
Magic Leap 1 addresses the vergence and accommodation conflict by using two focal planes, but this requires larger, more complex hardware. To enable a smaller form factor and a larger viewing volume, we needed to ensure comfortable viewing of near and far objects on a single focal plane.

Our Solution:
New Systems for Greater Visual Comfort

We developed a suite of solutions that address these common causes of discomfort, enabling users to view content at near (37cm) and far (infinite) distances. We have validated these solutions with both our own studies and review of the scientific literature:

- Robust eye-tracking:
  Magic Leap 2 tracks each eye with two unobstructed cameras, together with 6 Light Emitting Diodes (LEDs) to illuminate and generate eye "glints." This enables precise tracking of the very center of the eye, which improves rendering and therefore image quality and comfort.
- Smart focal plane choice:
  Our studies find that combining robust eye-tracking with smart choice of focal plane minimizes discomfort for a large comfortable range of operations. For additional comfort, Magic Leap 2 has a clip plane at 37cm—the distance where VAC can lead to negative effects.
- Automatic display calibration:
  Magic Leap 2 automatically calibrates the display to correct for any bionicle misalignment or color separation. When the user suspects mis-alignment or color separation, they can run a program with this system, which displays and detects an alignment test pattern, then makes necessary corrections to minimize color separation and binocular misalignment.

Magic Leap 2 enables comfortable near and far viewing



Why It Matters: Comfortable Viewing, Longer Use

Comfort is essential for real-world usage. Together with the smaller, lighter form factor, solutions for near and far viewing make Magic Leap 2 a practical tool for all types of workers and roles:

- Workers can comfortably view virtual content on Magic Leap 2 for extended periods, enabling them to use enterprise AR applications for longer, throughout the day.
- End-users can see both close-up content and distant content while minimizing eye strain.
- Magic Leap 2's clip plane prevents discomfort, nausea, or headaches from content that appears too close to the user.

Unmatched Manufacturing Ensures Precision at Scale and Enables High Performance from a Diffractive Eyepiece

The Challenge:
Make It All in High Volume

Optics technologies are only viable if they can be produced with high-quality at scale. This is the final hurdle for AR devices, and it comes with its own set of unique challenges.

At Magic Leap, we want to provide the AR platform that enterprises and end-users rely on to get work done. That requires reproducing our optics advances at industrial scale, while always maintaining image quality—fabricating tens of thousands of eyepieces, quickly, reliably, and without defects.

Our Solution:
100% Control of Eyepiece Fabrication

Magic Leap has built an unmatched in-house manufacturing capability. We control 100% of the eyepiece fabrication process, imprint, and manufacturing and metrology equipment, enabling us to achieve an impressive yield rate (currently >90%). Our proprietary, high-value processes and equipment include:

- Unique jet and flash imprint lithography:
  Magic Leap owns every aspect of this nano-patterning technology — a key enabler of display performance. By precisely controlling the volume of resin across the waveguide, this nano-imprint process achieves higher uniformity and efficiency performance.
- Versatile nanostructure fabrication:
  Our nano-imprint process opens many options for the structure of waveguides. We can develop 1D, 2D, and 3D nanostructures and combine different types of structures within a single waveguide element.
- In-house metrology and innovative quality control:
  Our team has also developed innovative solutions to detect defects and ensure quality. These include machine-vision-based inspection of transparent substrates, a stack and layer inspection system, and automated, in-line stack metrology.

Why It Matters:
Elevate User Experience,
Meet Enterprise Demand

Our manufacturing expertise and intellectual property adds value to our products and positions Magic Leap to meet growing demand. We estimate the capacity to produce more than 100,000 units each year, with the space, best practices, and machinery for further growth. This enables:

- Immersive AR solutions and incredible user experience, with Magic Leap 2's 2x sharpness, 2-3x color uniformity, 12x efficiency, and 100x reduction of rainbows.[2]
- Reliable products for large enterprise deployments, based on Magic Leap's 37 critical-to-quality parameters, including dimensional and optical key performance indicators (KPIs).
- Ongoing scaling and innovation, tapping our expert in-house teams and proprietary equipment to move quickly from research and development (R&D) to manufacturing at scale.

