3D-Simulation and Characterization of Subwavelength Grating Waveguides in SOI

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***Abstract*—Spectral properties of silicon subwavelength grating waveguides are simulated in 3D with eigenmode expansion and the impact of the number of included modes is investigated. Simulation results are validated against measurements.**

I. Introduction

Subwavelength gratings (SWG) allow the realization of various devices for optical signal transmission and processing. Depending on the grating geometry, an SWG can act as artificial medium with effective refractive index [1] to improve device performance [2], be used as a Bragg-reflector based filter or enhance integrated modulators exploiting slow light effects [3] .

II. Simulation of grating structures in 3D

Finite-difference time-domain (FDTD) is a common method for the accurate but computationally expensive simulation of integrated grating waveguides. The regular structure of SWG waveguides can also be simulated with eigenmode expansion (EME) method and Floquet-Bloch theorem, without sacrificing accuracy [4]. This approach allows for the extraction of the effective indices of the propagating modes and to reduce computation time significantly for many parameter variations by re-using previous intermediate simulation results.

First, the S-matrix of one grating period has to be calculated with a bidirectional eigenmode expansion and propagation tool. Applying Floquet-Bloch theorem on these results leads to an eigenvalue problem. The complex solutions include phase shift and loss of the propagating Bloch modes for one grating period, thus the propagation constants can be retrieved.

Simulations of such structures with plane-wave expansion / Fourier modal method have been done in [3], [5], [6]. In this work, eigenmode expansion method is used to determine the S-matrix. The computational window is limited by hard walls, i.e electric and magnetic walls without using perfectly matched layers. Thus, the optical field is a composition of guided modes and radiation modes with purely real and imaginary propagation constants, respectively. The optical simulation is done with the software tool FIMMWAVE from Photon Design, whereas the post-processing of the data is done in MATLAB.

In some cases involving laterally wide grating structures the mode propagation constants are close to the one of a one-dimensional slab mode. In this case the simulations can be reduced to two-dimensional simulations with a one-dimensional cross-section [7]. However this approach is not valid for typical single-mode waveguides, therefore the 2D cross-section has to be taken into account. Fig. 1 depicts the Si core of a waveguide, which is surrounded by a SiO_2 cladding. In the following this structure is investigated for different grating periods, a fixed filling factor of $FF = 0.5$, a waveguide width of $w_{\mathrm{wg}} = 400$ nm and a nominal thickness of the silicon layer of $t_{\mathrm{Si}} = 250$ nm. The etching depth is $t_{\mathrm{etch}} = 70$ nm. Fabricated waveguides with these dimensions are referred to as WG I. For some fabricated chips a dry oxidation step has been performed after the waveguide structuring, consuming approximately 18 nm of Si. Thus $t_{\mathrm{Si}} = 232$ nm and $w_{\mathrm{wg}} = 364$ nm are assumed for the simulations of these waveguides. The oxidation step additionally reduces the filling factor. Waveguides on these chips are referred to as WG II.

The simulation precision strongly depends on how accurate the optical field can be represented by a superposition of guided and radiative modes. Increasing the simulation window allows for finding more modes and achieving a better overall accuracy, but in turn a higher absolute number of modes is required to achieve the same accuracy. Increasing the number of modes for a given simulation window improves the simulation accuracy in principle. However, determining the optimum number of modes is not trivial, since the obtained results for this particular structure diverge from physical solutions for a too large number of modes. A silicon subwavelength grating with very small grating period, i.e. in the theoretical long-wavelength limit, acts as artificial medium with, theoretically, no loss. Thus the criterion for the optimum number of modes is chosen to attain a minimum loss of such a structure.

III. Simulation results

Fig. 2 shows the real and imaginary part of the effective index of the fundamental mode of WG I as a function of Λ/λ_0 for different numbers of modes at $\lambda_0 = 1.55$ µm. Three regions of operation can be identified. First, for $\Lambda/\lambda_0 < 0.22$, the grating waveguide acts as artificial medium with effective refractive index between those of Si and SiO_2, thus the effective index of the mode lies between the corresponding indices

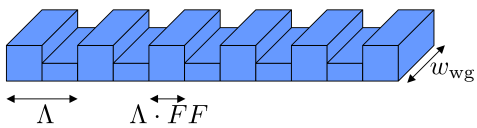

Fig. 1. Subwavelength grating waveguide with basic design parameters.

