Simulation of Waveguides for AR Glasses and HUD

Physics, Requirements, and a Unified Approach

White Paper Version 1.0

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Executive Summary

This white paper addresses the simulation of augmented reality waveguides and head-up displays (HUDs). Recent developments in AR glasses and HUDs use an LCOS (Liquid Crystal on Silicon) or other SLM as the input object, illuminated by a coherent source (laser or laser diode). The consequence is a **coherent electromagnetic field** that must be propagated through the incoupling lens system, the waveguide (with gratings for exit pupil expansion), and finally to the eye — in HUD systems possibly after reflection at a windshield.

Although the discussion is framed around these recent developments, the waveguide simulation principles presented — polarization, diffraction, temporal coherence, and OPL tracking — apply equally to other imager technologies for generating the incoupling light, including scanning systems and incoherent or partially coherent sources.

Key physical effects that must be simulated:

- Propagation of fields through lens systems (non-paraxial where required)
- Polarization-dependent grating modeling in waveguide
- Diffraction at grating region boundaries (aperture effects)
- Temporal coherence (finite bandwidth of the source)

The evaluation of the system performance should be flexible and include detectors like:

- Modulation Transfer Function (MTF)
- Field uniformity across the eye box
- System efficiency
- Luminance

Our approach: VirtualLab Fusion provides all required capabilities through its Digital Twin Platform — Lens Twins, Waveguide Twin, Detector Twins, and Eye Model — all powered by Field Tracing. All components share a common electromagnetic field representation.

This paper provides essential information for any team working on AR and HUD systems to understand the scope of the simulation endeavor. At the end, we provide a list of essential questions that any simulation approach must answer.

Contents

1 Introduction: The AR/HUD Scenario

Recent developments in AR glasses and head-up displays (HUDs) share a common architecture:

- An **input object** generated by an SLM, primarily LCOS (Liquid Crystal on Silicon)
- The SLM is illuminated by a **coherent source** (laser or laser diode)
- An **incoupling lens system** that directs the field into a waveguide
- A **waveguide with gratings** for exit pupil expansion
- An **eye model** (in HUD systems, possibly after reflection at a windshield)

The consequence of using a coherent source with an SLM is that a **fully coherent electromagnetic field** is generated at the object plane. This field — with its specific amplitude, phase, and polarization distribution — must be propagated through the entire optical system to predict final image quality.

Summary

Key Insight: Unlike scanning systems where different object points are illuminated at different times, a laser + LCOS system illuminates all object points simultaneously. The resulting field is a single coherent entity, and interference between different object points affects the final image. This is the fundamental difference that drives the simulation requirements.

1.1 Scope: Imaging Mode

This paper focuses on the **imaging mode** of LCOS operation — where the LCOS surface itself is the object plane. The holographic mode (phase-only encoding to create a virtual object plane) is not addressed in this paper, but it follows an analogous flow of arguments.

1.2 The Fourier Lens Configuration

The lens system must transform the incident coherent field into plane waves at the waveguide entrance. This is achieved by configuring the lens system as a **Fourier lens**: the object plane (LCOS) is located in its front focal plane, and the waveguide entrance is located in its back focal plane.

In this configuration:

- Each point in the object plane is transformed into a plane wave with a specific direction at the waveguide entrance.
- The superposition of all these plane waves forms the angular spectrum that couples into the waveguide grating.
- Mathematically, the lens performs the **inverse Fourier transform**: coefficients (object points) → series (plane wave superposition).

- For a coherent input field, the plane waves entering the waveguide are mutually correlated.

After the waveguide, the eye (cornea and crystalline lens) performs the **forward Fourier transform**: the plane waves are focused back to points on the retina. The system is thus symmetric: Fourier lens → waveguide → eye.

Summary

The Complete Transform Path:

$$\text{Object points (LCOS)} \xrightarrow{\text{Fourier lens}} \text{Set of plane waves (waveguide)} \xrightarrow{\text{eye}} \text{Focused spots (retina)}$$

The Fourier lens performs the inverse transform (coefficients → series); the eye performs the forward transform (series → coefficients).

1.3 Ideal Fourier Lens Twin

VirtualLab Fusion provides multiple ways to generate the plane wave set that represents the output field of the LCOS and by that the input for the waveguide coupling grating — whether through an Ideal Fourier Lens twin (will be released shortly), a direct plane wave decomposition, or other methods. This flexibility allows engineers to choose the most appropriate workflow for their specific application.