100k+	37	2x	100x
units per year	critical-to-quality parameters	sharpness	reduction in front rainbows

Conclusion: Looking to the Future of Enterprise AR

By solving four critical optics challenges, Magic Leap 2 is designed to be a best-in-class device for the most immersive enterprise AR applications. It's the result of years of hard work, collaboration, and investment—and we believe it represents the future of enterprise AR.

These proprietary solutions deliver real-world advantages. Doubling the FOV while shrinking the form factor by 50% enables more immersive experiences and a more comfortable headset. Developing a global and segmented dimmer enables solid virtual content across a huge range of ambient light conditions.

By minimizing render perspective errors, we made a device with one focal plane that still has the 37cm to infinite range of depth for virtual content. This results in a better form factor and much simplified device. And finally, Magic Leap 2 features huge improvements in eyepiece performance enabled by our design and unique manufacturing process and large improvements to sharpness, brightness, efficiency, and rainbows—all while maintaining a high yield manufacturing process.

By solving these issues and customizing the platform to support enterprise use cases, Magic Leap 2 is poised to become the leading enterprise AR platform. Our optics team looks forward to collaborating with developers, enterprises, and the ecosystem to deliver on that potential.

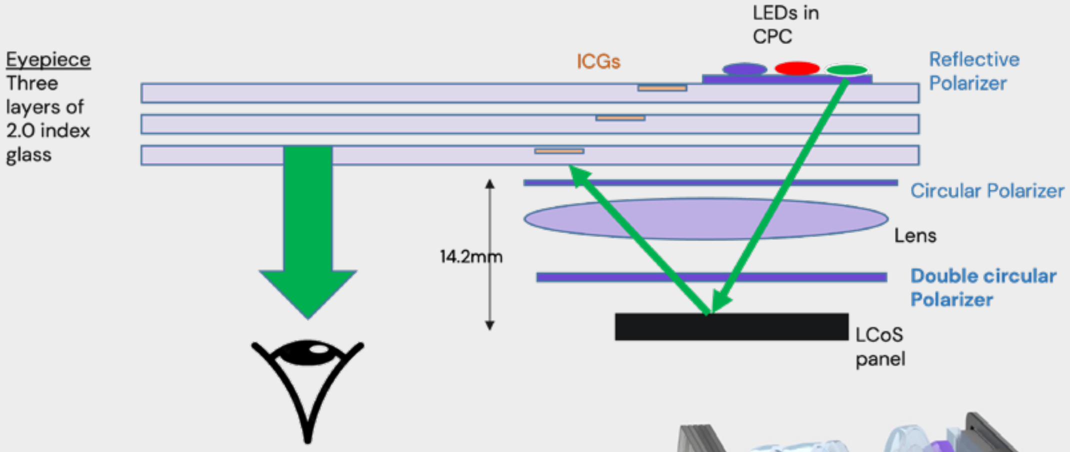
[2] Versus Magic Leap 1.

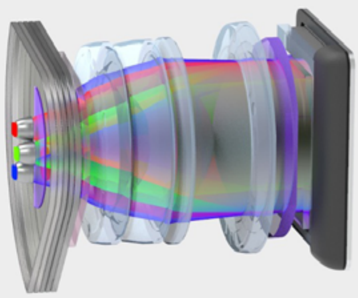
Technical Appendix

How It Works: FOV & Image Quality

In Magic Leap 2's architecture, the light follows a path optimized for FOV and comfort. The light module at top has three circular LED (RGB) in compound parabolic concentrators (CPCs) shining through a reflective polarizer to efficiently recycle light. The light then goes through three 2.0 index substrates, a circular polarizer (CP), and the lens. The lens has low birefringence and is temperature compensated, so the focal length changes very little with temperature. The light travels through a double CP (quarter wave plate - polarizer-quarter wave plate) to be incident on the LCoS. The LCoS reflects and sends the light through the double CP (which analyzes the light), the lens, and CP to be incident of the in-coupling grating (ICG) of the correct waveguide. The light goes down the waveguide, expands the pupil, and exits to the eye.

