White Paper

Design Optimization of Grating Fiber Couplers With RSoft Products

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Introduction

Optimum design of silicon photonics devices, such as grating couplers, can be achieved by numerically optimizing a large number of design parameters without in-depth knowledge of the complex underlying theories.

Optimization of the Apodized Grating

In silicon photonics, grating couplers (GCs) are essential for coupling light between optical fibers and silicon waveguides. To reduce insertion loss and achieve efficient coupling, significant effort has been made in the past, such as the inclusion of reflecting mirrors under the buried oxide (BOX) layer to stop leakage into the silicon substrate, as well as the use of apodized gratings to better match the coupled light with the fiber modal profile. The best result achieved to date is 0.58dB coupling loss, which was obtained by carefully engineering sub-wavelength photonic bandgap structures to provide the necessary refractive indices for optimum coupling [1].

With the help of Synopsys RSoft™ photonic simulation tools, complex device designs can be easily achieved by starting with simple design rules. For GCs, a simple design rule can be extracted directly from geometric optics as shown in Figure 1.

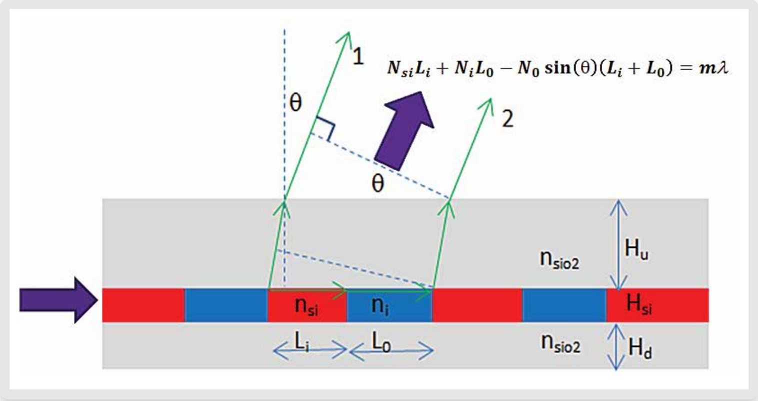

Figure 1. Schematic diagram of the coupler and phase matching condition

To maximize the coupling, the scattered light at different junctions must be in phase when it reaches the fiber. This phase-matching condition is given in Figure 1, where N_{si} and N_i are effective indices that include the oxide index, and N_0 is the index of air. Though approximated, it provides a good starting point for the optimization.

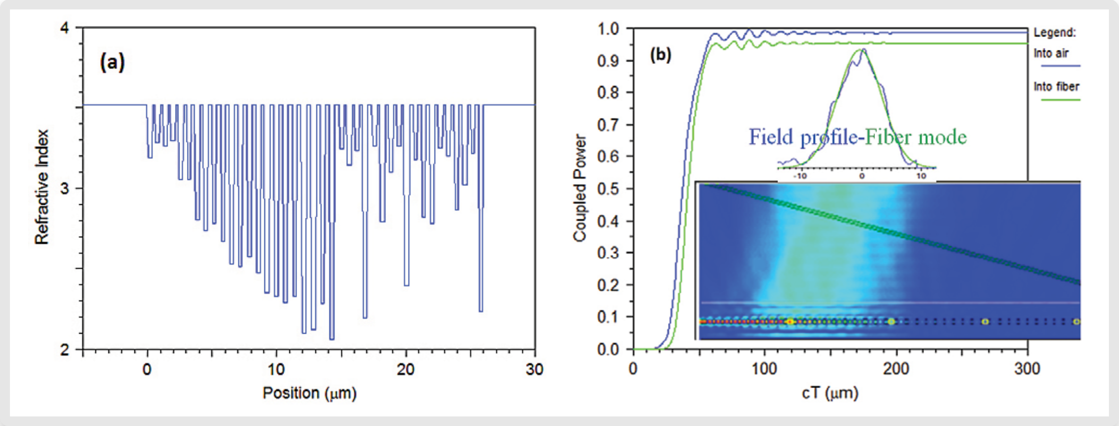

Figure 2. (a) 2D optimized index profile; (b) 2D FDTD verification, where the propagating field is shown in the inset

