

Basic silicon photonic building blocks for commercial applications

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Abstract

Silicon photonics has evolved in the last years into a vibrant ecosystem of foundries and design houses. This has enabled a broader set of commercial applications besides the traditional telecom fields, like optical chip interconnects, sensor interrogation or microwave filters and beamformers. Basic devices like Arrayed Waveguide Gratings (AWGs), Mach-Zehnder Interferometers (MZI), Multimode Interference Couplers (MMIs), or Ring Resonators (RRs) have already become standard building blocks, providing a reliable and customizable basis for more complex integrated optical systems.

Keywords: Silicon photonics, photonic integration, Arrayed Waveguide Grating, AWG, Mach-Zehnder Interferometer, MZI, Multimode Interference Coupler, MMI, Ring Resonator.

1. Introduction

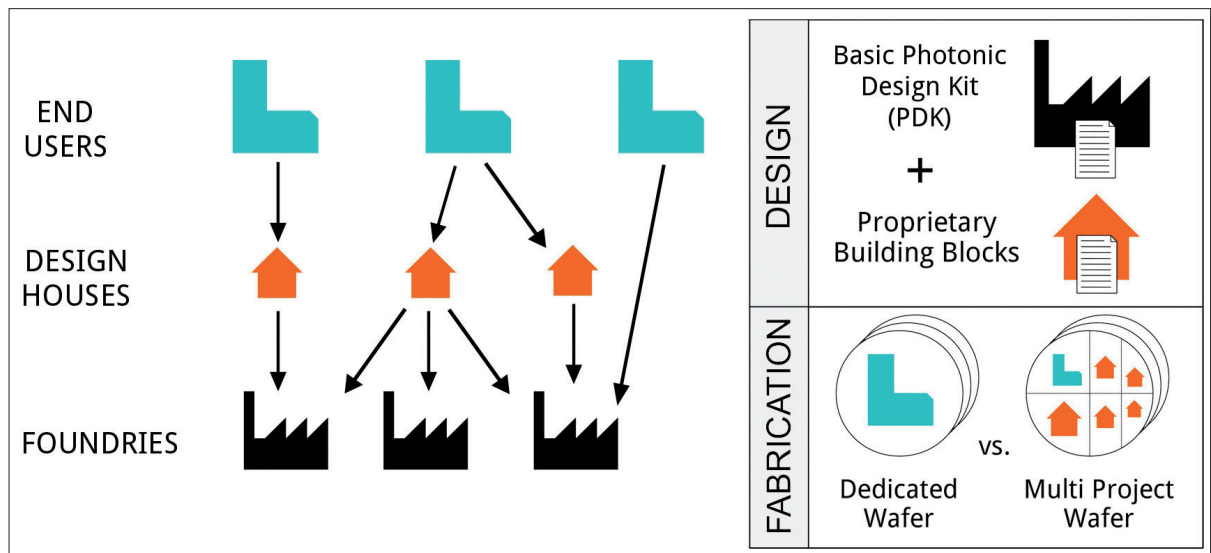
Photonic integration allows for the miniaturization of optical components and systems into a single chip, with the corresponding gains in size and volume, robustness against mechanical or thermal stress, or the issues of misalignments and optical cleanliness commonly found in free space bulk or micro optics. Multiple material technologies have been used along the years to achieve such monolithic integration, each of them more suited for a certain type of devices: lithium niobate for modulators, silica (also known as planar lightwave circuit, PLC) for passive devices like couplers, splitters and gratings, or indium phosphide for active components like lasers or amplifiers.

While all these technologies have been researched and already taken into production since approximately 10

years ago, it is silicon photonics that has gained a lot of traction now, due to the opportunity of implementing it into semi-standard complementary metal oxide semiconductor (CMOS) processes, with the large cost reductions this implies, and the corresponding increase in production volumes, system scalability and complexity. Moreover, this also allows for an easier integration of silicon photonic components along with electronic control functions [1].

There are currently several international silicon photonic foundries offering their services through stand-alone, dedicated wafer runs, or as part of what is known as multi-project wafer runs, where wafer space is shared among multiple users to decrease cost, at the expense of a tight fab schedule (see Fig. 1). Process standardization has allowed for a business ecosystem that is quickly evolving to mimic that of the electronics world, where end users and independent design houses alike submit their chip designs to generic foundries. Photonic design kits (PDK) are usually offered by each foundry, implementing the most common optical components as basic building blocks that have been thoroughly tested and are ready to be directly plugged into more complex designs. Additionally, design houses develop their own advanced Building Blocks (BBs) on top of these PDKs, offering extended functionalities and savings in cost and development time for their customers, the end users.