Waveguide Incoupling Gratings



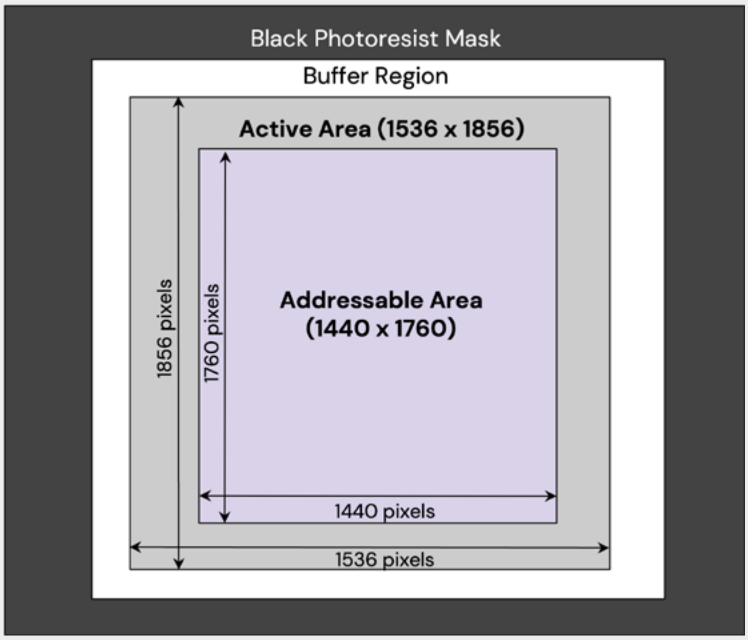


The lens is used as a projector lens relative to the LCoS and is a 4F imaging system for the CPC output to the ICGs. The CPs act to kill reflections and ghosts in the system. Red and blue light each follow a similar path but are routed instead to the ICG on their respective waveguides. The LCoS is driven at 120 frames per second with ~360 Hz color fields.

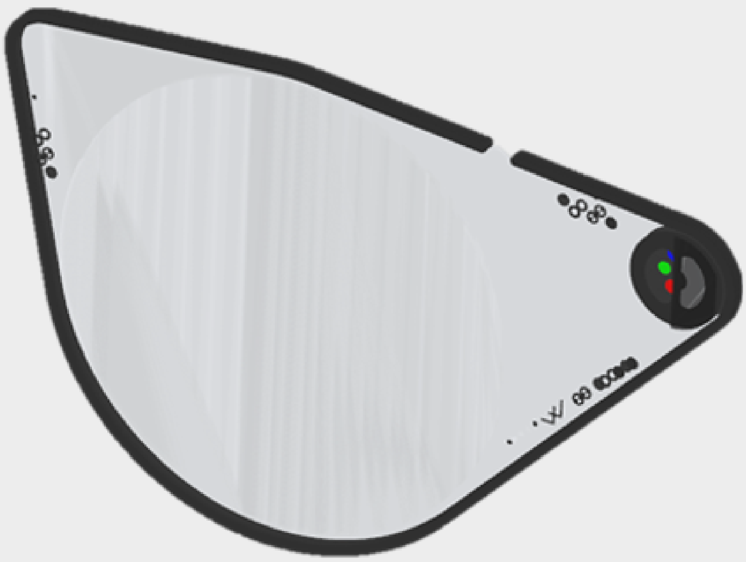
The FOV of the projector and the waveguides is designed to support 70-degree FOV; however, we use 45x55x67 degrees to allow for the image to be shifted on the LCoS, which can change the output angle to correct for boresight alignment during manufacturing, color separation, and binocular misalignment in the field. This is called function on-line calibration. The following formula uses the tangent of the angles to determine the diagonal angle:

$$\Theta_{diagonal} = 2 \cdot arctan\left(\sqrt{tan^2(\Theta_x/2) + tan^2(\Theta_y/2)}\right).$$

The next figure shows the use of the pixel on the LCoS. The addressable image size is 1440x1760 per eye; however, this block of pixels can be shifted in a 1536x1856 pixel array to correct for misalignments during manufacturing and to enable on-line calibration without affecting the FOV. On-line calibration corrects color separation bionicle misalignment automatically. The addressable area can be shifted by 96 pixels in both directions, and the shift is done per color field. The 45x55x67 FOV is slightly decreased by lenses in the integrated stack and by distortion correction in the display pipeline.



