Introduction to Photonic Design Automation

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In this article, I will briefly introduce what my research, photonic design automation (PDA), is about, including its concept, scope, and goal. I won't use scientific terms to scare readers and hopefully could convey basics to audience with undergraduate-level EECS knowledge. For readers who are interested to research in this area, a few useful references and open topics are included at the end. Speaking of PDA, we have to mention a closely related term — electronic design automation (EDA). In my words, EDA is the science of using algorithmic methods to ease human burden when designing an electronic chip. EDA is by all means not a novel area, and could be dated at least back to 1970s when the circuit simulator CANCER (later evolved into the well known SPICE program) was born in a graduate course at UC Berkeley [1]. Nowadays, in almost very step of electronic chip design regardless of digital or analog circuits, EDA is there. The basic component used in contemporary integrated circuits is metal–oxide–silicon (MOS) transistor [2]. Connecting MOS transistors in different ways could lead to the voltage signals in the concerned circuit presenting in a continuous (i.e., analog) or discrete $\{0, 1\}$ (i.e., digital) manner.

Let us illustrate the EDA tools you might encounter when designing a simple Operational amplifier (Opamp), a critical element used in almost all analog circuits [3]. To begin with, you might need an EDA software so that you could draw the schematic of Opamp and simulate your drawn circuit. Then you might need to repeatedly revise the schematic (by adjusting parameters of MOS) until the circuit reaches the customer's specification. Once it passes the specification test, you need a tool to somehow 'map' the circuit schematic onto a real silicon wafer. Roughly speaking, that is to say in manufacturing how to carve a silicon wafer so that the resulting device exactly reflects the circuit you draw? As the reader might have already realized, if the Opamp only contains a few MOS transistors, we might draw the schematic on a piece of paper, calculate the circuit response using your brilliant math techniques, and handcraft the silicon wafer under a microscope [4]. However, obviously, this won't work when the circuit size goes up (i.e., containing many MOS transistors). Luckily, EDA tools perfectly solve these problems. EDA is such a well developed field that for different design level (block, chip level), for different circuit type (digital, analog), there are different EDA tools to help you achieve your design goal [5]. Nowadays, the major EDA companies provide tools covering almost all problems you will encounter during electronic chip design. At the risk of scaring readers, some major terminologies in EDA include process design kit (PDK) files, circuit simulation, routing, placement, high-level synthesis. Top EDA companies are Cadence, Synopsys, and Mentor graphics. Top EDA conferences and journals include DAC, ICCAD, DATE, and IEEE TCAD. Interested readers might resort to these references.

Similar to EDA, yet possessing tremendous differences, PDA is a relatively new area[6]. Recall the definition of EDA, PDA is still about relieving human burden, but now is when designing a photonic (instead of electronic) chip. However, the reader might argue that is it necessary to treat PDA as a brand new area as we only make a one word change — from 'electronic' to 'photonic'? Dear lord, I hope they are the same as well! But, this is not what nature provides us. The fundamental reason is that electronics is described by a more abstract-level physics than photonics: (i) Electronics is accompanied with physical terms voltage V and current I, and governed by ordinary differential equation (ODE) based on Kirchoff's current/voltage laws; (ii) photonics is related to electromagnetic field (i.e., $\mathbf{E}$ and $\mathbf{H}$), and governed by

[1] The course was taught by Dr. Ron Rohrer, and he made it into a project course. The development of CANCER is led by Dr. Larry Nagel. Interested readers could resort to the historical references (Nagel; Newton).

[2] For readers who haven't heard about MOS before, it is just like a resistor we learnt in high school. However, a resistor with value r has two terminals, and its branch voltage v and current i follows Ohm's law: $v = ir$. On the other hand, a MOS transistor has three terminals called 'drain', 'gate', and 'source', usually denoted as $\{D, G, S\}$. Its current-voltage relationship is more complicated than that of a resistor though.

[3] Well, how do you think your phone could adjust the sound volume?

[4] Actually, this is what people do at the beginning of circuit design, prior to the birth of the concept 'integrated circuit'.

[5] For instance, see the circuit simulation tools for different applications listed here on Cadence website.

[6] Strictly, Not all parts of PDA is novel. For instance, the arts of simulating electromagnetic fields is pretty mature. The underlying principles of basic photonic devices are well understood.

partial differential equation (PDE) based on Maxwell's equation. Some immediate consequence includes: (i) In photonic circuit, the design variable of a device is its shape (a.k.a., geometry or topology). Because device shape directly impacts the boundary condition of Maxwell's equation, and thus the solution **E** and **H**. (ii) Human design intuition counts less proportion in photnoics circuit design than electronics, since PDE is more complicated than ODE.