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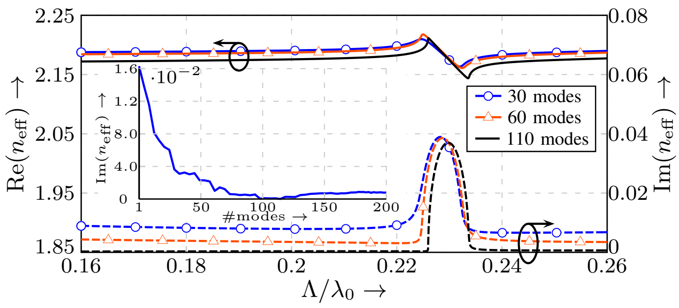

Fig. 2. Real part (solid lines) and imaginary part (dotted lines) of the fundamental mode effective index in the subwavelength grating waveguide for different numbers of eigenmodes used in the simulation. Inset: imaginary part of n_{eff} over the number of included modes for $\Lambda/\lambda_0 = 0.1935$.

of the straight waveguides. At $0.22 < \Lambda/\lambda_0 < 0.235$, the Bloch mode approaches the Bragg condition and is reflected, thus the imaginary part increases. This case corresponds to a 1-dimensional photonic band gap (BG). For even larger Λ/λ_0 the Bloch mode is able to propagate without high loss, until the first order diffraction is no longer suppressed or further band gaps appear. Two principal aspects can be observed when the number of modes is increased. First, the band gap shifts slightly to larger values of Λ/λ_0 and second, the imaginary part of the refractive index in the passband decreases, due to the more accurate field representation. The inset of Fig. 2 shows the mode loss as a function of the number of included modes. In this case, the lowest loss is attained for about 110 modes. This number may vary slightly when the wavelength changes.

The spectral properties of the grating waveguides are depicted in Fig. 3 with $\Lambda = 350$ nm and $FF = 0.5$ (WG I) and $\Lambda = 400$ nm and $FF = 0.41$ (WG II). Both waveguides have a photonic BG partly in the C-Band. Compared to WG I, the fraction of the electric field inside the Si core in WG II is smaller. The effective indices of its two waveguide sections are smaller too, leading to a blueshift of the BG for the same Λ. Furthermore, the reduced filling factor increases this effect.

IV. Validation

The devices were fabricated at the Institut für Mikroelektronik Stuttgart. Test structures consist of input and output grating couplers, tapers to standard waveguides and a 100 µm long grating waveguide. A coupling region with continuous profile transition between standard and grating waveguides is also included to better match the mode profiles.

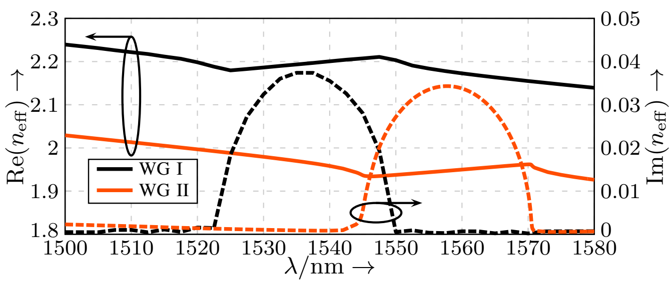

Fig. 3. Spectral characteristics of the real and imaginary part of n_{eff}. Waveguide parameters are $\Lambda = 350$ nm and $FF = 0.5$ (WG I), $\Lambda = 400$ nm and $FF = 0.41$ (WG II).

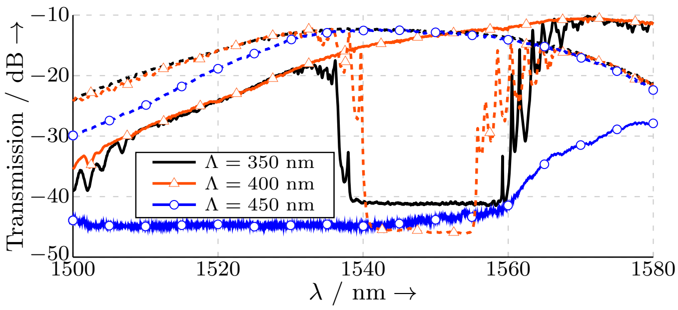

Fig. 4. Measured transmission spectra of waveguides without (solid curves) and with (dotted curves) oxidation step for different grating periods.

Fig. 4 shows measured transmission spectra of WG I and II for three different grating periods. The basic shape of the curve is given by the spectral characteristics of the grating couplers. Regarding WG I (solid lines), the photonic band gap can be identified for the waveguide with a period of $\Lambda = 350$ nm in the range of about 1538 nm and 1565 nm. For $\Lambda = 400$ nm the waveguide behaves, in terms of propagation loss, like a standard waveguide without grating. For WG II the waveguide with $\Lambda = 400$ nm has a band gap, as predicted by the simulations. For both waveguides with BG, the BG position is shifted. This can be explained by fabrication and wafer tolerances. According to simulations, a spectral shift by ± 5 nm is caused by variations of w_{wg}, t_{Si}, and FF by roughly ± 5 nm, ± 3 nm, and ∓ 0.05, respectively. Losses increase for waveguides with a large grating period of $\Lambda = 450$ nm due to Bragg diffraction. This can be observed in the whole measured spectrum (WG I) and for $\lambda < 1540$ nm (WG II).

V. Conclusion

3D-simulations of subwavelength grating waveguides have been done with eigenmode expansion and Floquet-Bloch theorem. Predicted spectral properties of grating waveguides are in good agreement with corresponding transmission measurements. The simulation methodology is thus suitable to engineer waveguides with tailored properties for various applications.

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