Eyepiece Design:
To enable the larger FOV, we designed a new proprietary eyepiece. The eyepiece architecture runs on high performance clusters written by our team, which allow us to accurately model subtle physics effects and evaluate performance over real-world tolerances found in the manufacturing process.



A major change was a higher refractive index substrate. In Magic Leap 1, we used a glass with index 1.8, and for Magic Leap 2, we used an index of 2.0, which greatly facilitated a larger FOV. Magic Leap's proprietary Jet and Flash Imprint Lithography process allows use of very high index substrates without necessitating a comparable increase in imprint resist index. In addition, using equipment built in-house, it was possible to place gratings on both sides of the substrate, giving even more design flexibility, helping achieve desired performance targets.

We also use spatially varying grating efficiency, achieved through the variation of grating depth. Magic Leap's process currently allows up to 32 distinct depths, which gives significant design degrees of freedom to optimize performance trades. Our unique imprint approach enables us to make maximum use of the variable etch depth, matching resist dispense volume to grating depths locally, resulting in an exceedingly faithful copy with constant ultra-thin residual layer thickness (RLT) everywhere. This ultra-thin RLT (10s of nm) means our imprint material's index of refraction does not need to be as high as the substrate's without sacrificing performance. This enables us to practice nano-particle free resists, which have an inherent advantage of low scattering loss. The resulting Magic Leap 2 eyepiece demonstrates 7x improvement in eyebox efficiency (average over the FOV), increased eyebox size for single SKU use, and 2x increase in out-coupling area.

How It Works: Dynamic Dimming

We developed and implemented the first global and segmented dimmer in Magic Leap 2's integrated stack. The components of Magic Leap 2's integrated stack include:

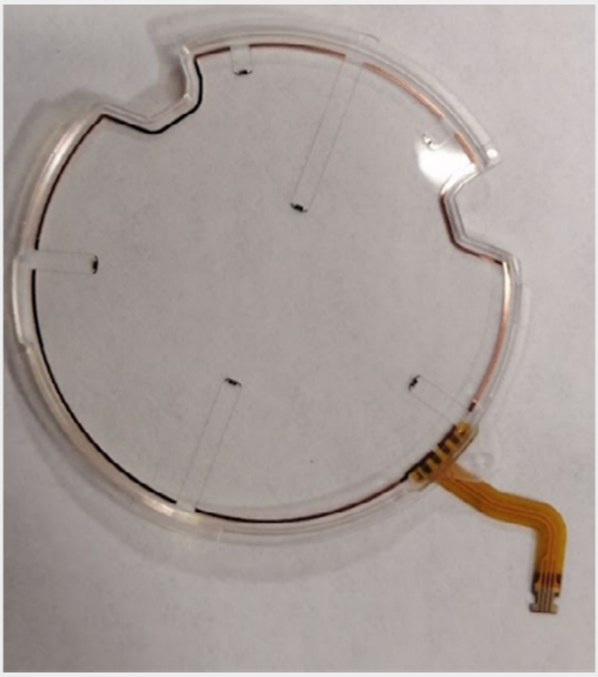
- A depolarizing film so that polarized screens (cell phone, laptops) can be viewed without artifacts
- A reflective polarizer to polarize the world light
- Two extended depth of field (EDOF) lenses that work together to keep the outside world unchanged while the virtual image is brought from infinity closer to the user
- A dimmer assembly that helps reduce rainbow artifacts by a factor of roughly 80 times. This plus the high 2.0 index of the waveguides kills most rainbows under usual conditions
- The eyepiece is with three active layers for red, green, and blue
- The second EDOF lens also has a LED layer which is used as illumination for eye tracking
- Rx inserts to correct the user's eyesight as needed

The overall optical transmission of the Magic Leap 2 is approximately 22%. To enable Magic Leap 2's use in settings like a bright operating room or outdoors, we needed to find a solution other than increasing brightness. Magic Leap 2's dimming technology enables us to globally dim the environment, or locally dim a part of the display where we are rendering virtual content. The dimmer runs at 120 Hz to match the display. The maximum dimming contrast ratio is about 100:1.

