Local normal vector field formulation for polygonal building blocks in a Gabor representation

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S. Eijsvogel[1], F. Sepehripour[1], L. Sun[1], R.J. Dilz[1], and M.C. van Beurden[1]

Department of Electrical Engineering, Eindhoven University of Technology, 5612 AZ Eindhoven, The Netherlands
s.eijsvogel@tue.nl, f.sepehripour@tue.nl, l.sun1@tue.nl, r.dilz@tue.nl, m.c.v.beurden@tue.nl

Summary. The usage of a spatial spectral domain integral equation solver for electromagnetic scattering from dielectric objects provides a means to execute scattering simulations for lithography. We consider the extension of the local normal vector field formulation to support polygonal building blocks in a Gabor series representation of functions.

1 Introduction

Possible improvement in both power efficiency and performance for integrated circuits (IC) is the resultant of extreme ultraviolet (EUV) lithography by further decreasing the node size to a mere 5 nanometer [1]. This lithographic production of ICs becomes a cost-effective process if one can ensure that parameters such as illumination and alignment between layers are controlled [2]. In other words, it is preferred that the equipment used for lithography is subjected to continuous monitoring and calibration in order to guarantee nanometer precision. A possible calibration method for the lithography process is scatterometry [2].

Recently, a spatial spectral Maxwell solver has been designed specifically for electromagnetic scattering by dielectric objects in layered media [3]. The main idea of this Maxwell solver is to calculate the scattered field from the scatterer by solving a domain integral equation, which originates from the frequency-domain Maxwell equations. It was shown that the integral equation can be solved more efficiently if one implements the Gabor series representation of functions with a Gaussian window function as defined in [4]. This ensures a fast and analytical transformation between spatial and spectral domain.

A key ingredient of [3] is the normal vector field formulation in order to respect the Fourier factorization rules [5]. The normal vector field formulation expresses the idea to construct a vector field **F** consisting of the continuous parts of electric field **E** and electric flux density **D**. The advantage is that the field-material interaction described by a Fourier series proved to be more accurate via an intermediate vector field **F** compared to direct the field-material interaction by **E** or **D** [5]. The extension of the normal vector field formulation to local normal vector field formulation can be found in [6]. The local normal vector field formulation enables to have an object of interest and normal vector field independent from each other. In [3], this local normal vector field formulation was implemented numerically for the Gabor series representation of bar-shaped and circular cylindrical objects.

The work of [6] is also an analytical approach to evaluate polygonal shapes with the local normal vector field formulation. This analytical approach incorporates parameters such as rotation and translation of objects. Thus, the approach is object-based and not pixel-based. However, [6] only describes the spatial and spectral local normal vector field formulation for functions described in terms of a Fourier basis.

We propose an approach to construct a local normal vector field formulation for polygonal building blocks while using a Gabor series representation of functions with a Gaussian window function as defined in [3], [4].

2 Gabor series representation

Given that we aim to extend the work of [3], we use the Gabor series representation with the following Gaussian window function

$$g(x,y) = 2^{1/4} e^{-\pi \frac{x^2}{X^2} - \pi \frac{y^2}{Y^2}} \quad (1)$$

where X and Y define the spatial period of the window function for x and y direction, respectively. This Gaussian window function is used to define the Gabor frame, which plays a central role in the Gabor series representation. The Gabor frame is defined as

$$g_{\mathbf{mn}}(x,y) = g(x - m_x\alpha_x X, y - m_y\alpha_y Y) e^{\mathrm{j}\beta_x n_x K_x x + \mathrm{j}\beta_y n_y K_y y} \quad (2)$$

with the indices $\mathbf{m} = (m_\mathrm{x}, m_\mathrm{y})$ and $\mathbf{n} = (n_\mathrm{x}, n_\mathrm{y})$. The spectral periods are expressed as $K_\mathrm{x} = \frac{2\pi}{X}$ and $K_\mathrm{y} = \frac{2\pi}{Y}$. The oversampling coefficients are defined as $\alpha_x\beta_x < 1$ and $\alpha_y\beta_y < 1$. The Gabor frame is used to represent a function such as the electric field as

$$\mathbf{E} = \sum_{\mathbf{m}} \sum_{\mathbf{n}} \mathbf{e}_{\mathbf{mn}}(z) g_{\mathbf{mn}}(x,y) \quad (3)$$

where $\mathbf{e}_{\mathbf{mn}}$ represents a Gabor coefficient.

