Non-paraxial Diffractive and Refractive Laser Beam Shaping

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In general, an optical design problem can be described as followed:

• given input field $E^{\text{in}}(x, y)$
• design an optical system: $E^{\text{in}}(x, y) \rightarrow E^{\text{sig}}(x, y)$
• obtain a detector function $\Omega(E^{\text{sig}}(x, y))$
Modelling of Diffractive Optical Element

The Fourier Modal Method (FMM) is a rigorous technique to model the electric field propagation through a grating.

\[ E^{\text{in}} \rightarrow \text{DOE} \rightarrow E^{\text{out}} \]

Local grating \[ \Lambda(x, y) \]
Modelling of Refractive Optical Element

“Local plane-interface approximation“ a method for propagating electromagnetic fields through the smooth surface of an optical system.
Modelling of Refractive Optical Element

Input: Gaussian beam
Diameter 10 mm

Amplitude $E_x(x,y)$

Simulation time < 1 sec
Modelling of Refractive Optical Element

Irradiance pattern is morphing while propagation
Modelling of Refractive Optical Element

input plane → freeform surface → target plane
Introduction

Inverse approach
1. **functional embodiment**: an ideal component function is introduced to realize the transmission between the two fields;
2. **structure embodiment**: suitable structure is developed to realize the functionality of the component.

\[ \mathbf{E}^{\text{in}}(x, y) \rightarrow \mathbf{E}^{\text{sig}}(x, y) \]

Pfeil, A. V. & Wyrowski, F. *Wave-optical structure design with the local plane-interface approximation* 
*Journal of Modern Optics, 2000, 47, 2335-2350*
Design Task: Focusing System

Task description: for a given spherical wave, to design an optical element to focus it with a specific NA.

The signal field is considered as a spherical wave.
The element is considered as a phase only function, which is the subtraction of the phase from input and output field: \( \varphi(x, y) = \varphi^{\text{out}}(x, y) - \varphi^{\text{in}}(x, y) \)
The local grating of the diffractive lens is chosen as a sawtooth type. The 1st order is selected as the working order. Local grating period $\Lambda(x, y)$ of the diffractive lens is obtained with the phase function:

$$\Lambda(x, y) = \frac{2\pi}{|\nabla \varphi(x, y)|}$$
Simulation with Designed Result

Diffractive Lens

Intensity After the Diffractive Lens

PSF
(Airy disk diameter $\approx 2.5\mu m$)

dot diagram

0th order
1st order
2nd order
Algorithm in brief:

1. propagate \(\rightarrow\) phase on reference plane \(\varphi_{\text{in}}(x, y), \varphi_{\text{out}}(x, y)\)
2. \(\varphi_{\text{in}}(x, y), \varphi_{\text{out}}(x, y)\) \(\rightarrow\) local wave vectors \(k_{\text{in}}(x, y), k_{\text{out}}(x, y)\);
3. \(k_{\text{in}}(x, y), k_{\text{out}}(x, y)\) \(\rightarrow\) gradient of the surface \(\nabla H(x, y)\);
Algorithm in brief:
1. propagate $\rightarrow$ phase on reference plane $\varphi_{\text{in}}(x, y), \varphi_{\text{out}}(x, y)$
2. $\varphi_{\text{in}}(x, y), \varphi_{\text{out}}(x, y) \rightarrow$ local wave vectors $k_{\text{in}}(x, y), k_{\text{out}}(x, y)$;
3. $k_{\text{in}}(x, y), k_{\text{out}}(x, y) \rightarrow$ gradient of the surface $\nabla H(x, y)$;
4. fit the gradient by B-spline to obtain a surface;
5. update the reference plane with the surface, and iteratively perform step 1 to 4 until a proper surface is obtained.
Designed Result and Simulation

- Height Profile (3D view)
- Height Profile (2D Contour line)
- dot diagram ($RMS \approx 4110nm$)
- PSF
  - Airy disk diameter $\approx 2.5\mu m$
1. Spherical Aberration

plane wave input

double-Gauss lens system

Freeform Structure?

dot diagram

PSF
Application: Aberration Control in Image System

Design Process

forward propagation

reference plane

backward propagation

phase from input field

phase from target field
Design and Simulation Result

freeform surface

Height Profile (3D view)

Height Profile (2D Contour line)

RMS = 42.27μm

RMS = 2.08μm

dot diagram

PSF
Design Task: Irradiance Redistribution

Task description: for a given input field, design an optical element to achieve required irradiance on target plane

\[ E^{\text{in}}(x, y) \rightarrow \text{optical element} \rightarrow \Omega(E^{\text{sig}}(x, y)) \]

Input plane \( E^{\text{in}}(x, y) \)

The input field is given.
The signal field is a freedom for the design.
Design Process: Functional Embodiment

\[ E^{\text{in}}(x, y) \]

reference plane

Input plane

\[ E_{e1}(x, y) \quad E_{e2}(u, v) \]

target plane
Design Process: Functional Embodiment

\[ E^{\text{in}}(x, y) \]

Input plane

reference plane

\[ \varphi^{\text{in}}(x, y) \quad \varphi^{\text{out}}(x, y) \]

Output plane

\[ u(x, y) \quad v(x, y) \]

\[ E_e^1(x, y)dx\,dy \quad E_e^2(u, v)dudv \]
Example: Homogeneous Irradiance

Task description: for an input Gaussian wave, design an optical element to achieve homogeneous irradiance on target plane.
Example: Homogeneous Irradiance

- Gaussian wave
  - high NA (0.27)

Input plane

Reference plane

Target plane

Irradiance on target plane

Mesh nodes for input irradiance

Mesh nodes for target irradiance
Designed Result and Simulation

- Field tracing result: irradiance
- Irradiance on cross-sectional line
- Output beam NA = 0.34
- Simulation time ~2s

3D View
2D Contour line
Designed Result and Simulation

field tracing result: irradiance with different polarization input field

output beam
NA = 0.6
Example: Specific Irradiance

Plane wave

optical element with freeform surface

input plane

3.5mm

irradiance on target plane

target plane

300mm

150mm

plane wave

3.5mm
Designed Result and Simulation

3D View
2D Contour line
Designed Result and Simulation

Field tracing result:
irradiance on target plane
Designed Result and Simulation

- Designed Result and Simulation

- 300mm

- 300mm

- Field tracing result: irradiance on target plane

- Field tracing result: irradiance on further plane

- Designed Result and Simulation

- 300mm

- 300mm
Conclusion

In summary:

• Modelling method is the basic for optical design;
• Base on the inverse approach, the directly design for the element structure is done in a fast way;
• The designed results can be used as the initial structure for further optimization.
Implementation

- All algorithms are implemented in the physical optics simulation and design software **VirtualLab Fusion**
- VirtualLab Fusion is developed, following the field tracing concept, by Wyrowski Photonics UG, Jena, Germany
Thank you