How It Works: Comfortable Viewing

Eye Tracking:
The hardware solution to render perspective error is robust eye tracking of the eyeball center (EBC). We made several key improvements to Magic Leap 2 to ensure robust eye tracking for all users in all wear and lighting conditions. The eye-tracking illumination layer (shown below) has 6 carefully positioned LEDs to illuminate the eye and generate glints.

Illumination Layer (6 Flip Chip IR LEDs)



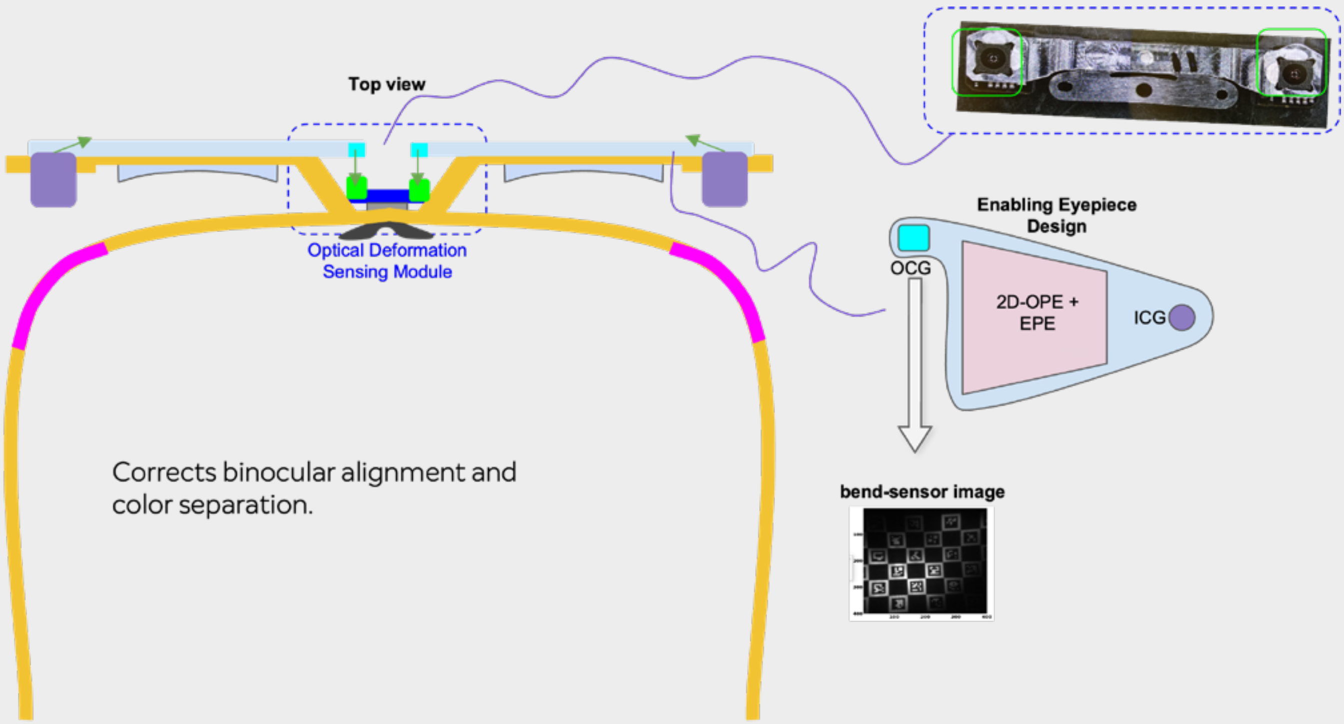
Magic Leap 2 then captures these glints with 2 unobstructed cameras per eye. These are shown in the two images on the righthand side of the figure above. The right top shows the position of the 2 eye tracking cameras on the frame for the right eye. The bottom right shows the cutouts (windows) in the Rx inserts to allow a clear view of the user's eyes.

With robust eye tracking to minimize render perspective errors—as well as smart choice of the focal plane—Magic Leap 2 can have just one depth plane with equivalent comfort as Magic Leap 1. This has been validated by several large studies.

