The Physical Foundation of VirtualLab Fusion

Optical Digital Twins and Connecting the Diversity of Simulation Models

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One Method Cannot Do It All

Optical systems are diverse. A lens behaves differently from a grating. A metalens is different from a waveguide. Each optical asset has its own physics and requires its own approach to simulation.

VirtualLab Fusion was built around this simple observation.

1. The Core Idea: Optical Digital Twins

In VirtualLab Fusion, every optical asset in your system is represented by an Optical Digital Twin.

- A **Source Twin** represents your light source.
- A **Component Twin** represents a lens, grating, metalens, waveguide, or other optical element.
- A **Detector Twin** represents your measurement or analysis.

Each Optical Digital Twin is a digital representation of a real lab asset. It provides a user interface with parameters—such as focal length, period, material, or geometry—and contains a tailored simulation model for its optical behavior.

Key point: Each twin uses a simulation model tailored for that specific asset. We put no restrictions on the type of simulation model used per twin. Instead, we can utilize the wealth of simulation concepts from different optics disciplines, add new ideas from in-house research and literature, and by that ensure that the twin receives a simulation model which enables the appropriate accuracy-speed balance. This can also mean that one asset comes in more than one twin, with different built-in models.

2. Three Enablers and One Orchestrator

For the twin concept to work, we need three enablers and one orchestrator.

Enabler 1: Each twin has its own simulation model

The simulation model inside each twin can be selected from any optics discipline or newly developed. This is how we achieve the diversity of modeling approaches needed for different assets.

Enabler 2: A common light representation for all twins

All twins must be able to communicate. Some of them require full electromagnetic field information—full information about light that any built-in method may need access to. Thus, there is no way around it: the universal light representation for all twins must be electromagnetic fields. That is the only way to obtain a unified platform on which all twins can communicate with each other.

Conclusion: VirtualLab Fusion uses electromagnetic fields as the common input/output language for all twins.

A twin does not have to use all information carried by the field. If its built-in method only needs part of it, the rest can simply be bypassed inside the twin. But the common representation must not limit what other twins and modeling techniques can access.

Enabler 3: Electromagnetic light representation demanded — approximations of light propagation welcome

This is the enabler that can be a source of confusion—and therefore the most important one to state clearly.

Enabler 2 demands that the light representation is never reduced to a subset—for example, only one component, only intensity, only phase, only local directions represented by rays.

However, this does **not** mean that the propagation of light, in free space or when interacting with matter, cannot be approximated. Often in textbooks and literature, the approximation of light propagation is linked to a specific representation. The most prominent example is the geometrical optics approximation—the neglecting of diffraction—which is commonly linked to a ray representation of light.

Here we cite from *Principles of Optics*, the famous book by Born and Wolf:

> *"It is, however, possible, and from our point of view quite natural, to extend the meaning of geometrical optics to embrace also certain geometrical laws relating to the propagation of the 'amplitude vectors'* **E** *and* **H**.*"* [1]

We follow exactly this advice and extend it to all simulation concepts, enabling them to work with fields.

Here is what this means in practice, with a brief description of what each approximation implies for fields for important cases:

- **Rigorous Maxwell solver:** When we solve Maxwell's equations, we naturally work with electromagnetic fields and no further consideration is needed.
- **Approximated Maxwell solver:** We still work with vectorial fields, but with some simplifying assumptions—for example, specific material models, reduced structural complexity, or simplified boundary conditions.
- **Scalar optics:** When we assume that the transversal field components experience the same effect and that we have no crosstalk, at least in a paraxial approximation we have no vectorial effects. That leads in literature often to the conclusion to work with a placeholder U for the field components and call it scalar. But that is not needed. We can work with fields by applying the same model on the transversal components. Then, the full field information is maintained.
- **Paraxial optics:** The propagation model uses the paraxial approximation. In terms of the field, this means the longitudinal (z) components of the field are approximately zero. The propagation itself can also be approximated within this regime.
- **Geometrical optics:** From a field point of view, this means propagation without diffraction. The fields have local directions—often associated with ray directions. These directions are associated with the wavefront phase, which is common to all field components. The extraction of this phase is not an approximation. But its use to define local directions is what makes geometrical optics for fields possible, including the high speed of simulating light propagation. This applies when fields are in their geometrical zone, which mainly means not in focal regions.

[1] Principles of Optics, p. 125, 7th edition, 1999.

- **Fourier optics:** We work with models in different domains—frequency and time, real space (x) and spatial frequency (k)—and connect them via Fourier transforms. This is a general framework, not an approximation level. It can be combined with any of the above approximations as needed.

Other approximations: Many more approximations exist in the literature. Many are already formulated for fields; others can be reformulated if needed. In either case, they can be used inside a twin. LightTrans has also invented and implemented specialized modeling approaches for specific assets.

The key distinction is between the light representation and the modeling of light propagation.

- **The light representation** = electromagnetic fields (the complete, un-approximated language).
- **The modeling of light propagation** = the simulation model inside each twin, with its chosen level of approximation.

This separation is the foundation of the entire approach. It allows us to keep the light representation consistent and complete across the whole system, while still using approximations for propagation and interaction wherever they are useful for a specific asset and the propagation between them. The light representation and the simulation model approximation are decoupled.

The Orchestrator: Field tracing

Fields are traced non-sequentially from source twins through the relevant component twins and finally to detector twins. This is what LightTrans refers to as field tracing.

Field tracing is the orchestrator of the Optical Digital Twin approach. It allows twins with different built-in methods to work together in one optical simulation and design workflow on a platform with a unified optical foundation.

It does not replace the tailored method inside each twin; it enables the twins to work together. Field tracing propagates the light between twins, including diffraction where needed.

3. The Virtual Lab – Built from Twins

In VirtualLab Fusion, you build your system by arranging twins in a virtual setup—just like you would arrange real assets on an optical table.

- You select the twins that represent your assets.
- You arrange them in the order that matches your system.
- You run the simulation. Field tracing connects the twins. Each twin applies its own method. The result is a unified simulation of your entire system.

This is your virtual lab. It grows with your needs. Add new twins when you need new assets. Add new tools when you need new capabilities.

4. Built-In Expertise

The built-in methods inside the twins are selected and tailored by LightTrans from a wide pool of optical modeling techniques. As a user, you do not need to be an expert in all these models. You use the twin; the appropriate model is already built in.

For users interested in the theory behind a twin, LightTrans provides white papers and further technical documentation.

Summary

The concept behind VirtualLab Fusion rests on three core principles:

- **Optical Digital Twins** represent your assets. Each twin uses a simulation model tailored to that asset, selected from any optics discipline.
- **All twins share a common light representation:** electromagnetic fields. This is the input/output language for communication between twins. It ensures that full information about light is available to any twin that needs it.
- **Approximations can be applied to the modeling of light propagation — not to the light representation itself.** The light representation by electromagnetic fields and the level of approximation of the simulation model are decoupled.

This is the concept behind VirtualLab Fusion: a unified platform for optical simulation and design, built from digital twins with tailored simulation models inside, connected by field tracing, and based on a clear separation between light representation and approximation of light propagation.

"Understand Scenario. Select Twins and Tools. Simulate and Design."