Advanced computational modeling of silicon waveguide devices based on Sub-Wavelength Gratings

Master internship project
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1. Scientific and technological context

Silicon photonics has great potential to bringing together two technological areas that have transformed the last century, electronics and photonics, and is gaining tremendous momentum in both academia and industry. Silicon waveguides are important components for tailoring photonic functions on silicon. They have been studied extensively over the pas two decades. There are a number of waveguide geometries that have bee developed in silicon. The most common are strip waveguides, rib waveguides and slot waveguides.

The Bragg grating is a fundamental component in various optical devices and has applications in areas as diverse communications, laser and sensors. In the simplest configuration, a Bragg grating is a structure with periodic modulation of the effective refractive index. This modulation is commonly achieved by varying the refractive index (e.g. alternating material) or the physical dimensions of the waveguide. At each boundary, a reflection of the travelling light occurs, and the relative phase of the reflected signal is determined by the grating period and the wavelength. The repeated modulation of the refractive index results in multiple and distributed reflections. The reflected signals only interfere constructively in a narrow band around one particular wavelength, namely the Bragg wavelength. Within this range, light is strongly reflected. At other wavelengths, the multiple reflections interfere destructively and cancel each other out, and as a result, light is transmitted through the grating.

Such periodic structures can generally operate in several regimes, depending on the ration between the structure's pitch and the free-space wavelength: (i) diffraction, where the incoming beam is scattered in different orders, (ii) reflection, where the incoming beam is reflected backwards, and (iii) sub-wavelength, where diffraction effected due to periodicity of the structures are suppressed, leading the concept of Sub-Wavelength Gratings (SWG). Recent advances in silicon photonics have led to the integration of Bragg gratings on so-called Silicon-On-Insulator (SOI) platforms. Generally, an integrated Bragg grating is formed in a waveguide with physical corrugations that lead to the modulation of the effective refractive index in the waveguide. Integrated Bragg gratings will be essential building blocks for silicon photonics. Although the research in this area has been making steady progress in the recent years, much more effort is still needed to improve the grating performance. This research is extensively relying on experimental design, but numerical modeling is also increasingly used, in particular in view of simulating the effects of lithography when fabricating the grating, which results in corrugations varying from the originally planned design. This Master internship is concerned with this topic, in the context of the OPENING (On-chiP wirEless quantum state eNgineerING) UCA JEDI (http://univ-cotedazur.fr/english/idex-uca-jedi/ucajedi-project) project recently awarded to the Information Quantique avec la Lumière & la Matière (QILM) group of INϕNI Laboratory. This study will in particular lead to the development of an innovative numerical modeling tool for the simulation of light propagation in complex silicon waveguide devices based on SWG.

The internship will take place at Inria Sophia Antipolis-Méditerranée with regular visits and meetings at INϕNI Laboratory. It will be supervised by Stéphane Lanteri (Nachos project-team at Inria) and Laurent Labonté (QILM group at INϕNI Laboratory), but the student will also interact with other researchers of the two groups involved in the OPENING project. Beside, this study will also be conducted in interaction with researchers from the Silicon Photonics group at C2N (Center for Nanoscience and Nanotechnology) in Orsay (http://silicon-photonics.ief.u-psud.fr/ - Eric Cassan, Carlos Alonso-Ramos and Diego Perez Galacho) who are experts of the design and study of silicon devices.

2. Mathematical and numerical modeling

Numerical modeling of light propagation in complex wave-guiding structures requires solving the system of Maxwell equations possibly coupled with an appropriate material law for metals at optical frequencies. During the last twenty years, numerical methods formulated on unstructured meshes have drawn a lot of attention in computational electromagnetics with the aim of dealing with irregularly shaped structures and heterogeneous media. In particular, the discontinuous Galerkin time-domain (DGTD) method has progressively emerged as a viable alternative to well established finite-difference time-domain (FDTD) and finite-element time-domain (FETD) methods for the numerical simulation of electromagnetic wave propagation problems in the time-domain. In this work, we will consider such a DGTD method that has been recently designed at Inria in the Nachos project-team for the simulation of nanoscale light/matter interaction problems [1].