Display calibration:
The figure below shows the display calibration system. The eyepieces are developed with an additional out coupling grating near the nose. In the nose area, there is a part that consists of 2 cameras rigidly attached together to maintain alignment to each other across temperature changes and usual wear (top right).

When the user suspects mis-alignment or color separation, they run a program that displays an alignment pattern in separate red, green, and blue fields by the two projectors into the two eyepieces and detected by the two sensors. Any relative change in boresight for each color can be determined. This detects and automatically corrects bionicle misalignment and color separation. By using a test pattern, the online calibration can correct for both optical and mechanical changes to the headset.

Online display calibration



How It Works: Optics Manufacturing

Image quality, efficiency, and yield improvements:
For Magic Leap 2, we wanted to dramatically improve image quality and efficiency, as well as yield. We focused on image quality KPIs like sharpness, measured in Modulation Transfer Function (MTF), and associated text legibility, color uniformity, luminance uniformity, and rainbow (diffraction of external light sources by the diffractive structures in the waveguide). To support the larger FOV, larger eyebox, and smaller form factor, we also needed to increase the efficiency of the system dramatically. And we had to do all of this in a way that was manufacturable in volume with high yield.

The three images below show the raw optical output of the units over the 66-degree FOV. This is before distortion correction or color uniformity correction has been applied, which typically improves uniformity by about 2x. The results are 2x MTF, 2-3x better color uniformity (raw) and reduction of rainbows of 100x, increase in efficiency of 12x.

PEQ1B Wearable - November 2020
Achieved lightfield production KPIs

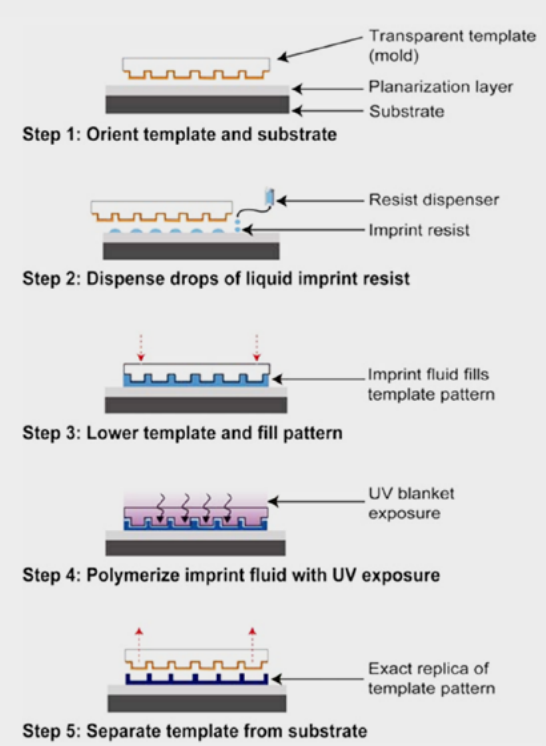
The eyepiece is a major contributor to MTF improvements. In Magic Leap 1, the distance between virtual content and the user was set by incorporating optical power into the out-coupling gratings. In Magic Leap 2, depth setting is accomplished using external lenses, allowing the eyepiece to avoid the negative MTF impact. In addition, many details in eyepiece design and manufacturing minimized stray light noise and ghosting to achieve excellent text legibility. Rainbow diffraction was reduced by as much as 80x by the addition of the dimmer assembly and further reduced in magnitude and angles by using 2.0 index glass.

The efficiency of the system was improved by 12x to allow for brightness of 20-2000 nits in a small form factor. The brightness was measured across 80% of the FOV. 7x improvement in waveguide efficiency was achieved by many small improvements, as well as gradation of resist across the eyepiece to improve the uniformity and thus the efficiency. This resulted in 2-3x better color uniformity. In addition, a color uniformity algorithm was developed that improves the uniformity by 2x more.

Eyepiece technology to enable image quality and yield:
Magic Leap has a unique eyepiece fabrication process that has been developed over the last 20 years. We also develop much of the fabrication equipment, the key metrology equipment, and the imprint material itself. We own and develop every aspect of the Jet and Flash Imprint Lithography (JFIL), including the imprint material, the imprint machine's hardware and software, and core process technology. This allows us to fully exploit JFIL's capabilities to move quickly and break down traditional design barriers, which was key to enabling Magic Leap 2.

