Geometrical Optics Reloaded

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Geometrical and wave optics are commonly considered as opposite poles in optical modeling. Often it is concluded that geometrical optics does not include phenomena like diffraction, interference, coherence, and polarization. We suggest another view on geometrical optics, in which we apply geometrical-optics based arguments to develop a fast algorithm for solving Maxwell's equations in its geometric field approximation.

1 Geometrical and physical optics

Because light appears as sun rays in daily life, it is no surprise that the investigation of the propagation and behavior of light has been based on the mathematical model of rays and its propagation by geometrical rules since the beginning of optics[1]. Till this day the use of geometrical optics, nowadays typically in the form of its software implementation by ray tracing, constitutes the indispensable fundament of optical modeling and design. However, the more advanced the applications of optics and photonics become, the more often we face the limitations of the geometrical optics approach. In Fig. 1 some of the basic limitations are listed. In particular so-called wave-optical effects like interference, polarization and diffraction are not included.

Quantity/Effect	Conventional Rays
Field amplitude and phase	No
Polarization	Restricted models only
Interference, Speckles	No
Temporal coherence	No
Spatial coherence	No
Pulse modeling	No
Scattering	Slow and simple models (Monte Carlo)
Diffractive lenses, DOE's, CGH's	Simple models only
Diffraction	No
Combination with FEM, FDTD, ...	No

Fig. 1 *Overview of typical limitations of conventional ray tracing.*

In order to overcome these limitations, optical modeling and design must be based on physical optics. In physical optics we deal with electromagnetic fields which solve Maxwell's equations. However, universal and rigorous Maxwell solver like FEM and FDTD cannot be used in optical system modeling because of their drastically high numerical effort. Solvers like FDTD and FEM are important to model those parts of a system with very small features, but nobody would or could apply them to propagate light through a lens system. So on the one hand we need to solve Maxwell's equations in order to overcome the limitations of ray tracing but on the other hand, a solution of these equations by a universal mathematical solver is not practical in most cases. So we are trapped between two conflicting demands. Probably because of that contradictory situation, physical optics has not found its natural place in optical modeling and design to date.

Quantity/Effect	Smart Rays
Field amplitude and phase	Yes
Polarization	Yes
Interference, Speckles	Yes
Temporal coherence	Yes
Spatial coherence	Yes
Pulse modeling	Yes
Scattering	Yes
Diffractive lenses, DOE's, CGH's	Yes
Diffraction	No/Yes (iterative)
Combination with diffraction integrals, FEM, FDTD, FMM, ...	Yes

Fig. 2 *In geometric field tracing smart rays are used which allow the inclusion of all wave-optical effects with the exception of diffraction.*

There is one logical conclusion out of this dilemma: If we cannot solve Maxwell's equations in the practice of optical design by a universal and rigorous Maxwell solver like Finite Element Method (FEM), then we must use specialized and/or approximated approaches to solve Maxwell's equations. As an example, it is well known how to rigorously propagate light through homogeneous media, for instance with the Rayleigh integral. No FEM is needed. But we can also use a simple Fresnel integral, if the light is paraxial. This is just an example to show, that we can quickly solve Maxwell's equations with high accuracy also in practice. Thus, we can combine specialized and approximated solvers of Maxwell's equations in different regions of an optical system and obtain a physical optics modeling concept which we refer to as field tracing [2].

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2 Geometrical optics as Maxwell solver

In this context an essential question arises: What is the role of geometrical optics and ray tracing in the context of physical optics? At first glance this question is confusing, because most of us understand geometrical optics as the antipode of physical optics. Historically that is not justified. It is true that Newton applied the ray concept to his corpuscular model of light, in which wave-optical effects are obviously not included. However, Huygens also used the ray concept but in the context of wavefronts. Born and Wolf suggested this concept to deal with Maxwell's equations already in their classic book Principles of Optics in Chapter III on geometrical optics[3]. We have further developed and implemented it to obtain a geometric field tracing technique, which solves Maxwell's equations in its geometric approximation. The geometric approximation leads to Maxwell's equations for local plane waves which deliver accurate solutions in regions in which the spatial evolution of a field is dominated by its wavefront. In practice the solution of Maxwell's equations in geometric approximation is obtained by a ray tracing algorithm with smart rays. Smart rays have the following properties:

- Smart rays know the full electromagnetic field information at their position. That includes amplitudes and phases of the electric and magnetic field components and by that also polarization.
- Smart rays know and remember their neighbors on the wavefront in the source plane. This is done by an appropriate ray index concept (wavefront indexes). This method is combined with different lateral interpolation techniques for all field quantities which are allocated to a ray. Interpolation techniques include spline interpolation and mesh-based interpolation with barycentric coordinates.
- Smart rays come with another index concept (spatial coherence indexes), which enable their association to mutually coherent and incoherent modes and its combination. That allows the modeling of partially spatially coherent light, including the special cases of fully coherent and incoherent light.
- In order to include color, temporal coherence, and ultrashort pulses, the frequencies which are allocated to a ray also come with an index to distinguish frequency contributions to stationary and pulsed light (frequency indexes).

By tracing smart rays we obtain a solver for Maxwell's equations which overcomes most of the limitations of conventional ray tracing (see Fig. 2) but delivers the results as fast as it is known from ray tracing.

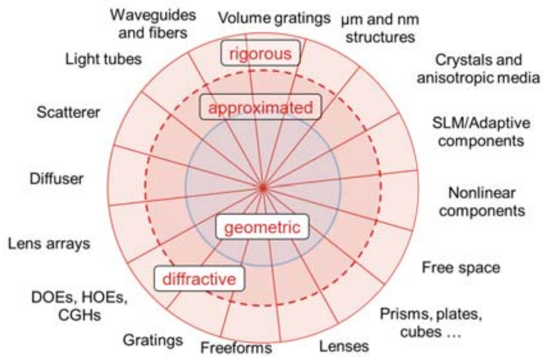

Fig. 3 *systems with different components can be modeled by unified field tracing. Geometric field tracing is an important method among others.*

3 Geometrical optics in unified field tracing

Figure 3 illustrates by the sectors of a circle different components which might be combined in a system. The circles indicate the modeling of the components by approximated or rigorous solutions of Maxwell's equations. The inner circle (blue) emphasizes, that geometric field tracing is one essential technique among others to solve general modeling problems.

Wyrowski Photonics UG has developed the software *VirtualLab Fusion* which will be releases in fall 2015. It includes ray tracing, geometric field tracing, and unified field tracing [4]. An example of the modeling of a zigzag waveguide by smart ray tracing is shown in Fig. 4.

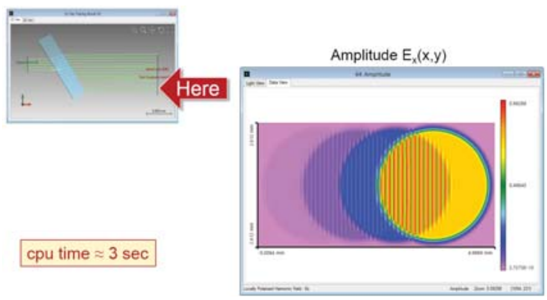

Fig. 4 *Non-sequential zigzag waveguide modeling with geometric field tracing including interference of decoupled light.*

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