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An Overview of Modeling and Design Software for Silicon Photonics Devices and Systems

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Abstract—*This paper outlines the critical tools and methodologies for designing and simulating silicon photonics components and circuits. The design process begins with the simulation of individual passive and active photonic components, followed by the synthesis of optical models to predict circuit behavior under various stimuli. The workflow includes creating a physical layout from the schematic, supported by design aids, and performing extensive verification steps such as design rule checking, layout versus schematic comparisons, and lithography simulations. Verification results are used to refine the circuit models to account for manufacturing variations and environmental factors, ensuring robust design and performance of silicon photonic systems. This comprehensive approach integrates foundry-provided design rules and component libraries, facilitating an efficient and accurate design cycle.*

Keywords—*Silicon Photonics, Component Design, Circuit Simulation, Passive Components, Active Components, Optical Model Synthesis, Physical Layout, Design Verification*

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I. INTRODUCTION

Silicon photonics has emerged as a promising technology for integrating photonic and electronic components on a single chip, offering significant advantages in terms of speed, bandwidth, and energy efficiency. This paper delves into the comprehensive suite of simulation and design tools that are pivotal for the development of silicon photonic components and circuits. The design process encompasses the initial simulation of both passive and active photonic elements, progressing to the synthesis of optical models for accurate circuit behavior prediction under various stimuli. Subsequent steps involve translating circuit schematics into physical layouts, supported by sophisticated design aids, and conducting rigorous verification procedures. These procedures include design rule checking, layout versus schematic comparisons, lithography simulations, and parasitic extraction. The feedback from these verification steps is crucial for refining circuit models to account for manufacturing imperfections and environmental influences, ensuring the reliability and performance of silicon photonic systems. This integrated design methodology, bolstered by foundry-provided design rules and component libraries, facilitates an efficient and precise design workflow for silicon photonics.

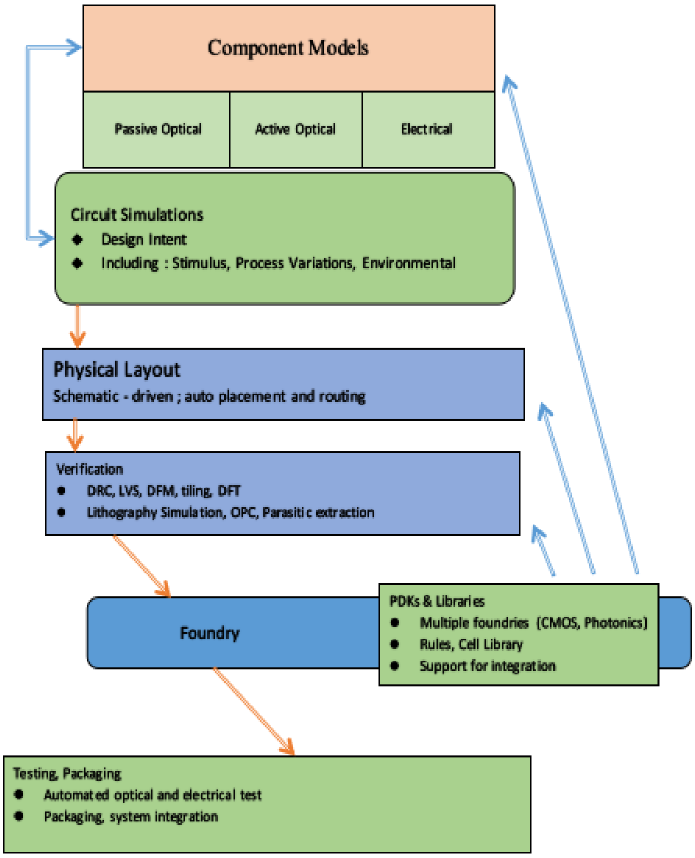

Fig 1. A visual roadmap illustrating the sequential stages in designing a silicon photonic system, encompassing simulation, verification, fabrication, testing, and packaging, with support from foundry-provided design rules and component libraries.

II. OPTICAL WAVEGUIDE MODE SOLVER

Eigenmode solvers are essential tools in silicon photonics, used to determine the optical modes in waveguide geometries at specific frequencies. These solvers find the transverse field distributions that propagate without changing shape, providing time-invariant solutions critical for precise waveguide design. They solve time-harmonic Maxwell's equations in the frequency domain, requiring multiple simulations to analyze waveguide dispersion. Key methods include the Finite Element Method (FEM), Finite Difference (FD) algorithm, and the Effective Index Method (EIM), with fully vectorial techniques necessary for high refractive index contrast waveguides in silicon photonics. Finite element solvers, with their unstructured meshes, are ideal for non-rectangular and three-dimensional structures, while finite difference methods excel in high-index contrast structures and mesh compatibility with the Finite Difference Time Domain (FDTD) technique. Mode calculations support various design aspects, such as waveguide propagation parameters, radiation in bends, coupling coefficients in directional couplers, reflection coefficients for Bragg gratings, and mode overlap for edge coupling efficiency. Additionally, exact analytic solutions for one-dimensional problems and approximate methods like EIM are used for designing components like fiber grating couplers and pn-junction phase shifters, implemented in tools such as MATLAB and Mentor Graphics Pyxis. These solvers are indispensable for the accurate design and optimization of silicon photonic systems, ensuring robust performance in practical applications.