Once the system performance is understood, a real lens system can be designed (using the Lens Group Twin in VirtualLab Fusion) to replace the ideal Fourier lens, with full physical-optics simulation of all aberrations and real lens elements.

Twin	Purpose	When to Use
Ideal Fourier Lens Twin	System investigation, performance limits	Early design phase
Lens Group Twin (LPIA)	Real lens simulation, aberrations	Later design phase

Table 1: Two twins for Fourier lens simulation in VirtualLab Fusion.

2 Propagation Through the Coupling Lens System

The previous section described how to generate the ideal plane wave set representing the LCOS output. In a real system, however, the lens is not ideal. We must propagate the coherent field emerging from the LCOS through the real lens system — including all aberrations, apertures, and diffraction effects.

Although coherent field propagation through lens systems in the paraxial approximation is well understood from Fourier optics textbooks, this approximation is **not sufficient for AR systems**. A more general propagation concept is required for the simulation of lens systems with coherent inputs in this application domain. This is where VirtualLab Fusion's physical-optics propagation capabilities come into play.

For a deeper dive into the general approach, it is sufficient to point out three essential steps in such a simulation:

1. **Decompose the input field** into suitable subfields before propagation.
2. **Propagate the electromagnetic subfields through curved lens surfaces.** The Local Plane Interface Approximation (LPIA) provides a fast and accurate fully vectorial, non-paraxial method for this purpose, validated against FEM[1].
3. **Include diffraction effects where needed.** Diffraction at apertures, lens edges, or other obstacles along the optical path must be included where it affects the field distribution.

These three steps form the foundation of coherent lens system simulation in VirtualLab Fusion.

Summary

Coherent Lens System Simulation in a Nutshell:

- Three essential steps: field decomposition, LPIA propagation through curved surfaces, diffraction where needed
- LPIA is fully vectorial, non-paraxial, validated against FEM (<0.1% deviation)
- For AR systems, paraxial approximation is not sufficient

2.1 The Local Plane Interface Approximation (LPIA)

LPIA provides a fully vectorial method for propagating electromagnetic fields through curved surfaces.

- Validated against FEM with deviation <0.1% for fields in the geometric zone
- For arbitrary coherent fields, adaptive lateral decomposition ensures the geometric zone condition
- The decomposition is a **computational technique** — not a physical approximation

3 Propagation Through the Waveguide

Once the field enters the waveguide, several physical effects must be simulated correctly.

3.1 Polarization-Dependent Grating Modeling

Waveguide gratings (in-couplers, out-couplers, and intermediate gratings) are fundamentally polarization-sensitive. Efficiency, diffraction angles, and the polarization state of output fields depend strongly on the input field. This sensitivity is particularly critical because the LCOS itself introduces polarization effects — the reflected

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[1] R. Shi, C. Hellmann, and F. Wyrowski, "Physical-optics propagation through curved surfaces," Journal of the Optical Society of America A, Vol. 36, No. 7, pp. 1252–1260 (2019). https://doi.org/10.1364/JOSAA.36.001252

field from the LCOS has a specific polarization state determined by the liquid crystal orientation and the illumination geometry.

Figure 1 illustrates the change of polarization in the waveguide for a basic HoloLens-type layout. The grating regions are indicated by their boundaries in red. This simulation demonstrates the importance of accurate modeling of the state of polarization.

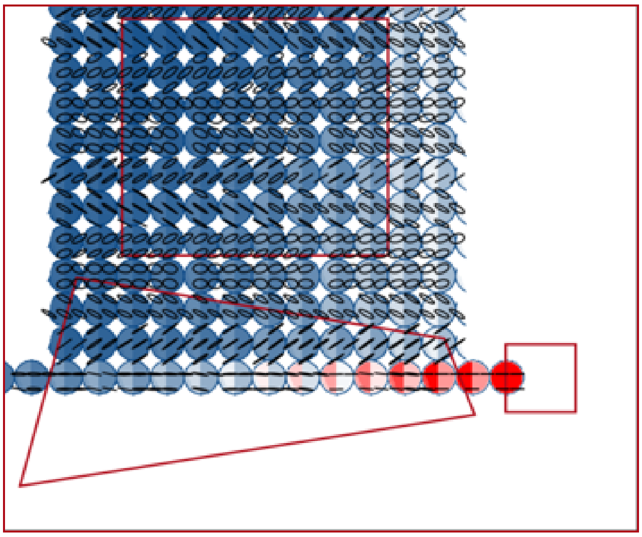


Figure 1: The polarization, indicated by polarization ellipses, of the incident light, which is here linearly polarized at the incoupling grating, changes significantly along its path through the waveguide.

