From Phase to Structure

A Two-Step Design Workflow with Wavefront Phase Modifier Twins

Technical White Paper

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Executive summary

This white paper introduces a two-step design workflow: first define the phase, then build the structure. At the heart of this workflow is the function-based **Wavefront Phase Modifier** (WPM) twin family in VirtualLab Fusion.

A WPM twin adds a prescribed wavefront phase profile to an incoming field on a plane or curved surface. This lets you explore system performance with idealized phase elements – fast, flexible, and without committing to a physical structure. Once the phase profile is optimized, you transfer it to a structure-based twin – HOE, metalens, or refractive/reflective surface – to realize the design physically.

This paper introduces the concept, the available twin variants, and the workflow that connects phase design to physical realization.

For a high-level introduction to the Digital Twin Platform concept, see the overview paper series.[a]

[a] LightTrans Document IDs: LT-OP-001, LT-OP-002, LT-OP-004. Available at https://www.lighttrans.com/docs/ once published; upon request until then.

Key Insight: Design the Phase, Then Build the Structure

The WPM workflow separates the *what* (the desired phase profile) from the *how* (the physical structure that realizes it). You design the phase first, evaluate performance, and only later decide how to realize it – as a diffractive structure, a metasurface, or a refractive surface.

Reader Guide: Box Colors

Red boxes mark maximum emphasis, such as executive summaries, key results, and central takeaways. Green boxes contain definitions, terminology, and specification-relevant statements. Blue boxes provide explanatory model context, interpretation, workflow logic, or reader guidance. Yellow boxes highlight cautions, validity limits, risks, or concepts that should not be confused.

Contents

1 Introduction: The Two-Step Workflow

In optical design, the traditional approach often forces you to commit to a physical structure early – a lens, a grating, a metasurface – before you know what phase profile you actually need. This ties your hands: you optimize within the constraints of a structure you may later wish you had chosen differently.

The Wavefront Phase Modifier (WPM) twin family in VirtualLab Fusion offers a different way: **first define the phase, then build the structure**.[1]

1.1 What Is a Wavefront Phase Modifier?

In physical optics, the **wavefront phase** is the common phase factor shared by all components of an electromagnetic field. It determines the local propagation direction in a geometric zone of a field, and it is the quantity that optical design traditionally controls through lenses, mirrors, and other optical elements.

A **Wavefront Phase Modifier** (WPM) is a function-based optical digital twin that adds a prescribed wavefront phase profile to an incoming field on a plane or curved surface.

Mathematically, the operation is described by the phase-sum equation:

$$\psi^{\text{out}}(u, v) = \psi^{\text{in}}(u, v) + \Delta\psi^{\text{prf}}(u, v), \tag{1}$$

where (u, v) are coordinates on the WPM surface. This addition changes the wavefront and, through the phase gradients, modifies the local propagation direction of the field.

Definition: Wavefront Phase Modifier (WPM)

A **Wavefront Phase Modifier** is a function-based component twin that adds a prescribed, unwrapped wavefront phase profile to the incoming wavefront phase on a plane or curved surface. It operates on the common wavefront phase of the field representation, not on the complex field amplitudes.

The WPM twin is **function-based**: it specifies the optical action directly, without simulating a physical structure. This makes it fast, flexible, and ideal for the first step of the workflow.

Because the WPM modifies the local propagation direction and thereby the energy flow, energy conservation requires an accompanying matrix transfer function that also affects the field component amplitudes. This is a byproduct of the wavefront phase modification, not an independent operation. The field-tracing engine handles this consistently.

2 The Workflow: Phase First, Structure Second

The WPM twin enables a two-stage design workflow that accelerates optical development:

2.1 Step 1: Explore with Wavefront Phase Modifier Twins

Start with a WPM twin to investigate the ideal performance of your system. At this stage:

- Define the desired phase profile analytically, numerically, or from a design algorithm.

[1] For practical illustrations of this workflow, see the feature demos on Beam Expander Simulation with Wavefront Phase Modifier Twins, Off-Axis Focus Correction for a Reflective Conical Surface, and Wavefront Phase Correction on the Curved Surface of a Rocket Window.