To effectively couple light into a fiber, we must not only match the phase, but also the fiber mode profile. The mode profile can be matched by appropriately apodizing the grating refractive index n_i. The apodization is determined by choosing the n_i's as design variables and then optimizing them, using 2D simulations, for maximum coupling efficiency. Figure 2(a) shows the resulting optimized index profile along the grating.

The simulation software used in this example is RSoft ModePROP™, which is based on the eigenmode expansion method (EME) [2]. The optimization tool used is RSoft MOST™ (Multi-variable Optimization and Scan Tool), and the optimization algorithm used is the genetic algorithm (GA). In total, 43 design parameters were optimized and about 500,000 simulations were completed. The ModePROP simulation shows that the final optimized structure can couple 99% of the total power out of the chip and about 93% (-0.3dB) into the fiber. This was validated by the FDTD-based RSoft FullWAVE™ simulation [3], and the results, shown in Figure 2(b), are consistent with the ModePROP results.

Optimization of the Coupler Width

The previous grating optimization example matched the fiber mode profile in one direction along the grating. In order to achieve efficient coupling, the fiber mode profile must also be matched in the other direction; i.e., we need to determine the optimum width of the grating coupler as shown in Figure 3 (a).

The coupling efficiency can be calculated by RSoft BeamPROP™, which is based on the beam propagation method (BPM) [5], with overlap with the fiber mode. The MOST scan result, shown in Figure 3 (b), indicates the optimum coupler width is 14.5μm, where the coupling efficiency is more than 99%. Compared with the 12μm width used in the reference [1], an extra 0.2dB efficiency can be achieved.

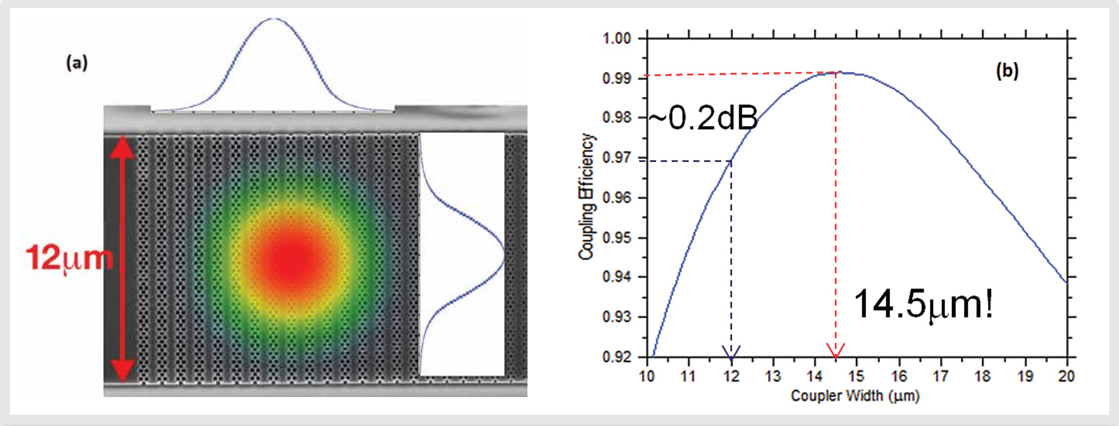

Figure 3. (a) Optimization of the coupler width; (b) MOST scan result

Construction and Simulation of the 3D Grating Coupler

To realize the optimized refractive index profile in the 3D structure, sub-wavelength photonic crystal (PC) arrays are used [1]. The characteristics of the PC array, including the hole diameter and filling factor, are given respectively by [4]:

$$D = d_0\sqrt{\frac{8}{3\sqrt{3}\pi}f} \qquad f = \frac{(n^2{}_{Si}+n^2{}_{SiO_2})(n^2{}_{Si}-n^2{}_i)}{(n^2{}_{Si}-n^2{}_{SiO_2})(n^2{}_{Si}+n^2{}_i)}$$

The filling factor is determined by the n_i profile from the 2D optimization, d_0 is the length of each n_i segment, and the holes are filled with SiO_2. Shown in Figure 4(a) on the left is part of a structure consisting of about 6,000 holes.