In the above paragraph, we discuss mainly from the aspect of physics, but wait... We even haven't formally defined what a photonic circuit is, and why it is important. In my words, photonic circuit is an object which could manipulate light (a.k.a., electromagnetic wave). This definition is very general and inclusive, in the sense that your glasses are also photonic circuits: they refracts light. These devices/circuits in the size of our daily objects are usually referred to as bulk optics [7]. In recent decades, researchers have been attempting to integrate different light processing functions onto a single chip (i.e., photonic integrated circuit (PIC) or integrated photonics). Marching from bulk optics to PIC is every similar to the development from discrete devices (e.g., Breadboard) to electronic integrated circuit. Currently, many platforms are readily available for realizing a PIC, such as III-V semiconductors, Lithium Niobate, and silicon (Bogaerts und Chrostowski, 2018). Silicon is the most popular choice because of many reasons, two of which is (i) its process has been extensively studied in electronic circuit; and (ii) it is easier to do electro-optical integration [8]. Now, why is integrated silicon photonics important and what advantages does it have over electronic circuit? **In one word, it has the ability to work at a high frequency (clock speed).** As we all know, a modern electronic CPU usually works at GHz scale. If a CPU works at a higher frequency, then it indicates that it could perform more operations in a given time period. To this end, have you ever wondered why we don't have a CPU working in THz? Well, partly the reason is because when increasing the working frequency to THz, parasitic effects of electric components will introduce large loss into your electronic integrated circuit [9]. Alternatively, silicon photonics provides a way to process signals at THz scales [10]. That is remarkable [11]! A few integrated silicon photonics products have alreay been on the market. For instance, optical phased array will be the future of Lidar in autonomous vehicle (see the post here). Nevertheless, still the products are quite limiting. It is predicted someday in the future, photonics integrated circuit will be as important as electronic integrated circuits, and many electro-optical integrated circuits will emerge to change our daily life.

In my opinion, to expedite the development of integrated silicon photonics, we first need to make standards. Standardization plays crucial roles in the early days of electronic integrated circuit (such as IEEE Verilog standards). At present, silicon photonics is still missing standard guidelines. This, hopefully, will be resolved when noble researchers in this area led a bunch of people making rules in the near future [12]. Secondly, more research in photonic design automation are in emergent needs. As an example, recently I am working on automatic synthesizing light processing functions on programmable photonics, where currently people still do this in a hand-crafted way [13].

Ok, as promised, several useful references: (i) Electromagnetic basics: Griffiths's textbook is more newbie friendly (Jackson, 1999), while Jackson's textbook is more comprehensive and challenging (Griffiths, 2005). Both these two books start from electrostatics. If you want one more cut to the point, please consider textbooks by Jin Au Kong. (ii) Overview of silicon photonics design: the review article by Bogaerts und Chrostowski (2018) covers many aspects and open problems. The book by Chrostowski und Hochberg (2015) is good, but I suggest you reading it when you have relatively good background. (iii) Light propagating mode: See the first two chapters of Okamoto (2021). (iv) FDTD simulation: See the textbook by Schneider (2010). (v) Device basics: to understand directional coupler, you need to know couple mode theory (e.g., see Huang (1994)). See Heebner, Grover und Ibrahim (2008) about ring resonator. Other devices/circuits you might need to know: MZI, optical neural network, programmable photonics.

[7] To understand light behaviour at this scale, we might not need Maxwell's equation, while ray/wave optics is sufficient.

[8] Imagine how complicated the manufacturing process will be if you use silicon based MOS transistor and III-V semiconductor based photonic device?

[9] See answers in this post for various explanations from different aspects.

[10] Well, readers should by now notice the word 'signal' refers to electromagnetic signal in this context.

[11] Curious readers will ask why silicon photonics could work at such high frequency? Well, briefly speaking, because at this high frequency, when a beam of light is injected to silicon photonics, it will be confined there, propagating with little loss. This relates to the concept of light mode. See the first two chapters of Okamoto (2021).

[12] This still doesn't happen because I guess it is still not the right time. Nevertheless, we should notice that there are many photonic circuit design lectures, summer schools, etc., happening in recent years.

[13] It is worthy mentioned that personally I won't recommend using too much deep learning techniques in silicon photonics. I am not saying it is bad or wrong. However, many open problems are fundamental and could be solved adapting basic methods from statistics, graph theory, or optimization techniques. Deep learning of course is a sharp tool, but focusing too much on it will cause us lose our novelty in research.

Author Notes

This brief article is written for science popularizing, and will be continuously updated along my understanding of and research in silicon photonics. If you find any descriptions problematic, please feel free to contact me at zhengqi@mit.edu. I am planning to write a formal academia paper in the future, probably when I am about to graduate my PhD, which is five years later :-)

About Author Zhengqi Gao is a first year PhD student at MIT EECS, advised by Prof. Duane S. Boning. Previously, he obtained M.S. and B.E. from School of Microelectronics, Fudan University. His current research interests lie mainly in photonic design automation and machine learning. More info is available on his homepage: https://zhengqigao.github.io/.

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