Our Waveguide Twin implements Rigorous Coupled-Wave Analysis (RCWA), which:

- Solves Maxwell's equations exactly for periodic structures
- Preserves full vectorial field information (amplitude, phase, polarization)
- Propagates plane waves through the waveguide — including any aberrations inherited from the incoupling lens system and possibly introduced in the waveguide, e.g., by bent surfaces
- Performs all calculations within the waveguide twin — no tool hopping, no external solvers, no data export

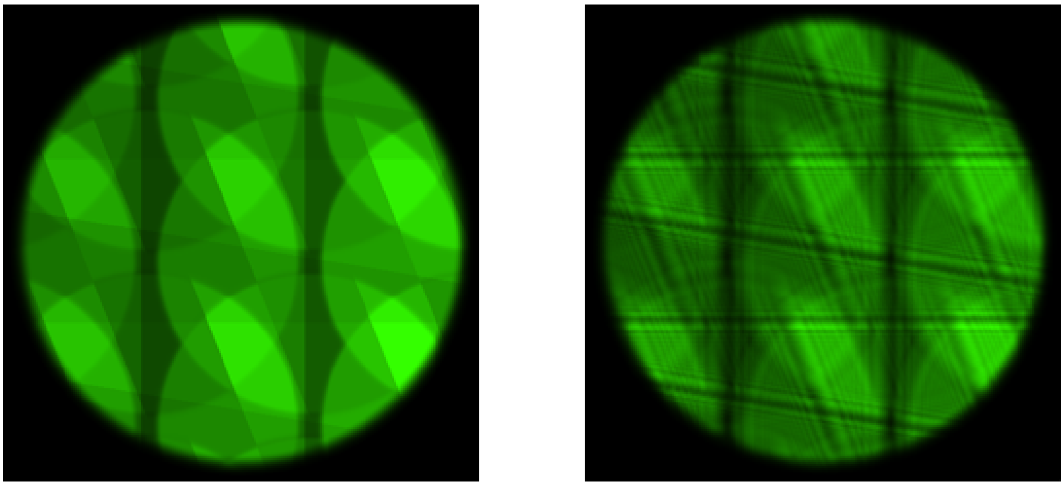
To achieve even more accurate modeling from source to eye, we are also developing a dedicated LCOS Twin that captures all polarization and phase effects of the LCOS itself.

3.2 Diffraction at Grating Region Boundaries

In typical exit pupil expanders, the field encounters multiple grating regions separated by boundaries. These boundaries create aperture-like effects that cause diffraction as the field propagates through the waveguide, affecting the field distribution and, consequently, the MTF.

Our Waveguide Twin allows both the inclusion (accurate) and the neglect (fast) of diffraction effects inside the waveguide. Accurate modeling is essential for resolution and MTF evaluation, whereas for the investigation and optimization of uniformity, diffraction can be discarded.

The importance of the inclusion of diffraction is discussed next for the same waveguide layout as indicated in Fig. 1. We consider the entrance pupil of the eye at a certain position in the eye box. The irradiances in the pupil are shown in Fig. 2.



(a) Without diffraction

(b) With diffraction

Figure 2: Irradiances in the eye pupil: (a) without and (b) with inclusion of diffraction inside the waveguide.

The resulting MTFs are shown in Fig. 3.