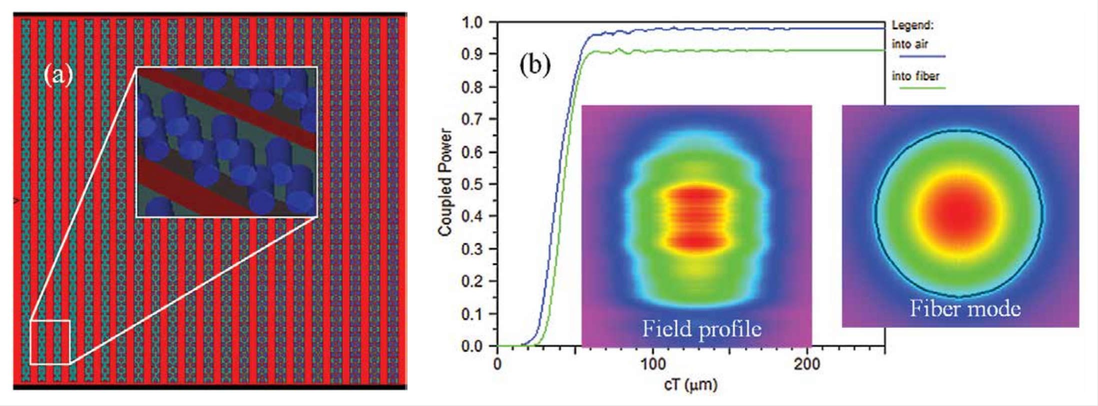

Figure 4. (a) Sub-wavelength PhC-based grating fiber coupler; and (b) 3D simulation results, where the field profile is shown in inset

3D FullWAVE simulation results as shown in Figure 4(b) are in good agreement with the 2D optimized results. The total power coupled into air is 98% and coupling efficiency into the fiber is 91% (-0.4dB).The small loss is due to the remaining mismatch between the coupled field profile and the fiber mode, as shown in the insets.

Optimization of Spot-Size Converter

To link a 14.5μm wide grating coupler to a 0.45μm wide silicon wire, a tapered spot-size converter (SSC) is needed. The shape has to be optimized in order to achieve minimum insertion loss at a given taper length. The taper shape, which is the taper width W(z) as a function of taper position z, can be defined as a power function $W(z) = z^p$, where p=0.5, 1, and 2 corresponding to parabolic, linear, and quadratic tapers, as shown in Figure 5(a).

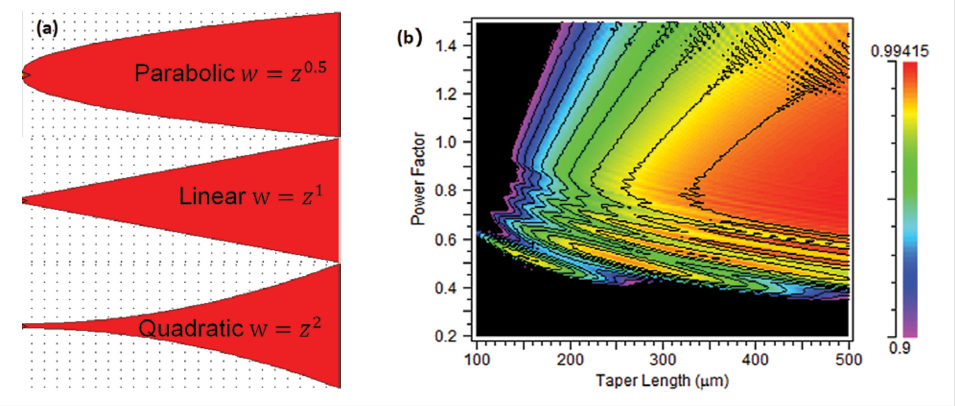

Figure 5. (a) Tapers with different power factors; (b) Coupling efficiency vs. taper length and shape

