Simulation and optimization with step-transition perturbation approach in diffractive optical elements

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Project objectives

- We propose the method for optimizing the diffractive optical elements(DOEs) such as 1D fan-out gratings. It is useful for calculating the gratings with large grating period and small feature sizes where thin element approximation(TEA) is inaccurate.
- The diffractive efficiencies of gratings in a non-paraxial domain are calculated by using the step-transition perturbation approach.
- Gradient descent method with step-transition perturbation approach for optimizing the gratings is expressed.

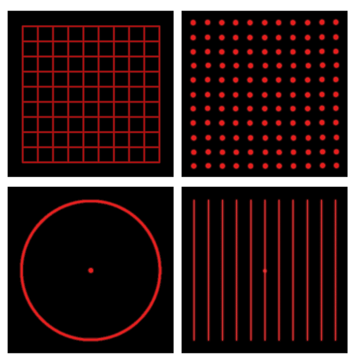
Diffractive Optical Elements

Features

- Light and compact components
- Generation of the desired light distribution
- High design flexibility
- Low-cost fabrication

Applications

- Metrology
- Imaging
- Sensor technology
- Biotechnology



Simulation of DOEs

- By using **rigorous methods**, e.g. Rigorous coupled wave analysis (RCWA), we can calculate the diffraction efficiencies **accurately**. However, these methods require **too long simulations times** for 2D gratings with a large grating period.
- **Thin element approximation(TEA)** is a **simple and fast** method. However, the TEA becomes **inaccurate** in the case where the feature sizes are comparable with the wavelength of the incident beam.

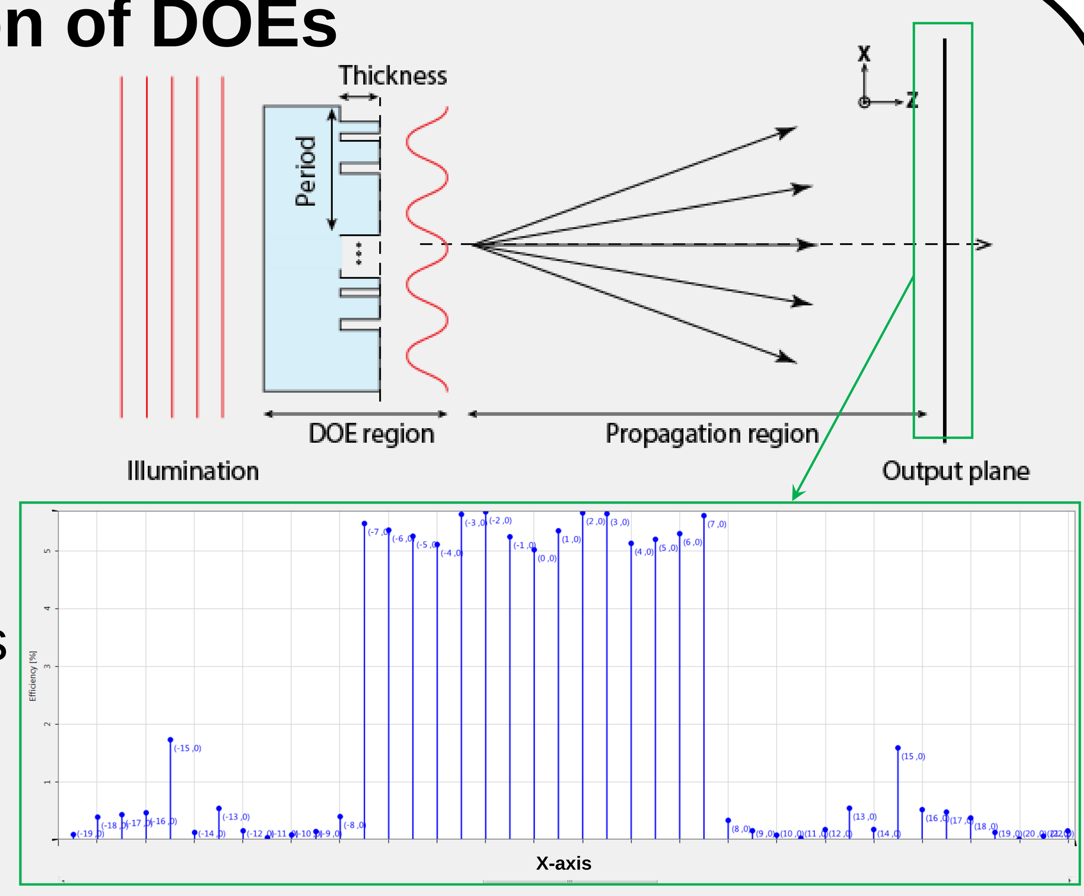


Fig.1. The calculated diffractive efficiencies by RCWA

Step-transition perturbation method

Motivation

We require the methods to calculate the diffraction efficiencies of gratings with the **large grating period and small features** where the **TEA is no longer accurate**, and **RCWA is practically difficult** to use due to the high computational effort.