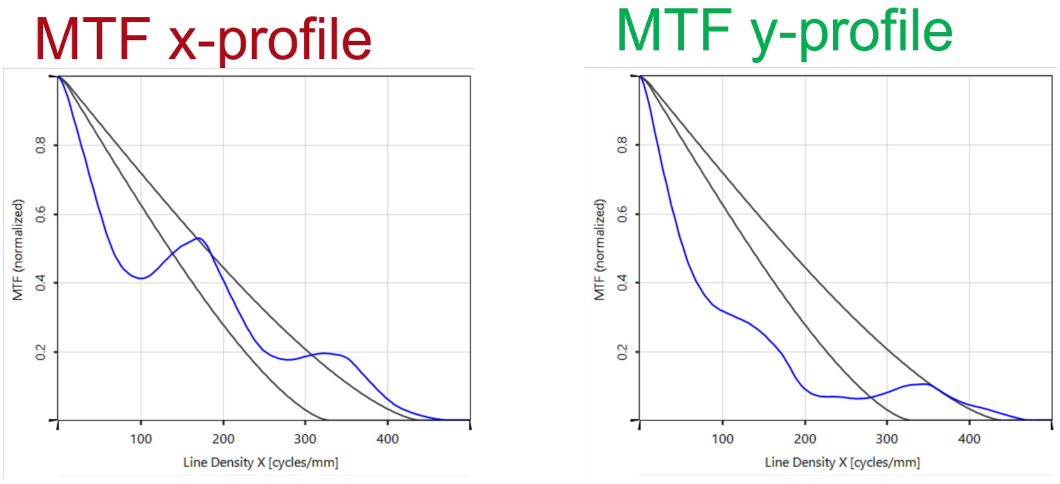
Summary

Waveguide Simulation in a Nutshell:

- Grating simulation by RCWA — solves Maxwell's equations exactly for periodic structures
- RCWA is highly polarization-sensitive. The polarization of input fields is taken into account, and changes in polarization are provided to the output field for further processing. RCWA preserves full vectorial field information.
- Propagates plane waves through the waveguide — including any aberrations inherited from the incoupling lens system
- Diffraction: accurate mode for MTF, fast mode for uniformity — on demand
- The waveguide simulation is handled entirely within the Waveguide Twin, sharing the common field representation — no tool hopping, no external solvers

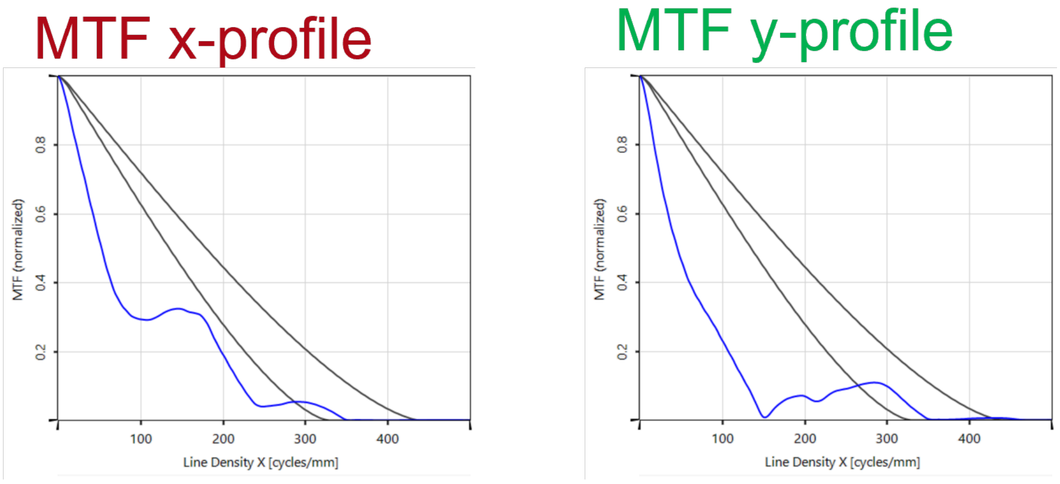
3.3 Temporal Coherence from Path Length Differences

As discussed before, the coherent input field is decomposed into subfields for propagation through the lens system and the waveguide. In addition, during pupil ex-



(a) x-profile, without diffraction

(b) y-profile, without diffraction



(c) x-profile, with diffraction

(d) y-profile, with diffraction

Figure 3: MTFs along the x and y axes corresponding to the irradiance distributions in Fig. 2. Diffraction has a significant effect on the MTF.

pansion, each subfield of the object field is split multiple times. At the output of the waveguide, we therefore have a set of fields — consisting of all object subfields and all their replicas — each having traveled a different optical path length.