Regarding end user applications, as silicon is transparent in the infrared above 1.1 μm , it is a good material technology for optical communications in the O to U wavelength bands (1270-1675 nm), from long-range telecom to shorter datacom links. Moreover, due to the CMOS



■ **Figure 1.** Photonic integration ecosystem, from application to chip design and fabrication.

compatibility, low power consumption and extreme compactness, silicon photonic links and devices are very appropriate for chip-to-chip and on-chip optical interconnects. However, silicon photonics is not restricted only to the communications field, as there are already commercial examples of optical chips for e.g. fiber sensor interrogation, microwave signal generation and processing, or biophotonic diagnostic chips.

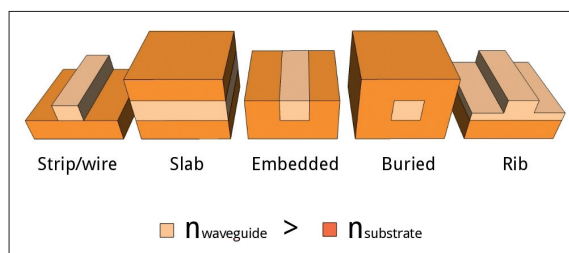
Independently of the application, there are several photonic components that are usually found in optical systems due to the basic functionality they perform. These basic building blocks (BBs) are already mature in most platforms, and can be found in most PDKs ready to be plugged into more complex layouts. We will now describe some of them, and introduce some end applications that include these BBs as an example of mature devices that are ready to go into production.

2. Silicon waveguides and couplers

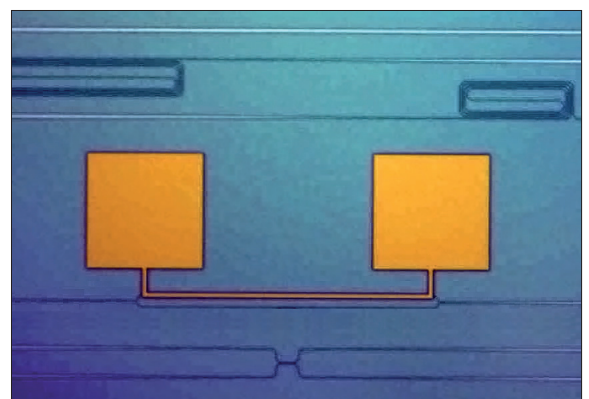
Silicon photonics is a general term that mostly refers to the lithographic process performed over Silicon-on-Insulator (SOI) wafers, using Silica (SiO_2) as the insulation layer between a thin device layer and the silicon substrate layer. The high contrast index of silicon versus the silica layer allows for the fabrication of optical

waveguides with different geometries in scales from tens of nm to hundreds of μm (see Fig. 2). Depending on these geometries, propagation losses and bending radii can vary, but for standard strip waveguides (also known as silicon nanowires) of 220 nm high and 450 nm wide, these are usually around 2.5 dB/cm and 5 μm , and lower values can be achieved through careful design. mm^2

Simple waveguides allow for more advanced structures like splitters (also referred as Y-junctions), parallel couplers, delay lines or spiral light sinks. An example of a telecom device designed with basic waveguide BBs is the optical code division multiple access (OCDMA) demultiplexer shown in Fig. 3, where 450 nm wide buried waveguides, separated 200 nm apart, where used as parallel waveguide couplers along with spiral delay lines of 10 ps. The coupling ratio was controlled here by the straight coupling section length and the longitudinal offset. Additionally, phase shifters were implemented by using thermo optic heaters, resulting in a total chip size of $8 \times 9 \text{ mm}^2$ [2].



■ **Figure 2.** Basic silicon waveguide BBs with different geometries.