- Use the WPM as a placeholder for the optical element.
- Evaluate system performance (MTF, efficiency, uniformity, etc.).
- Explore design sensitivity and tolerances.

The WPM twin applies the phase profile directly, without simulating a physical structure. This allows rapid iteration and exploration of the design space.

2.2 Step 2: Transfer to Structure-Based Twins

Once the phase profile is optimized, replace the WPM with a structure-based twin that realizes the required phase profile physically:

- **Holographic Optical Element (HOE):** A diffractive structure that implements the phase profile.
- **Metalens:** A metasurface that realizes the phase profile through sub-wavelength structures (plane WPM only; rotational symmetric profiles in version 2026.2, general metasurface twin coming in 2026).
- **Refractive or Reflective Surface:** A physical surface (e.g., an asphere) that realizes the phase profile through refraction or reflection (inverse design for direct replacement coming in 2026).

VirtualLab Fusion provides design algorithms for the structure-based twins which ensure the design of the structure to realize the phase profile specified in the WPM.

Structure-based twins come with their tailored in-built simulation model.

Key Result: Phase First, Structure Second

The WPM workflow separates the *what* (the desired phase profile) from the *how* (the physical structure that realizes it). This accelerates design by allowing you to optimize the phase profile independently of the fabrication technology.

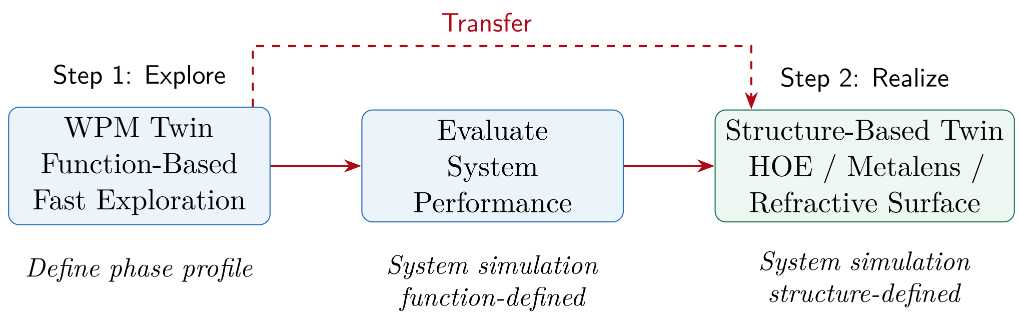

Figure 1: *The WPM design workflow: first define the phase, then build the structure.*

3 WPM Twin Variants

The WPM family includes four distinct twins, distinguished by the surface on which the phase is added and by how the profile is defined:

3.1 Plane vs. Surface WPM

- **Plane WPM:** The phase is added on a plane perpendicular to the optical axis. This is the simplest case and is equivalent to a thin phase element in a plane.
- **Surface WPM:** The phase is added on a curved surface. This is useful for modeling phase profiles on curved substrates, such as in HOEs. It also helps to understand how much the shape of a surface must be refined to realize the desired phase profile effect. This means the surface can be redesigned to obtain the functionality (coming in 2026).

The surface variant requires a local coordinate transformation: the phase profile may be stored in reference coordinates, but the phase addition occurs in the local surface coordinates. The model handles this transformation automatically.

3.2 Profile-Defined vs. Output-Defined

- **Profile-Defined WPM:** The phase profile is supplied directly as a function of coordinates. This is the primary variant. The profile can come from analytical formulas, data import, design algorithms, or import from Zemax OpticStudio (see Section 5).
- **Output-Defined WPM:** The required profile is computed from a desired output wavefront phase. This is useful for design problems where the target output is known.

Specification Principle: WPM Variants

The twin family name is **Wavefront Phase Modifier**. The variant is indicated by bracketed specifiers:

- Wavefront Phase Modifier [Plane, Profile-Defined] CF-WPMP01
- Wavefront Phase Modifier [Surface, Profile-Defined] CF-WPMS01
- Wavefront Phase Modifier [Plane, Output-Defined] CF-WPMP02
- Wavefront Phase Modifier [Surface, Output-Defined] CF-WPMS02

4 Transmission and Reflection Channels

The WPM twins operate in either the transmission (T) or reflection (R) channel. The user selects one channel; all other channels are closed. This avoids ambiguous interpretation of the opposite channel.