When these fields recombine at the out-coupling area, the degree of coherence between them depends on the source bandwidth. In the case of a monochromatic field, all fields would be perfectly correlated, and their superposition would lead to strong interference and a speckle pattern. However, **monochromatic light is an academic exercise without practical relevance for waveguide simulations**. Light always has a finite bandwidth and, consequently, a finite coherence length.

The coherence length L_c is related to the source bandwidth $\Delta\lambda$ by:

$$L_c = \frac{\lambda^2}{\Delta\lambda} \tag{1}$$

Source Type	**Bandwidth $\Delta\lambda$**	**Coherence Length L_c**
Single-mode laser (stabilized)	< 0.01 nm	> 4 cm
Laser diode (single mode)	≈ 0.1 nm	≈ 7 mm
Laser diode (multimode)	≈ 1 nm	≈ 0.7 mm
LED	≈ 50 nm	≈ 14 μm

Table 2: Typical coherence lengths. For laser diodes in AR/HUD systems, coherence lengths are in the range of 0.5 mm to 10 mm — the same range as optical path length differences in pupil-expanding waveguides.

Thus, it must be investigated which of the many fields superimpose coherently and which do not. Our approach uses OPL tracking: we propagate each subfield once, record the optical path lengths, then compute the degree of coherence between all fields based on the source spectrum. If the degree of coherence is high, coherent summation applies; if low, incoherent summation applies; if medium, a partial coherence sum is required.

The importance of the inclusion of temporal coherence is illustrated in Fig. 4. It shows the effects of diffraction and temporal coherence on the MTF. As a reference, the MTF for coherent beams of four-millimeter and three-millimeter diameter are shown.

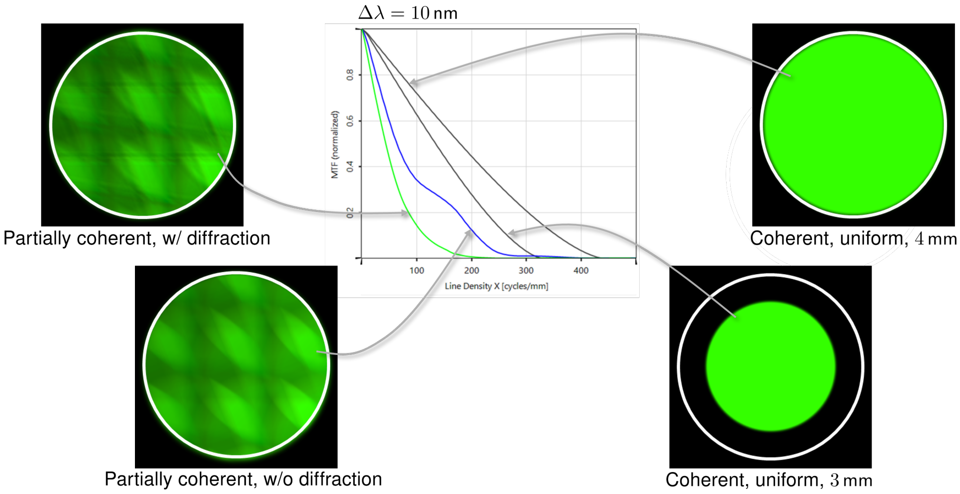


Figure 4: Irradiances in the pupil for different simulation scenarios and their effect on the resulting MTF.

Figure 5 shows measured MTFs for a waveguide layout similar to the one used in the simulations.[2] The shape of the measured MTFs agrees very well with the simulated ones when all effects are included.

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[2] The measurement was performed in the framework of a collaboration inside the AR Consortium.

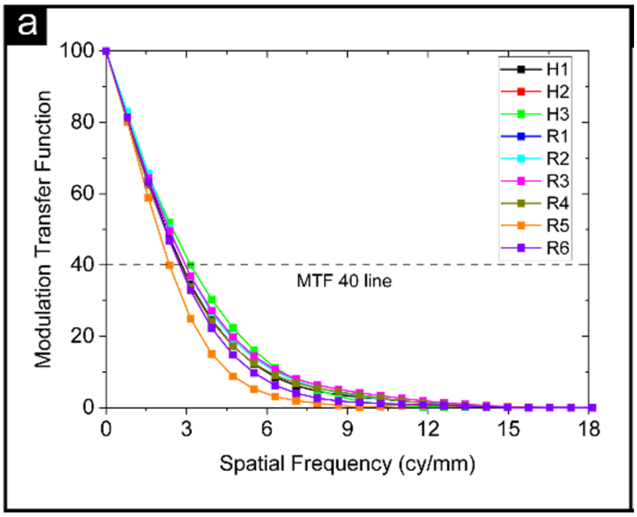

Figure 5: Measured MTFs performed on a waveguide of similar layout to the one used in the simulations.