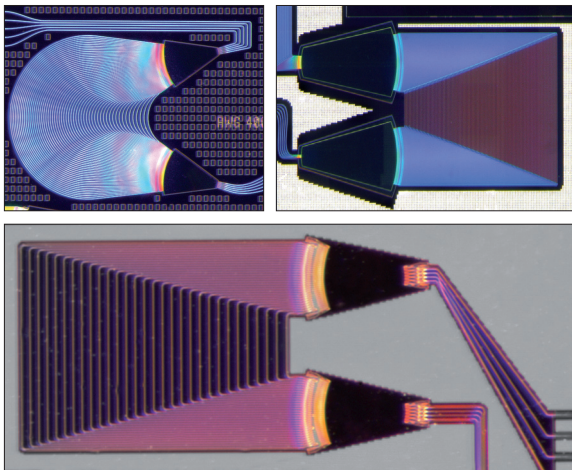
■ **Figure 3.** OCDMA decoder chip including delay lines and waveguide couplers, along with thermo-optic heaters to introduce phase shifts, designed by VLC Photonics.

3. Arrayed Waveguide Gratings

The arrayed waveguide grating (AWG) is a very versatile BB, and depending on its configuration, it can be useful for multiplexing and demultiplexing different wavelengths, switching or NxN routing, and as part of an add-drop filter.

The AWG is based on three regions, the first and last act as passive star coupler slabs, and the middle one is an array of rib waveguides of progressively increasing length, to allow multiple beam interference at the output by introducing incremental phase shifts to the rays emerging from the waveguides. Silicon AWGs benefit from the very small bending radii allowed by SOI, yielding much more compact devices than the common PLC AWGs previously used in telecom. Currently reported AWGs in SOI reach channel counts as high as 50 wavelengths, with channel spacings ranging from 0.2 to 3.6 nm (25 to 400 GHz at 1550 nm).

There are multiple design variations depending on the requirements of the end device, but the most critical design features of an AWG BB will be the minimum bending radius of the rib waveguides, the straight lengths (large enough to taper the waveguides into the slab in a lossless manner), and the minimum waveguide separation at the centre (as to avoid coupling interaction). The length of the waveguide array should always be kept to a minimum as to minimise phase errors. Fig. 4 shows multiple AWG designs at different foundries.

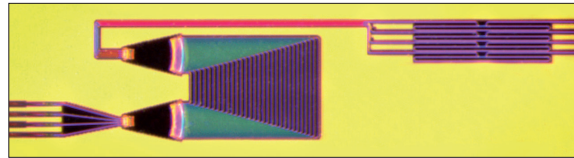


■ **Figure 4.** Different AWG BBs designed at multiple foundries: LETI (up left), IME (up right), and IMEC (down).

As an example of an application for these AWG BBs, Fig. 5 shows a microwave photonic beamformer chip, where single side-band signals coming out of a Mach-Zehnder modulator are demultiplexed by an AWG and phase-shifted by means of tunable all-pass ring resonators. The AWG was designed with 4 input and 4 output channels, and the additional channels at the input side were used for testing purposes. The AWG channel spacing was set to 3.2 nm with a Gaussian response and a FSR of 22.4

Silicon allows for small footprint and CMOS compatible photonic integrated circuits.

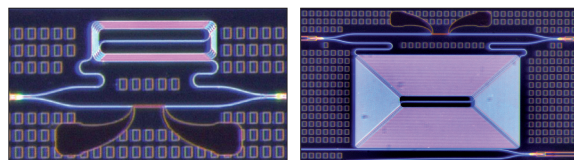
nm, enough to locate several resonances of the ring resonators into the passband. The cross section of the waveguides was 220×450 nm width, and for all the waveguide apertures to the slab region of the star couplers in the AWG, an extra shallow etch process was been employed to reduce the insertion losses [3]. © 2013 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim.



■ **Figure 5.** Optical beamformer chip in SOI, including an AWG and multiple ring resonators, courtesy of Universitat Politècnica de València designers.

4. Mach-Zehnder Interferometers

Interferometers are the core building block to many optical systems, and one of the most frequently used configurations is the Mach-Zehnder interferometer (MZI). As any interferometer, it is used to measure phase shifts between two arms through power interference at the combined output. Depending on the length difference of each arm, MZIs can be symmetric or asymmetric (see Fig. 6). By dynamically varying the relative phase of the two arms of the interferometer (e.g. by using heaters or by inserting an optical phase modulator into one of the interferometer arms), the intensity at the output of the MZI can be modulated.



■ **Figure 6.** Different Mach-Zehnder interferometer BBs designed by VLC Photonics.