III. INTRODUCTION TO WAVE PROPAGATION TECHNIQUES IN PHOTONIC DEVICE DESIGN

The design of photonic devices necessitates a thorough understanding of light propagation within various structures. For uniform devices like waveguides, mode solvers are adequate because the mode remains consistent along the propagation path. However, many photonic devices feature structural variations that cause reflections, interference, scattering, radiation, interactions between multiple modes, and changes in the mode profile. Various techniques are available to solve wave propagation problems, ranging from those developed for specific issues to more general approaches. The most general and rigorous time-domain method is the finite difference time domain (FDTD) technique. FDTD is particularly versatile and robust, making it a fundamental tool in silicon photonics design and extensively utilized in this field.

IV. 3D FDTD

The Finite Difference Time Domain (FDTD) technique offers a numerical solution to the three-dimensional Maxwell equations, particularly adept at analyzing light interactions with intricate structures featuring sub-wavelength-scale features. Operating in the time domain, FDTD simulates the propagation of light pulses containing a broad spectrum of wavelength components, enabling a comprehensive system response across wavelengths in a single simulation. While computationally intensive due to its sub-femtosecond simulation time-step, FDTD scales well to multiple processors and compute clusters, enhancing simulation volume and accuracy. Lumerical FDTD Solutions is utilized in this work for its efficiency in modeling device responses over wide optical bandwidths, including material dispersion effects and the generation of scattering parameters. Additionally, FDTD calculations are instrumental throughout the book, from analyzing waveguide bends, coupling coefficients in directional couplers, and Bragg gratings, to designing fiber grating couplers, edge couplers, and detectors, with applications extending to Y-branch splitters, waveguide crossings, and polarization splitter rotators.

A. FDTD Modelling Procedures

The general procedure for performing simulations using the Finite Difference Time Domain (FDTD) technique begins with defining the optical materials, ensuring they are suitable for the simulation, which is critical for consistent and accurate results, especially when created and compared by a team of designers. Next, the structure is drawn, including geometries for silicon substrates, oxide claddings, waveguides, and other materials, and the simulation volume is defined, ensuring it encompasses the necessary extent of the device. Several parameters, such as mesh size, boundary conditions, and simulation time, are then specified, with mesh size significantly impacting simulation time. Optical sources, typically mode sources, are added, injecting light into a waveguide mode, followed by the placement of monitors to measure optical field quantities at chosen locations. Convergence testing is crucial to validate the simulation by adjusting mesh size and simulation volume to ensure stability. Finally, analyses are performed to decompose output fields into eigenmodes, determine power transmission, generate scattering parameters, and evaluate other device-specific metrics, ensuring comprehensive and accurate simulation results.

Q = 2 pi (Energy Stored / Energy dissipated per optical cycle)

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The quality factor is determined by fitting a curve to the time-domain monitor data, where the slope corresponds to the rate of energy decay and the quality factor, Q.

V. BEAM PROPAGATION METHOD

The Beam Propagation Method (BPM) is an approximate solution that was widely used before the advancements in FDTD software and increased computer processing speeds enabled the "exact" solution of Maxwell’s equations. BPM was initially developed for slowly varying structures, approximating paraxial (small angle) forward-only propagation in structures with small refractive index contrasts, typically as a scalar solution. The method has since been expanded to accommodate wide-angle propagation, forward and backward propagation including reflections (as seen in Synopsys RSoft BeamPROP), and vectorial calculations. BPM remains useful for designing "sub-circuit" components such as arrayed waveguide gratings and Mach–Zehnder interferometers. This method is available in various software, including PhoeniX Software OptoDesigner, Synopsys RSoft BeamPROP, and OptiBPM by Optiwave.

VI. PHOTONIC CIRCUIT MODELLING

Designing silicon photonic circuits with multiple components involves several approaches and tools that simplify modeling and simulation. Simple component models allow simulations to focus on circuit performance. Methods include analytic solutions for 1D structures like thin-film filters and phenomenological models like parameterized waveguides for larger systems. Desired simulations involve both frequency-domain responses (e.g., optical filter characterization) and time-domain analyses (e.g., transient, eye diagrams, bit error rate). For optical circuit modeling, options range from using programming languages like MATLAB and open-source tools like Caphe, to commercial tools such as ASPIC, Photon Design PICWave, Optiwave OptiSystem, Synopsys RSoft OptiSim, VPIsystems VPItransmissionMaker, and Lumerical INTERCONNECT. Light propagation in optical fibers, accounting for linear and nonlinear effects, typically uses the Schrödinger equation, available in tools like SSPROP and Synopsys RSoft OptiSim. Nonlinear silicon photonics may use FDTD simulations. Electronic-photonic co-simulation may be required for integrated systems, approached either from established electronics tools adding optical functionality or photonic tools adding electronic modeling. This book uses Lumerical INTERCONNECT for integrated circuit design, which supports time-domain and frequency-domain simulations, utilizing experimental data, analytic or phenomenological models, or numerical models from FDTD or mode solvers for accurate circuit response analysis.

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