Summary

Temporal Coherence in a Nutshell:

- The output of the waveguide consists of many fields — all object subfields and their replicas — each having traveled a different optical path length (OPL)
- The degree of coherence between these fields depends on the source bandwidth and the OPL differences
- For laser diodes in AR systems, this degree is often in the medium range — requiring partial coherence simulation
- Our OPL-tracking method computes the degree of coherence from the source spectrum
- Assuming full coherence or full incoherence without analysis is insufficient

4 Quality Criteria and Detectors

To evaluate system performance, several quality criteria must be accessible:

- **Modulation Transfer Function (MTF)** — derived from the coherent transfer function, which is the Fourier transform of the amplitude point spread function
- **Field uniformity** across the eye box
- **System efficiency** (coupling into waveguide, transmission to eye)
- **Luminance** — perceived brightness accounting for human eye sensitivity

VirtualLab Fusion provides a comprehensive set of Detector Twins (power, phase, polarization, intensity, MTF, luminance) and an Eye Model Twin for retinal field calculation. All detectors work with the same field representation as the rest of the system.

5 The Digital Twin Platform: A Unified Approach

All required capabilities are addressed within a single framework: the Digital Twin Platform for Light.

- **Lens Twins** — Ideal Fourier Lens Twin (system investigation) and Lens Group Twin (real lens simulation with LPIA)
- **Waveguide Twin** — grating propagation (RCWA) + aperture diffraction
- **LCOS Twin** (in development) — defines the coherent field at the object plane with full polarization and phase accuracy, enabling even more precise end-to-end simulation from source to eye
- **Detector Twins** — power, phase, polarization, intensity, MTF, luminance
- **Eye Model Twin** — retinal field calculation (performs the forward Fourier transform)
- **Windshield Twin** (for HUD) — additional LPIA propagation

All twins share a common electromagnetic field representation. The Field Tracing Engine orchestrates propagation between twins. No data export, no loss of phase or polarization between components.

Summary

What makes this unique: The platform architecture and concept are perfectly suitable for dealing with coherent light — while also handling incoherent and partially coherent scenarios naturally. Unlike patchworks of different engines, we use a unified approach: LPIA for lenses, RCWA for gratings, aperture diffraction for boundaries, OPL tracking for temporal coherence — all sharing a single field representation throughout the entire system.

6 Essential Questions for Any Simulation Approach

For any simulation approach to be complete for the scenario described above, it must provide clear answers to these questions:

6.1 On Coherent Field Propagation

> *How is the coherent field propagated through the coupling lens system? Is the method non-paraxial when required? Does it preserve phase and polarization? Is it validated against rigorous methods?*

6.2 On Waveguide Gratings

> *Does the grating solver accept arbitrary vectorial input fields (not just plane waves)? Does it return full vectorial output fields? How is polarization handled for grating simulation?*

6.3 On Workflow Integration (Lens to Waveguide)

> *How are aberrated plane waves from the incoupling lens system propagated through the waveguide twin? Does the grating solver accept non-ideal, aberrated input fields, or does it assume ideal plane waves?*

6.4 On Aperture Diffraction

> *Does the simulation include diffraction at grating region boundaries? If not, how is the MTF determined?*

6.5 On Temporal Coherence

> *How are optical path length differences between field copies handled? Does the simulation compute the degree of coherence from the source spectrum? Can it handle partial coherence when the degree is medium?*

6.6 On Workflow Integration (Overall)

> *Are all these aspects implemented within a single simulation framework with a common field representation, or are different methods combined through external interfaces?*

6.7 On System Evaluation

> *What detectors are available? Can the simulation provide MTF, uniformity, efficiency, and luminance directly from the same field data?*

7 Conclusion

Laser-illuminated AR waveguides and HUDs require a simulation approach that addresses:

1. Propagation of coherent fields through lens systems (Fourier lens configuration)
2. Polarization-dependent grating modeling
3. Diffraction at grating region boundaries
4. Temporal coherence from finite source bandwidth
5. Flexible evaluation including MTF, uniformity, efficiency, and luminance

VirtualLab Fusion provides all these capabilities within a single, unified platform — the Digital Twin Platform for Light. We provide this information to any team working on AR and HUD systems to help understand the scope of the simulation endeavor from a physical optics perspective. That is our expertise.