3 Computation of spectral operators

The work of [6] refined the ideas proposed in [5] by expressing the 3D electric field **E** as

$$\mathbf{E} = \mathrm{C}_\varepsilon \mathbf{F} = \begin{bmatrix} C_{xx} & C_{xy} & C_{xz} \\ C_{yx} & C_{yy} & C_{yz} \\ C_{zx} & C_{zy} & C_{zz} \end{bmatrix} \begin{bmatrix} F_x \\ F_y \\ F_z \end{bmatrix} \tag{4}$$

in case of dielectric media. Vector field **F** represents an intermediate vector field while linear operator C_ε is used to transform **F** back to **E** and similar for

$$\mathbf{D} = \varepsilon C_\varepsilon \mathbf{F} \tag{5}$$

where ε expresses permittivity.

An important aspect of [3] is the transformation between spatial and spectral domain. This means that we are interested in performing a spectral transformation on linear operator C_ε. Therefore, we evaluate the following integral

$$c_{ij}(\mathbf{m}, \mathbf{n}, z) = \iint_{A_u} g_{\mathbf{mn}}(x, y)\, dx dy \tag{6}$$

where $\mathrm{A_u}$ represents the support of the polygonal shape in *xy*-plane. The main issue of Eq. (6) is that we need to solve 2D integral for each **m** and **n**, which results in a heavy burden in computation time.

A closed contour provides us a way to introduce Gauss's theorem to reduce the surface integral to a line integral where the contour is the sum of the line integrals along the edges of a closed polygon [6]. This reduces the computation time. An extra advantage of this method is that one would only require the edge points of a polygon to obtain all required information necessary to go from spatial to spectral domain. Another interesting aspect of the linear operator C_ε is that it can be obtained independently for each vertical position along z of a shape, which readily enables the implementation of parallel computing. Overall, these components can help to decrease the computational effort while solving Eq. (6).

4 Spectral C_ε calculations for FinFET

We show the conversion from a FinFET structure [7], Fig. 1, to polygonal building blocks with corresponding normal vector for each boundary as seen in Fig. 2. These polygonal building blocks are used to define our spatial version of the C_ε for each z-position of a FinFET. Our main focus is to display a cut-and-connect strategy with Eq. (6) as outlined in [6]. This strategy employs the idea to generate polygons for shapes such as in Fig. 2.

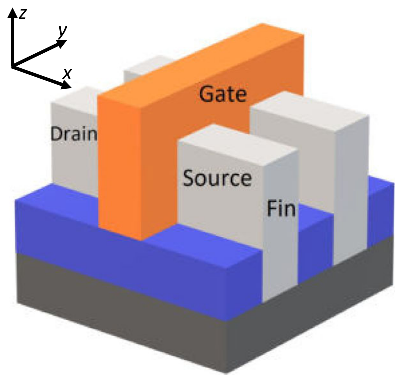

Fig. 1. A simplified example of a FinFET structure

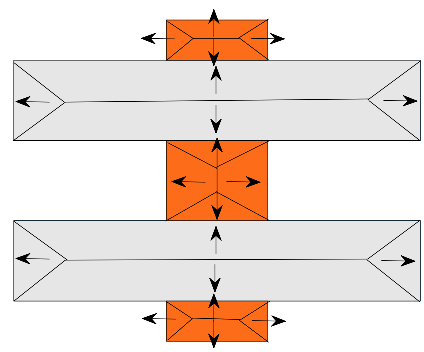

Fig. 2. An example of a z-position of a FinFET by polygonal building blocks. The arrow represents the direction of the normal vector for each polygonal building block

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