Graphics Processor Unit Accelerated Design of Multimode Interference Reflectors

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***Abstract*—A modified three-part algorithm based on extracting effective scattering matrix parameters is presented for the design of multimode interference reflectors. In contrast to previous work, each stage of the suggested simulation strategy is completed in the frequency domain. We demonstrate that this new approach is able to calculate the reflectivity of a multimode interference reflector across a 2D parameter space 7.2 times faster than a standard GPU accelerated three-part simulation and over 68 times faster than a typical CPU implementation.**

***Index Terms*—FDFD, MMIR, GPU acceleration**

I. Introduction

With applications as broadband reflectors, power splitters [1] and temperature insensitive laser devices [2], multimode interference reflectors (MMIRs) are versatile components. The design of MMIR devices is complicated by the omni-directional propagation of light between the angled mirrors (see Fig. 1b), which renders the fast uni- and bi-directional methods typically employed in photonic simulations unsuitable. Omni-directional solvers are computationally intensive, constraining the practicality of running full device simulations on personal computers. First introduced by Kleijn et al. in 2013, two classes of approach have previously been used to circumvent these issues: the equivalent geometry approach (EGA) and three-part simulations [3]. In their original formulation, neither approach is conducive to efficient parameter sweeps and, therefore, efficient device optimisation. The EGA is inherently flawed in several ways. The method neglects mirror losses and reflection induced phase shifts, and the equivalent geometry prevents the investigation of mirror defects.

The focus of the present work is the efficient implementation of a three-part simulation enabling the practical design of MMIRs on personal computers.The use of graphics processor units (GPUs) in photonic simulations can reduce run times by factors as large as 20 [4]. Combining GPU acceleration with an effective scattering matrix technique, we reduce the time taken to span a two-dimensional parameter space by a factor of 68, compared to traditional CPU simulations.

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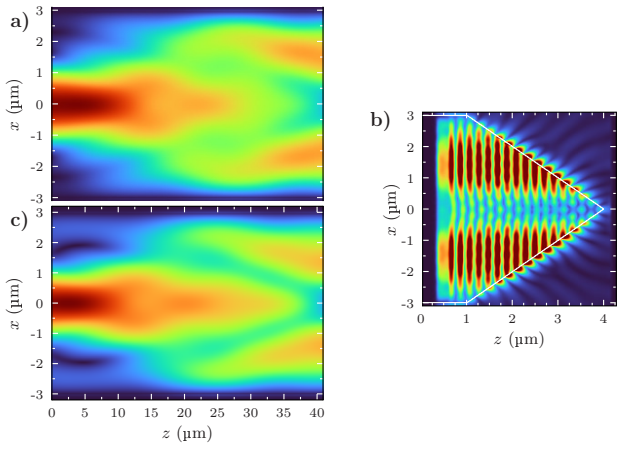

Fig. 1. The absolute magnitude of E_x at each stage of a three-part simulation of an MMIR. a) The input fields propagated through the straight waveguide sections with EME. b) An FDFD simulation inbetween the angled mirrors. c) The reflected waves from b) propagated back through the straight waveguide sections using EME.

II. Simulation

A. Three-part simulations in three dimensions

Typically, the three-dimensional simulation of an MMIR has three stages. First, the input field is propagated through the straight waveguide sections using a fast uni- or bi-directional technique. The field at the end of the straight waveguide section can then be loaded into an omni-directional solver to propagate the fields through the angled mirrors. The reflected waves can then be quickly propagated back through the straight waveguides.

Previously, the finite-difference time domain (FDTD) method has been used in the second part of the simulation. However, information about the fields at intermediate time steps is not required to calculate the reflectivity. The finite-difference frequency domain (FDFD) method provides a natural way to compute the steady state fields directly. When discretised according to Yee's scheme [5], using Maxwell's equations to calculate the steady state solution to a frequency domain scattering problem reduces to solving an equation of the form:

$$f = A^{-1}b. \tag{1}$$

Here f is a column vector containing the steady state field components at each point on the grid, b is a column vector containing the source field calculated at each point on the grid in the absence of the device, and A is a large sparse matrix [6].