For profile-defined twins, the same profile $\Delta\psi^{\mathrm{prf}}$ is applied to the selected channel. For output-defined twins, the profile is computed for the selected channel from the desired output phase ψ^{out}:

$$\Delta\psi^{\mathrm{prf}} = \psi^{\mathrm{out}} - \psi^{\mathrm{in}}. \tag{2}$$

Two flags are provided to adjust the sign:

- *Flip Profile Phase Sign*: Multiplies the supplied profile by -1. (For profile-defined WPMs.)
- *Flip Output Phase Sign*: Multiplies the selected output phase by -1. (For output-defined WPMs.)

These flags allow you to correct a wrong sign setting without redefining the profile or the desired output.

5 Where Does the Phase Profile Come From?

The WPM twin requires a phase profile $\Delta\psi^{\mathrm{prf}}$. The origin of the profile depends on the design scenario. VirtualLab Fusion supports multiple ways to obtain the profile.

5.1 Known Profiles

In some scenarios, the phase profile is already known from previous design work, analytical considerations, or specification requirements:

- **Analytical formulas:** A spherical wavefront, a quadratic phase, a Zernike polynomial, or a custom mathematical function.
- **Data import:** A measured or simulated phase map imported from a file.
- **Legacy designs:** A binary surface phase profile from Zemax OpticStudio, imported for further investigation and structure design.

For these cases, the profile is supplied directly to the Profile-Defined WPM twin.

5.2 Output-Defined Twins

The two output-defined twins compute the required profile automatically from a desired output wavefront:

- Wavefront Phase Modifier [Plane, Output-Defined]
- Wavefront Phase Modifier [Surface, Output-Defined]

Instead of specifying the profile directly, you specify the desired output wavefront phase. The WPM then dynamically computes the required profile internally. The output phase can be formulated by any formula or by data import.

This is useful for common design tasks:

- **Spherical wavefront generation:** Define a desired spherical output wavefront; the WPM computes the required profile.
- **Collimation:** Define a plane wavefront as output; the WPM computes the profile needed to collimate an incoming field.
- **Wavefront shaping:** Define any desired wavefront shape; the WPM computes the profile.

5.3 Inverse Design Algorithms

For more complex scenarios, the output-defined twins may not be sufficient. The required profile may depend on more system parameters and its function is not specified by the output wavefront alone but by more specific mappings between input and output wavefront phase and local directions. In these cases, the profile is obtained by an inverse design algorithm.

VirtualLab Fusion provides a growing library of design tools that can be attached to a Profile-Defined WPM. These tools compute the required profile based on the design scenario.

5.4 Import from Zemax OpticStudio

We support the use of Zemax OpticStudio to design phase profiles. Binary surfaces, extended polynomials, and other phase profiles designed in Zemax can be exported and imported into VirtualLab Fusion as WPM profiles. This provides a bridge between ray-optical design of a phase profile and the use of the profile in a field-tracing environment and its replacement by suitable structure-based twins.

Key Result: Flexible Profile Origins

The WPM profile can come from:

- Analytical formulas or mathematical functions
- Data import (measured or simulated phase maps)
- Output-defined design (specify the desired output wavefront)
- Inverse design algorithms
- Import from Zemax OpticStudio (binary surfaces, extended polynomials)

The same WPM twin works with any of these profiles.

6 Connection to Zemax Binary Surfaces and Beyond

The WPM concept is a generalization of the idea behind Zemax binary surfaces and other idealized phase surfaces in ray-tracing software. In Zemax, a binary surface adds a polynomial phase profile to a surface, modifying the ray direction.

