Finite-Difference Time-Domain Simulations of Surface Bragg Gratings

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***Abstract*—Bragg gratings are an essential component of semiconductor lasers. One of the most precise methods to calculate an optical response of such a component is the 3D FDTD method. However, due to its computational effort, it is usually not used for the simulation of large structures. Here, we investigate the performance of 2D and 3D Finite-Difference Time-Domain (FDTD) methods for Bragg grating simulations. We demonstrate, that the 2D FDTD method can be used for grating structures of interest, while the 3D FDTD can only be used for short structures up to 500 μm. We show that the 2D simulation results can be utilized to set up an efficient 3D FDTD simulation. We demonstrate that the combination of the 3D FDTD method and the coupled mode theory provides an efficient way of predicting the reflectance of longer Bragg gratings.**

***Index Terms*—Surface Bragg gratings, FDTD simulations, couple-mode theory.**

I. Introduction

State-of-the-art concepts for the realization of semiconductor lasers include long (up to 2 mm) distributed Bragg-reflectors [1], [2]. Grating structures serve as frequency selective feedback, which enables longitudinal single-mode operation of the laser. Due to their narrow bandwidth, Bragg gratings are very sensitive to effects such as chirp, apodization, etc. As a result, the theoretical description of the gratings becomes very tedious.

One of the most efficient ways of simulating Bragg gratings is based on the coupled mode theory (CMT) [3]. CMT describes an interaction between different modes of the waveguide on the grating as a perturbation. Due to its approximations, which include a) weak index perturbation and b) no effect of the index pertubation on the transverse mode profile, the precision of the coupled mode theory is rather limited. To increase the precision of the Bragg grating simulation we consider the application of 2D and 3D Finite-Difference Time-Domain methods, which are among the most precise numerical methods for optical simulations. We compare the performance of 2D and 3D FDTD methods and demonstrate that the combination of the 3D FDTD method and the coupled mode theory provides the most efficient way of predicting the performance of the long grating structures.

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II. Finite-difference time-domain method simulation setup

To investigate the performance of the FDTD method we consider a GaAs ridge waveguide with a ridge width and height of $5\,\mu\text{m}$ and $1.4\,\mu\text{m}$ respectively (figure 1. Such a geometry was designed for a single-mode operation [4]. The structure has 50 periodic rectangular grooves which form the 7th-order Bragg grating (figure 1). It has a total length of $55.86\,\mu\text{m}$ and a period of $1.12\,\mu\text{m}$. The width of the Bragg gratings is fixed at $5\,\mu\text{m}$ and coincides with the ridge width.

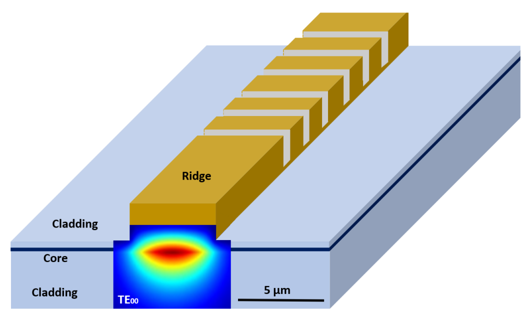

Fig. 1: (Colour online) 3D scheme of a single-mode ridge waveguide. The inset indicates the fundamental TE_{00} mode profile.

Simulations of the light propagation in the Bragg grating are done with the Lumerical FDTD solver. One of the main parameters of every FDTD solver is the mesh size. There are 2 types of mesh that can be set. One of them is a uniform mesh with a fixed mesh size and the other is a non-uniform mesh. In general, the influence of the mesh size on the simulation results can be seen as a shift of the spectrum and a change of its amplitude (figure 2). The shift of the spectrum is caused by the numerical dispersion. It is an artifact resulting from the discrete spatial sampling of the FDTD mesh. If a simulated structure is long enough the numerical dispersion shift might be even bigger than the Bragg grating bandwidth. The spectrum shift and the amplitude change obtained with the 2D FDTD simulation can be used as an estimate for a corresponding 3D simulation.