In three dimensions, the size of A usually prohibits direct matrix division, but the use of stretched coordinate perfectly matched layers (SCPMLs) allows (1) to be solved iteratively. When using MATLAB, (1) can be solved on the GPU by simply passing f, A and b to the GPU using the `gpuArray()` function, without the need for low-level CUDA programming [7]. The field profile through an example MMIR calculated using a three-part simulation based on the eigenmode expansion (EME) and FDFD techniques is shown in Fig. 1.

B. Computationally efficient parameter sweeps

Two common parameter sweeps in the design of MMIRs are device length and the wavelength of the input field. In the standard three-part (ST) model, the entire simulation must be repeated at each point in the 2D parameter space. However, if we make the approximation that there is no coupling between the modes as a result of the mirrors, then we can extract effective scattering matrix parameters from a single FDFD simulation, and use this to calculate the reflectivity at other lengths, following the improved-scattering matrix formalism [8]. Using this effective three-part (ET) model, only one FDFD simulation is required per wavelength, significantly reducing run times without any major alterations to the algorithm. The no-coupling approximation is expected to hold best near the optimum device length, so the FDFD simulation should be performed here. As the value of the optimum length is not known in advance, we perform the simulation at the value predicted by the beat length in the multimode section (which neglects mirror phase shifts and the non-quadratic mode spacing in real devices) [3].

III. Results and Discussion

A. GPU acceleration

We simulated a typical AlGaAs MMIR structure with an input width of 3 µm, mirror width of 6 µm and total multimode length of 44 µm, under the injection of the fundamental mode with wavelength 1.36 µm. We found that when solving (1) on an NVIDIA GeForce RTX4090 GPU the simulation took on average 140 s, whereas when solving on an intel Core i9 14900HX processor with 64 GB of RAM the total run time was 1340 s. In this case, GPU acceleration reduces the run time by a factor of 9.6 without any other alterations to the algorithm.

B. Effective scattering parameters

The ST and ET models were used to perform length scans on the device described in the previous section for several input wavelengths. Fig. 2 shows that the agreement between the two approaches is excellent near the optimum lengths, with only minor discrepancies towards the ends of the scans where the no-coupling approximation is less valid.

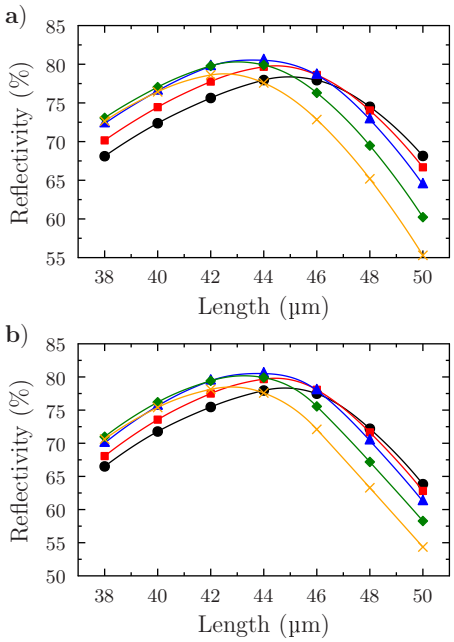

Fig. 2. The reflectivity of a multimode interference reflector as a function of length at wavelengths of 1.32 µm (circles), 1.34 µm (squares), 1.36 µm (triangles), 1.38 µm (diamonds), and 1.4 µm (crosses). a) The standard three-part method. b) The effective scattering matrix three-part method.

However, there is a significant difference in the total run times, with the ST method on the GPU requiring 5389 s and the ET method on the GPU requiring only 747 s. The ET method is 7.2 times faster than the ST method, meaning that in total GPU acceleration in combination with the effective scattering matrix algorithm spans the parameter space over 68 times faster than standard three-part simulations on the CPU.

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