The simulation can be performed with BeamPROP by launching the mode of the narrow waveguide and overlapping the propagating field at the end of the taper and the mode of the wide waveguide. Shown in Figure 5(b) is the MOST scan result of the coupling efficiency as a function of the taper length and power factor. For a long taper at 500μm, the optimal power factor is about 0.8, at which nearly 99% efficiency can be achieved. For a short taper at 150μm, however, about 97% efficiency can still be achieved with a power factor of 0.52.

Tolerance Study

With MOST, any design and operational parameter can be scanned to investigate the tolerance. The spectral response of the device can be obtained by scanning the operation wavelength, as shown in Figure 6(a).The sensitivity of the fiber orientation can be investigated by scanning the fiber input/output angle, as shown in Figure 6(b). Note that the simulations were performed on a 2D structure for efficiency. It has been proven that 2D decomposition is a feasible solution to a complex 3D problem, and it is not necessary to perform time-consuming 3D simulations for scanning and optimization, unless it is needed for validation purposes.

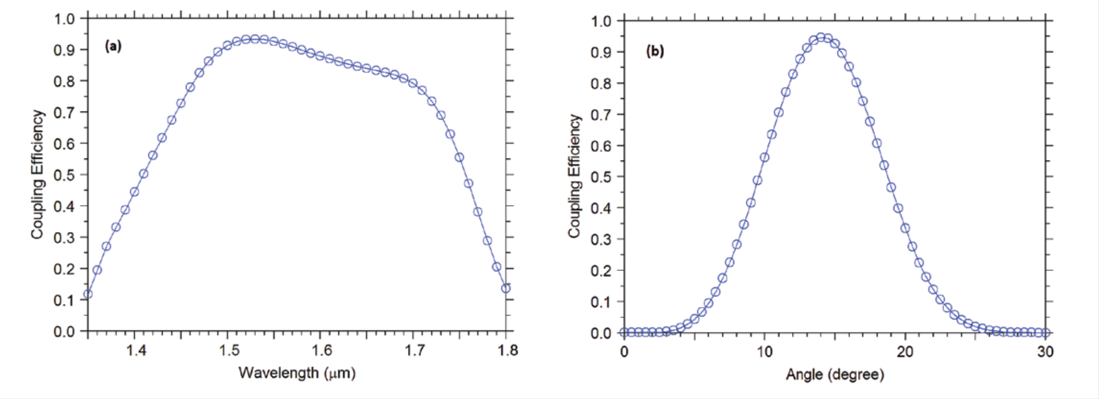

Figure 6. (a) Spectral response of the coupler; (b) Sensitivity of the fiber orientation

Summary

In summary, design optimization of silicon photonic devices can be readily achieved by using a combination of RSoft design tools. With the grating coupler as an example, the 2D decomposition of the complex problem is a viable approach and is validated by rigorous 3D simulation. Such a complex optimum structure can be achieved by numerically optimizing a larger number of design parameters, leading to effective results.

Reference

[1] Ding, Yunhong, et al. “Fully etched apodized grating coupler on the SOI platform with −0.58 dB coupling efficiency,” *Optics Letters* 39.18 (2014): 5348-5350.

[2] *ModePROP User Guide*, Synopsys, Inc., RSoft Products. (2015).

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[4] Gao, Dingshan, and Zhiping Zhou. “Nonlinear equation method for band structure calculations of photonic crystal slabs,” *Applied Physics Letters* 88.16 (2006): 163105.

[5] *BeamPROP User Guide*, Synopsys, Inc., RSoft Products. (2015).

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