In general, the computational complexity of an FDTD simulation is defined by the number of mesh elements and time steps. The number of mesh elements depends on both the mesh density and size of the simulated structure. In the

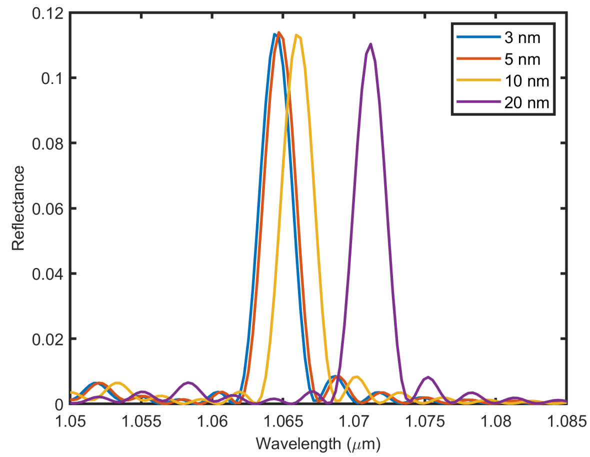

Fig. 2: (Colour online) Reflectance spectra of $55\,\mu\text{m}$ Bragg grating calculated with 2D FDTD method for different uniform mesh sizes.

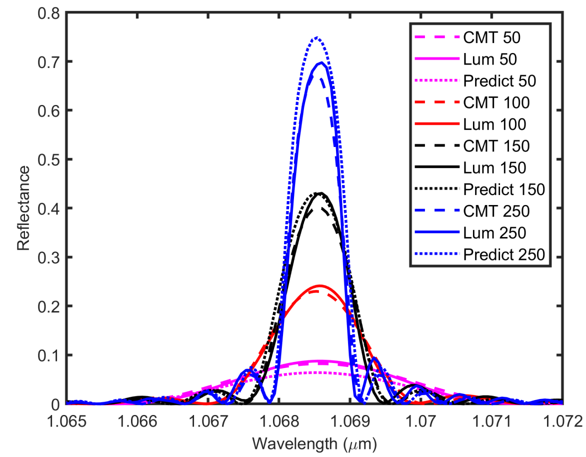

Fig. 3: (Colour online) Reflectance spectra calculated with the 3D FDTD and CMT for different lengths of the Bragg gratings. Dashed lines show the spectra predictions based on the 100 um CMT fit.

case of a Bragg waveguide the size of the simulation should be selected the way that the fundamental mode is confined within the simulation region. Using a symmetry plane helps to reduce the simulation size by 2 times. For example, for a transverse electric (TE) mode a perfect electric conductor boundary condition should be used.

The simulation time can be calculated based on the waveguide length. Alternatively, an automatic shut-off of the simulation can be used. A typical approach would be to stop the simulation as soon as the energy in the system would fall below a given threshold.

III. Evaluation of simulation results

As a result of an FDTD simulation, the time-dependent field distribution is calculated. When the cross-section is considered, the field could be decomposed into the guided modes and then the transmission and reflection can be analyzed. We performed the mode projection to calculate the reflectance for each of the simulations.

As an example problem, in this part we simulated Bragg gratings with 50, 100, 150, and 250 grooves (3). The nonuniform mesh was used in the simulation with the unit cell approximately equal to 17 nm. The simulation results were fitted with the coupled mode theory. The reflectance of higher-order Bragg gratings can become asymmetric with respect to the wavelength maximum amplitude due to radiation effects. Here we limited ourselves to a standard CMT without account of radiation losses. We used a spectrum of the structure with 100 notches as a reference and found CMT parameters based on the fit. Then we used the results to predict the spectra of structures with 50, 150, and 250 grooves. We observe a relatively good agreement of amplitudes and the bandwidths of predicted spectra with the 3D FDTD simulation results. As a result, we demonstrate that even a simple CMT can be used to predict the spectra of longer structures.

To summarize, the 3D FDTD method can be used for Bragg gratings simulations. It can outperform other methods when non-periodic structures, such as chirped gratings are considered. We show that the results of a 3D FDTD simulation can be used to identify parameters of coupled mode theory, which can be used to predict a spectrum of a longer structure. There are grating structures where you would see large differences between CMT and FDTD simulations which could appear as a result of high radiation loss or multimode interaction. However, from the practical point of view, such structures are less interesting. As a result for laser applications, the amplitude of the reflectivity of longer structures can be predicted so that the manufacturing tolerances are larger than the error introduced by the prediction.

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