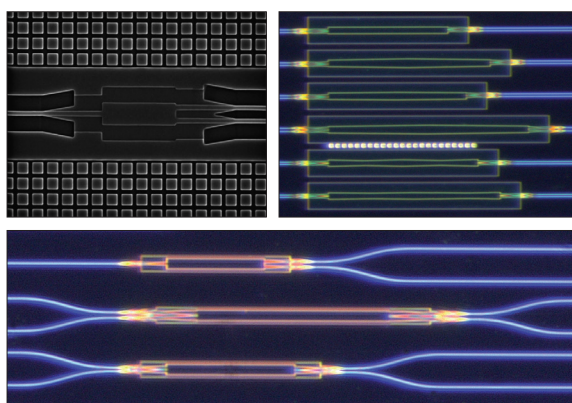
A MZI can serve as the basic BB of several devices such as thermo-optic modulators or filters. Microring-enhanced MZI structures are used as advanced BBs for sensing and switching applications, using ring resonators coupled to one arm of the MZI to give a resonant enhancement of the phase shift in that arm.

5. Multimode Interference Couplers

A Multimode interference (MMI) coupler is based on the self-imaging property of a multimode waveguide, where an input field profile is reproduced in single or multiple images at periodic intervals along the propagation direction

of guide [4]. Thus, MMIs can provide signal routing and coupling over wide optical bandwidths, while being largely polarization insensitive. Additionally, they usually show good excess losses and crosstalk, and its phase relations can be utilized to obtain phase dependent switching. While they have relatively low port counts, silicon MMI couplers prove to be the most robust splitting devices when compared to directional couplers, Y-branches or star couplers.

In a MMI coupler BB, light is launched from a number of N input waveguides into a central section, which is a waveguide designed to support a sufficiently high number of modes. After the multimode interference, light is captured back into a number M of output waveguides, providing effectively the $N \times M$ coupling functionality. Common configurations for MMI BBs are e.g. 1×2 , 1×4 , 2×2 or 4×4 , and this will determine the device's shape and length, from a few tens of μm to a few mm, as depicted in Fig. 7. Coarse multiplexing functionality can also be achieved, with usual wavelength channel spacings ranging from 3.2 up to 34 nm.



■ **Figure 7.** Multiple MMI coupler BBs, fabricated at different foundries: IMEC (up left), IME (up right), and LETI (down).

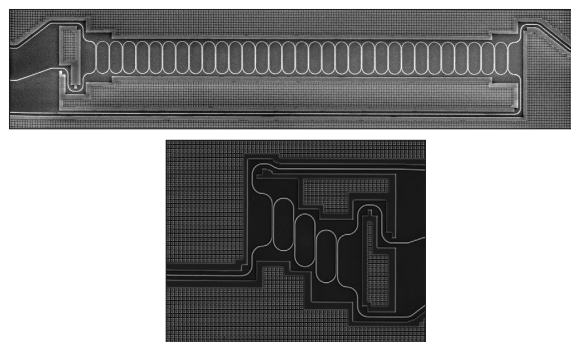
Silicon MMI BBs have mainly commercial application as broadband couplers with arbitrary power ratios and increasing port counts. MMIs are also a fundamental BB to build Mach-Zehnder delay interferometers, used in differential phase-shift keying (DPSK) demodulation and all-optical wavelength conversion, and on thermo-optical and electro-optical switches.

6. Ring Resonators

The strong light confinement achieved in SOI waveguides allows for very small losses at sharp bends, with radii of only a few micrometres. Thus, very compact rings resonators can be made and used in multiple configurations (e.g. coupled resonator, all-pass filter, cascaded).

The design trade-offs for a ring resonator BB are between resonantly enhanced group delay, device size, insertion loss and operational bandwidth.

Most of the developments towards commercial application of ring resonator BBs are in the direction of optical switching matrix, optical filters (as shown in Fig. 8, [5]) or thermally reconfigurable multiplexing devices, and there are currently efforts towards their use for optical buffering applications [6] and label-free biosensing.



■ **Figure 8.** CROW filters composed of parallel and apodized racetrack shaped ring resonators, courtesy of Universitat Politècnica de València designers.

7. Conclusions

Silicon photonics is an optical integration platform with vast opportunities ahead, due to its potential CMOS integration to reduce cost and power consumption, miniaturize functionalities, and scale up production. Multiple basic building blocks like the ones described here are already available at most foundries and included in their corresponding photonic design kits. More advanced functionalities are being customized by emerging design houses at the request of end users, extending the number of optical applications that can benefit from their integration in silicon. While there are certainly challenges ahead, the flourishing silicon photonics ecosystem is progressing and maturing rapidly, opening its doors to new fields and markets.