The WPM extends this concept in several important ways:

- **Electromagnetic fields, not rays:** The WPM operates on the electromagnetic field, preserving amplitude, phase, and polarization information.
- **Curved surfaces:** The WPM can be defined on any surface, not just planes.
- **Field tracing:** Through field tracing, the effect of the WPM on system performance includes diffraction where needed, polarization effects, and can be used for any light source from coherent to incoherent.
- **Most general profile definition:** Programmable any formula, and data via spline interpolation representation.
- **Structure-based transfer:** The WPM provides a direct path to replace the idealized phase profile with a physical structure.

From Rays to Fields

In ray tracing, a binary surface changes the ray direction by adding a phase profile. In field tracing, a WPM does the same for the electromagnetic field – but with the full vectorial field information preserved. The local phase gradient gives the local direction change, just as in ray optics, but the field is propagated with diffraction, coherence, and polarization included.

7 The Path to Structure-Based Twins

The WPM twin is not an end in itself. It is a tool for the first step of the workflow: exploring the phase. The ultimate goal is to replace the WPM with a structure-based twin that realizes the same phase profile physically.

The structure-based twins available for this transfer include:

- **Holographic Optical Element (HOE) Twin:** Designs a diffractive structure which consists of locally varying linear gratings to realize the desired phase profile. It simulates the resulting wavefront phase in the working order and higher orders. A linear phase profile leads to a grating via the HOE.

- **Metalens Twin:** Designs the meta-atom grid on a planar surface in order to achieve the desired phase profile. It simulates the resulting effect on the wavefront phase and the additional effects on the electromagnetic field. Currently (version 2026.2) supports rotational symmetric profiles. A general metasurface twin is planned for release in 2026.
- **Refractive or Reflective Surface Twin:** Designs the surface which generates the desired phase profile in transmission or reflection. It simulates the transmitted or reflected wavefront phase and all accompanying effects on the field components, i.e., Fresnel and coating transfer matrices. Inverse design for direct replacement is planned for release in 2026.

The choice of structure-based twin depends on the application, the fabrication technology, and the required accuracy. The WPM workflow ensures that the phase profile is already optimized before the structure-based simulation begins.

8 Conclusion

The Wavefront Phase Modifier enables a two-step design workflow: first define the phase, then build the structure.

In Step 1, you use a function-based WPM twin to explore system performance with idealized phase elements – fast, flexible, and without committing to a physical structure. In Step 2, you transfer the optimized phase profile to a structure-based twin – HOE, metalens, or refractive/reflective surface – to realize the design physically.

The profile can come from multiple origins: analytical formulas, data import, output-defined design, dedicated design algorithms, or import from Zemax OpticStudio.

This workflow separates the *what* (the phase profile) from the *how* (the physical structure), accelerating optical design and enabling field-tracing simulation from the earliest design stages.

The WPM concept generalizes the idea of binary surfaces to the electromagnetic field regime, preserving amplitude, phase, and polarization information while enabling full field tracing with diffraction, coherence, and polarization included.

9 Next Steps

Explore Feature Demos

See the Feature Demos on WPM in the LightTrans Document Center. The following feature demos illustrate the two-step procedure and how to work with Wavefront Phase Modifiers:

- Beam Expander Simulation with Wavefront Phase Modifier Twins – Wavefront re-collimation after a plano-concave lens using a tailored phase correction.
- Off-Axis Focus Correction for a Reflective Conical Surface – Modeling and correcting off-axis focusing effects on reflective conical surfaces.
- Wavefront Phase Correction on the Curved Surface of a Rocket Window – Wavefront phase correction directly on a curved surface.

Explore the WPM in VirtualLab Fusion

The Wavefront Phase Modifier twin is available in VirtualLab Fusion as part of the component twin library. Start with a plane WPM to explore a simple phase profile, then move to surface WPM for more complex geometries.

From WPM to Structure

Once you have identified the required phase profile, use the structure-based twins (HOE, Metalens, Refractive/Reflective Surface) to realize the phase profile physically.

Get Expert Support

Contact us at support@lighttrans.com to discuss your specific application. We identify the right twins and tools for your design workflow.

Contact:

- Website: www.lighttrans.com
- Email: support@lighttrans.com

A Glossary

Acronym	Meaning
WPM	Wavefront Phase Modifier
HOE	Holographic Optical Element
MTF	Modulation Transfer Function