8 Geometric (Reflective) Waveguides

In geometric (reflective) waveguides (e.g., Lumus technology), the functions of incoupling, pupil expansion, and outcoupling are performed by arrays of partially reflective mirrors (facets) embedded in the waveguide, rather than by diffractive gratings.

- **Incoupling:** Light enters via a coupling prism or an angled entrance face.
- **1D expansion:** A first array of transflective facets expands the pupil in one dimension.
- **2D expansion and outcoupling:** A second array of facets expands the pupil in the second dimension and couples light out to the eye.

The core physical principles from this paper remain valid:

- Propagation between surfaces uses the same field tracing engine (with or without diffraction).
- Diffraction at facet edges matters, especially in miniaturized designs.
- Polarization must be handled correctly (facets are polarization-sensitive).
- Temporal coherence and OPL tracking apply identically.

The primary difference is the local interaction at the optical elements: RCWA for gratings versus coating S-matrix for partial reflectors. Hybrid architectures (e.g., grating incoupling with geometric expansion) are also possible and follow the same principles.

Current availability: VirtualLab Fusion does not yet have a dedicated twin for geometric waveguides. However, based on market demand, we will add such a twin. If your application requires geometric waveguide simulation, please contact us to discuss your requirements.

For all other aspects — coherent input propagation, diffraction at edges, polarization, temporal coherence, and system evaluation — the existing platform capabilities apply directly.

9 For Deeper Understanding

The simulation techniques described in this paper — field decomposition, LPIA, RCWA, aperture diffraction, OPL tracking for temporal coherence — are built into the twins and the Field Tracing Engine in VirtualLab Fusion. Users do not need to be experts in these techniques to use the platform.

However, for those interested in a deeper understanding, we are preparing a series of white papers covering:

- *Coherent Light Propagation Through Lens Systems* (expected Q2 2026)
- *Temporal Coherence in Optical Simulation* (expected Q2 2026)
- *Optical Simulation with Electromagnetic Fields* (expected Q3 2026)
- *Seamless Inclusion of Diffraction in Optical Simulation* (expected Q2 2026)
- *Paraxial Simulation of Lens Systems* (expected Q3 2026)

These white papers will provide the mathematical and physical foundations for readers who wish to go beyond the application-focused discussion presented here.

10 Next Steps

We hope this white paper has provided a clear understanding of the physical effects that matter for laser-illuminated AR waveguides and HUDs, and how VirtualLab Fusion — The Digital Twin Platform for Light — addresses them.

Existing Resources (VirtualLab Fusion Learning Center):

- **Tutorials:**
  - Hands-on, Step-by-Step AR/MR Lightguide Design
  - Construction of a Light Guide
  - How to Set Up a Lightguide with Real Grating Structures
  - Footprint Analysis of Lightguides
- **Use Cases:**
  - Simulation of Lightguide with 1D-1D Pupil Expander and Real Gratings
  - Control of Accuracy-Speed Balance for MTF Analysis
  - Complex Lightguide System with 2D Eye Pupil Expansion (includes Uniformity Detector)
  - Grating Analysis and Smoothly Modulated Grating Parameters

To learn more:

- **Contact us** for a detailed introduction to our solution tailored to your specific application.
- **Evaluation version:** We offer a 4–6 week evaluation license with close support from our application engineering team — allowing you to test the platform on your own optical systems.
- **Prism Award 2026:** Our Waveguide Twin has been recognized with the XR Prism Award for excellence in waveguide simulation.
- **Specification Sheet:** A dedicated specification sheet for the Ideal Fourier

Lens Twin will be available shortly.

Platform extensibility:

- The Ideal Fourier Lens Twin introduced in this paper is just one example of the platform's flexibility. Because we are a platform — not a fixed set of tools — we can extend capabilities easily.
- Upcoming: Solution Guides for AR waveguides (in preparation) — providing step-by-step workflows, tutorials, and use cases.
- Foundational white papers announced in this document.

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A Document Version History

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1.0	April 2026	LightTrans GmbH	Initial release