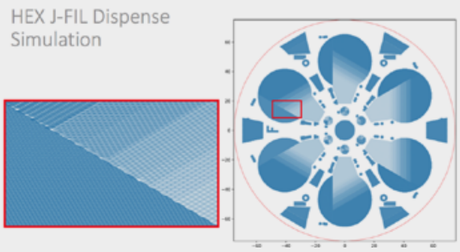
Magic Leap acquired Molecular Imprints in 2015 (7 years ago) to secure the enabling JFIL. Molecular Imprints was founded in 2001, so the imprint technology we are using today leverages more than 20 years of experience. As you can see on the left in the picture below, we replicate a submaster pattern by pushing it into an ink-jettable ultraviolet (UV) curable resin, exposing to UV, and finally separating with precise control. This enables us to reproduce the features with high fidelity over thousands of imprints. We can precisely control the volume of resin across the waveguide by using an inkjet (as seen in the upper right-hand images). This enables the gradation and thin RLT mentioned earlier that results in higher uniformity performance without sacrificing efficiency. Additionally, inkjetting has minimal material waste compared to traditional spin-on techniques.

In addition, the ultrathin inkjet-like approach allows us to use resists that have lower index of refraction than the substrate. Thus, we can use resists that do not have nanoparticles and therefore have inherently lower scatter and better performance.

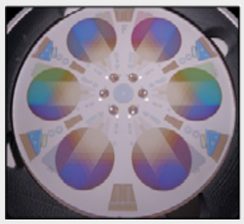


MolecularImprints

Design calls for gradation and double side patterning (modeling of drop patterns)

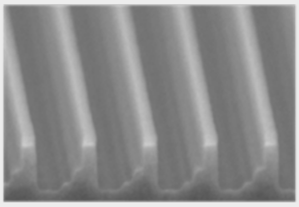


Imprint showing gradation

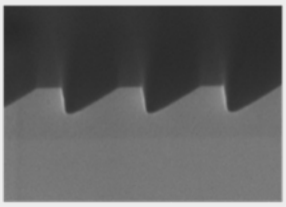


Patented chemicals and equipment turn key delivered at scale

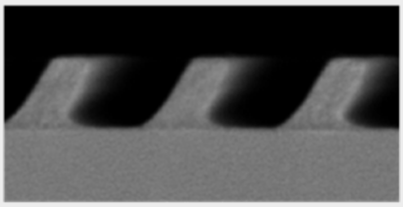
The nanoimprint process opens up many options for the types of structures we can implement in our waveguides (examples below). Through in-house fabrication techniques, we can combine different types of structures within a single waveguide element (for example blazed and binary gratings in a single imprint). With the founding Molecular Imprints team, we have 20+ years of expertise and partnerships to create master and submasters with these types of features.