Concepts

The diffraction pattern describes the diffracted field as a superposition of a geometric wave and the wave generated at the edges. Therefore the predictions of the **TEA** are complemented **with field perturbation arising from sharp transition steps** [1].

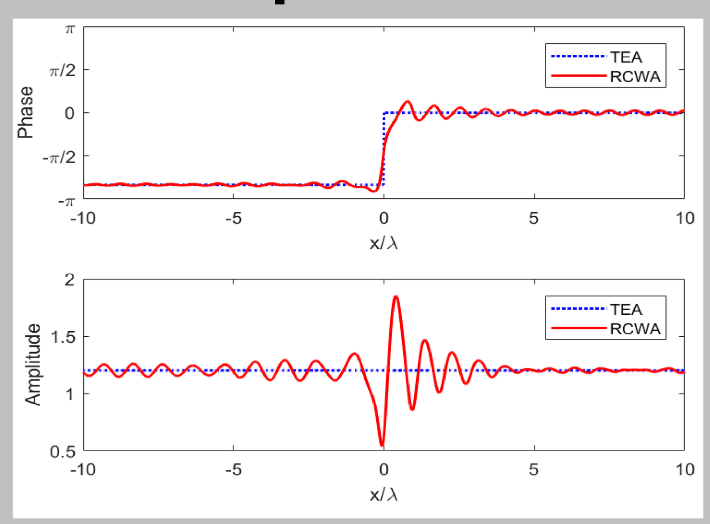


Fig.2. Phase and amplitude of electric field behind a sharp transition step

1. Define the field perturbation caused by k:th transition point

$$P_k(x) = \begin{cases} U_k^{RCWA}(x) - U_k^{TEA}(x) & \text{if } |x| < \Delta_T \\ 0 & \text{elsewhere} \end{cases}$$

2. Constructed field behind the element

$$U(x) = U^{TEA}(x) + \sum_{k=1}^{2K} P_k(x)$$

3. The Fourier coefficients of total field

$$T_m = \frac{1}{d}\int_0^d U(x)\exp(-i2\pi mx/d)dx = T_m^{TEA} + D_m$$

Fourier coefficients of perturbation D_m can be obtained **by superposing the perturbations** which can be easily calculated **by applying Fourier shifting theorem.**

Gradient optimization with step-perturbation method

$$\eta_m = \frac{\sin^2(\Delta\Phi/2)}{(m\pi)^2}(C_k^2+S_k^2)+\sum_{k=1}^{K}\cos(2\pi m(x_{2k-1}-x_{2k})/d)\left\{\mathfrak{F}(P_1)-\mathfrak{F}(P_2)+2\mathfrak{F}(P_1)\cdot\mathfrak{F}(P_2)\right\} \quad \text{if } m \neq 0$$

$$\eta_0 = 1-4Q(1-Q)\sin^2(\Delta\Phi/2)+4K^2P^2+4KP\left[\cos(\Phi_1)-Q\left\{\cos(\Phi_1)+\cos(\Phi_2)\right\}\right]$$

where

η_m is the diffraction efficiency of each diffraction order m

$\Phi_1 - \Phi_2 = \Delta\Phi$ — Φ_1 is the phase of field in air, Φ_2 is the phase of field in DOE

$2K$ is total transition points — x_k is the k:th transition points

$$C_K = \sum_{k=1}^{2K}(-1)^k\cos(2\pi m x_k) \qquad S_K = \sum_{k=1}^{2K}(-1)^k\sin(2\pi m x_k) \qquad Q = \sum_{k=1}^{2K}(-1)^k x_k$$

$$P = \int_0^d P_1(x)dx = \int_0^d P_2(x)dx$$

For 1D binary fan-out gratings, we express the **diffraction efficiencies as a function of the transition points including the contribution of field perturbation** created by the abrupt steps.

In the equation, the variables are about the transition points; x_{2k-1}, x_{2k}, and x_k. Therefore, we can implement the gradient as a function of transition points [2].

References

[1] T. Vallius, M. Kuittinen, J. Turunen, and V. Kettunen, “Step-transition perturbation approach for pixel-structured nonparaxial diffractive elements,” J. Opt. Soc. Am. A, vol. 19, no. 6, p. 1129, 2002.

[2] L. L. Doskolovich, V. A. Soifer, G. Alessandretti, P. Perlo, and P. Repetto, “Analytical initial approximation for multiorder binary grating design,” Pure Appl. Opt. J. Eur. Opt. Soc. Part A, vol. 3, no. 6, pp. 921–930, Nov. 1994.

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