Acknowledgments

The authors would like to thank the Optical Communications Group of the iTEAM Institute from the Universitat Politècnica de Valencia, Spain, for some of the chip examples illustrated in this article.

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Biographies



Iñigo Artundo obtained the M.Sc. in Telecom Engineering at the Universidad Publica de Navarra (Pamplona, Spain) in 2005, and received his Ph.D. in Applied Physics and Photonics at the Vrije Universiteit Brussel (Brussels, Belgium) in 2009. He has been involved in several national and European research projects and networks of excellence

focused on reconfigurable optical interconnects, the design, fabrication and characterization of micro-optic devices, and on flexible access and in-building fiber network architectures. He has worked as a reviewer for several scientific journals and national funding agencies. He holds specializations in Business Financing, Commercial Management and Research, and Strategic Marketing. He is a member of IEEE, SPIE and COIT.



Pascual Muñoz obtained the M.Sc. degree in Telecommunication Engineering from Universitat Politècnica de Valencia (UPVLC) in 1998. After one year in the industry as IT Engineer, he returned to UPVLC to obtain his Ph.D degree in 2003, where he developed reference models for the design and modeling of integrated optics Ar-

rayed Waveguide Grating (AWG) devices. The models were validated in collaboration with the company Alcatel Optronics (Livingston, UK). After his Ph.D. he moved to Technische Universiteit Eindhoven (TUE), where he was engaged on the design of AWG-based ASPICs for ultra-short pulses processing. Back into UPVLC, Pascual was appointed as coordinator for the "Joint Research Activity on InP AWG based devices" (2007-2009) in the ePIXnet network of excellence, where several research institutes and companies collaborated to develop multi-wavelength lasers for optical burst/packet switched networks. From 2008, Pascual was an Associate Professor at UPVLC.



José David Domenech received the B.Sc. degree in Telecommunications and the M.Sc. degree in Technologies, Systems and Networks of Communication from the Universidad Politécnica de Valencia (UPVLC) in 2006 and 2008 respectively. He is currently working towards the Ph.D. degree in optics at the Telecommunications and Multimedia Applications Institute (iTEAM) from the Universidad Politécnica de Valencia, inside the Optical and Quantum Communications Group, and his research has been focused in the use of integrated ring resonators for microwave photonics applications. Since 2006, he has been working on the design of integrated optic circuits in Indium-Phosphide/Silicon Nitride/SOI technologies within several European and national research projects.



Jan Hendrik den Besten graduated in Physics and Dutch Literature at the University of Groningen in 1999 and received his Ph.D. degree from the Eindhoven University of Technology in 2004 for his work on the modeling and design, the technology and characterization of RF-modulators and multi-wavelength lasers in InP.

From 2004-2006 he coordinated a "facility access activity" in the European "Network of Excellence" ePIXnet. In practice, this meant the coordination of researchers throughout Europe cooperating with researchers in Eindhoven in the development of various ASPICs. He helped shaping the "Joint European Platform for InP-based Photonic Integrated Components and Circuits" (JePIX), about which he wrote an MBA-thesis (TiasNimbas Business School, 2006). From 2006-2011, he worked as development analyst and senior designer at ASML.



José Capmany obtained the M.Sc. degrees in Telecommunications Engineering and Physics from Universidad Politécnica de Madrid (UPM) and UNED respectively. He holds a Ph.D. in Telecommunications Engineering from UPM and a Ph.D. in Physics from the Universidad de Vigo. In 1991 he moved to the Uni-

versidad Politécnica de Valencia (UPVLC) where he has been a full Professor in Photonics and Optical Communications since 1996. In 2002 he was appointed Director of the Institute Of Telecommunications and Multimedia (iTEAM) at UPVLC. He has been engaged in many research areas within the field of photonics during the last 25 years including Microwave Photonics, Integrated Optics, Fiber Bragg Grating design and fabrication, Optical Networks and, most recently Quantum Information systems. He has published over 375 papers in scientific journals and conferences. He is a Fellow of the Institute of Electrical and Electronic Engineers (IEEE) and the Optical Society of America (OSA). In 2012, he was awarded with the Rey Jaime I on New Technologies.