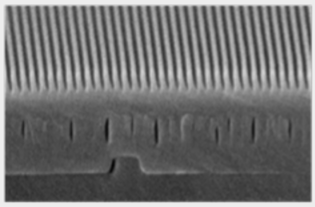
Multi-Step grating



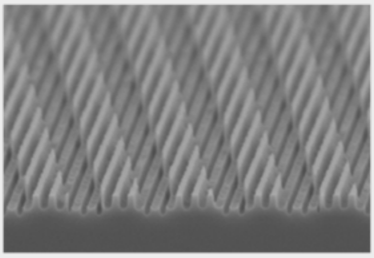
Sawtooth grating



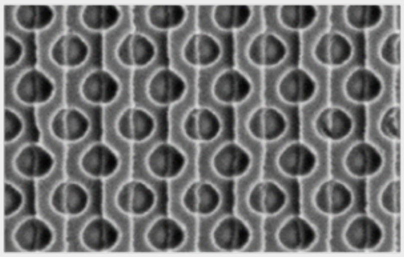
Slanted grating



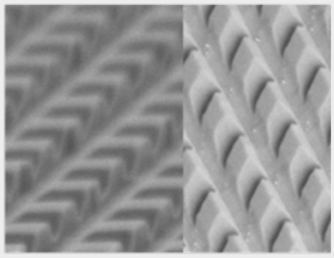
2D structures



3D structure – stack of two sets of gratings



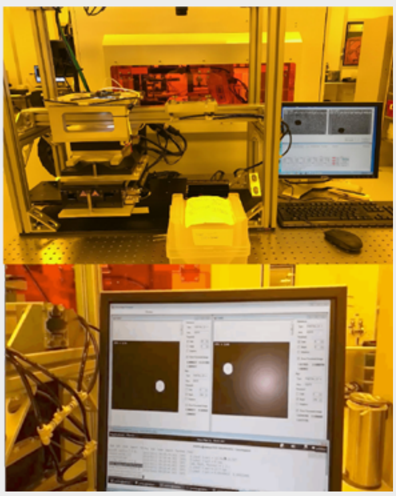
3D structure – lines and holes



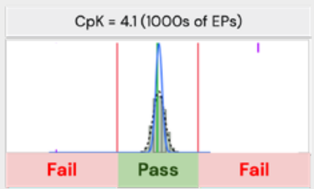
3D blazed grating array

In addition to building the imprint machines, our in-house equipment team delivers other critical and unique manufacturing equipment. By leveraging the imprint machine's hardware and software modules, we can move quickly and use best practices in machine vision and controls, over and over again. This is valuable for both early R&D, as well as getting new process technology quickly into high volume manufacturing (HVM). Below and on the left, you can see an early prototype used to support Magic Leap 2 R&D. On the right, you can see the same process technology scaled-up in the factory in just 9 months with process capability index (CpK) > 4.0.

Benchtop supporting early prototypes

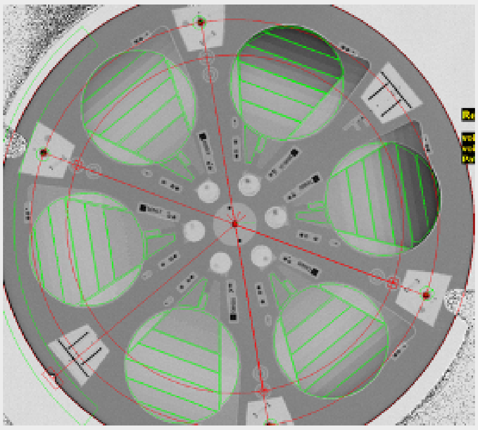


HVM Machine delivered in 9 months with high CpK

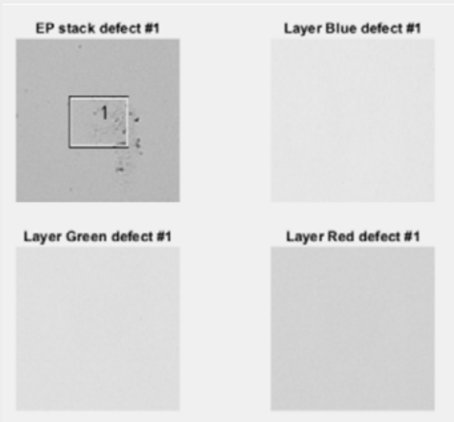


We have also developed in-house metrology to support dimensional and defect detection for eyepiece fabrication. The left two images show custom, machine-vision-based defect inspection capability on transparent substrates. When we started looking for these solutions 7 years ago, there was virtually no interest from traditional defect inspection companies. So, we partnered with a local optics company and eventually developed solutions enabling large-area defect detection and characterization that we've been able to embed into the imprint and downstream equipment.

Some of the dimensions, particularly in the waveguide stack, can be quite challenging and push the boundaries of existing measurement technologies. Similar to the defect inspection, we partnered with a few key component providers and built software and hardware solutions supporting our R&D and HVM needs.



Automated Pre and Post-imprint Wafer-level inspection system



Stack and Layer Inspection System (SALIS)

Automated, in-line stack metrology — Optical KPIs, Quality control

Lastly, we have demonstrated scalability to our EP process flow. Over our last few builds of 2000+ eyepieces, we have demonstrated > 90% rolling throughput yield (RTY). That RTY is the product of yield for 37 critical-to-quality parameters including dimensional and optical KPIs. We are currently at 110k units per year and have the space and expertise to expand as we grow.