The DGTD method can be considered as a finite element method where the continuity constraint at an element interface is released. While it keeps almost all the advantages of the finite element method (large spectrum of applications, complex geometries, etc.), the DGTD method has other nice properties, which explain the renewed interest it gains in various domains in scientific computing:

- ✓ It is naturally adapted to a high order approximation of the unknown field. Moreover, one may increase the degree of the approximation in the whole mesh as easily as for spectral methods but, with a DGTD method, this can also be done locally i.e. at the mesh cell level. In most cases, the approximation relies on a polynomial interpolation method but the method also offers the flexibility of applying local approximation strategies that best fit to the intrinsic features of the modeled physical phenomena.
- ✓ When the discretization in space is coupled to an explicit time integration method, the DG method leads to a block diagonal mass matrix independently of the form of the local approximation (e.g the type of polynomial interpolation). This is a

striking difference with classical, continuous FETD formulations. Moreover, the mass matrix is diagonal if an orthogonal basis is chosen.

- ✓ It easily handles complex meshes. The grid may be a classical conforming finite element mesh, a non-conforming one or even a hybrid mesh made of various elements (tetrahedra, prisms, hexahedra, etc.). The DGTD method has been proven to work well with highly locally refined meshes. This property makes the DGTD method more suitable to the design of a *hp*-adaptive solution strategy (i.e. where the characteristic mesh size *h* and the interpolation degree *p* changes locally wherever it is needed).
- ✓ It is flexible with regards to the choice of the time stepping scheme. One may combine the discontinuous Galerkin spatial discretization with any global or local explicit time integration scheme, or even implicit, provided the resulting scheme is stable.
- ✓ It is naturally adapted to parallel computing. As long as an explicit time integration scheme is used, the DGTD method is easily parallelized. Moreover, the compact nature of method is in favor of high computation to communication ratio especially when the interpolation order is increased.

As in a classical finite element framework, a discontinuous Galerkin formulation relies on a weak form of the continuous problem at hand. However, due to the discontinuity of the global approximation, this variational formulation has to be defined at the element level. Then, a degree of freedom in the design of a discontinuous Galerkin scheme stems from the approximation of the boundary integral term resulting from the application of an integration by parts to the element-wise variational form. In the spirit of finite volume methods, the approximation of this boundary integral term calls for a numerical flux function, which can be based on either a centered scheme or an upwind scheme, or a blend of these two schemes.

3. Objectives of the study

The global objective of this internship is to study numerically the influence of the corrugation geometry on the transmission of light in silicon waveguide devices based on SWG. Two situations will be considered: (1) in a first step, an *ideal* configuration corresponding to a virtual design will be simulated; (2) in a second step, several *deformed* configurations, which are more in line with actual designs (i.e. from lithography), will be studied with the goal of identifying the main sources of performance degradation from the transmission point of view.

The realization of this numerical study will necessitate the development of two software tools: on one hand, a preprocessing tool will be specified and programmed for the definition of the geometry and associated computational domain for silicon waveguide devices based on SWG; on the other hand, a dedicated DGTD-based solver will be developed for the simulation of light propagation silicon waveguide devices based on SWG, and the calculation of relevant observables such as transmission spectra. The later simulation tool will exploit the DIOGENeS software suite (https://diogenes.inria.fr/), which is under development by the Nachos project-team at Inria. This software suite is based on a core library of Fortran 2008 classes, which implements all the required data structures and functions for developing dedicated simulation software leveraging the capabilities of discontinuous Galerkin formulations.

References

[1] X. Wang, *Silicon photonics waveguide Bragg gratings*, PhD thesis, The University of British Columbia, December 2013.
https://open.library.ubc.ca/cIRcle/collections/ubctheses/24/items/1.0165738

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