# Wavelength-division-multiplexing based electronic photonic network for high speed computing

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## ABSTRACT

Integrated photonics has shown its extraordinary potential in optical computing owing to ultrafast speed, ultrawide bandwidth, and ultralow power consumption. Multiplexing techniques can also scale down the size of the photonics circuits because of the unique properties of bosons. As various passive or active building blocks for optical digital computing have been proposed, it becomes essential to develop architectures suitable for large bit-size computation. In this paper, we propose a novel wavelength-division-multiplexing (WDM) based electronic-photonic network which can implement multiple logic functions for computing. Such network arrays along with electrical circuits are capable of composing large scale electronic-photonic circuits, where the latency of the computing module is further reduced while the footprint of the circuit is also optimized. Design and experimental demonstration of multiple WDM-based fundamental building blocks that compose an optical arithmetic logical unit (ALU) is presented, showing its practicality in future large bit-size, high-speed and energy-efficient optical computing.

**Keywords:** Optical logic; integrated photonics; optical computing

## 1. INTRODUCTION

In the past decades, the development of integrated circuits follows Moore's law, which claims that the number of transistors on a chip doubles every two years while the costs are halved. However, the growth of transistor-based circuits has started to slow down recently because of the overwhelming heat issues as well as physical constraints generated when the channel length of transistor length is reduced to serval nanometers[1]. Therefore, researchers have done many investigations on various fields to extend Moore's law, including but not limited to developing new materials, exploring new fabrication technology, and proposing new computing mechanisms [2–8].

Optical computing is one of the most promising candidates for continuing Moore's law since optical circuits enjoy higher bandwidth, lower latency, and lower power consumption compared to transistor-based circuits. Currently, almost all essential building blocks for fully integrated optical circuits, such as lasers[9], modulators[10–13], passive waveguide structures [14–16], and photodetectors[17,18] have been proposed and are available in the libraries of foundries[19]. Both theoretical and experimental demonstrations of optical computing modules, from fundamental logic gates to complex optical computing circuits as well as high-level architectures[6,20–27], have been published. On the other hand, current fabrication technologies allow electronics circuits and photonics circuits being integrated on the same chip, which will dramatically increase the integrability of optical computing architectures that needs electronics parts and photonics parts working together, such as directed logic based optical computing architectures[28].

Directed logic is one paradigm of optical computing architecture that combines the advantage of electronic circuits and photonic circuits, which utilizes mature electrical circuits to control the active components in the photonics circuits and let light travel through the photonics circuits to process the signals[29]. Directed-logic based computing architectures avoid using all-optic logic gate, which requires a high input power to trigger non-linearity. It also reduces the number of conversions between electrical signals and optical signals, the latency of which is quite large according to state-of-the-art technologies.[30]

Though numerous directed logics based optical circuits realizing various logic functions have been investigated, optical computing is still in its infancy, and better computing architectures are called for replacing electrical counterparts. One critical issue of the photonics circuit is that the footprint of optical components is significantly larger than transistor-based logic gates, scaling technologies are needed to optimize the size of computing architectures. Thanks to the properties of bosons, photons with different wavelengths as well as other properties can propagate independently in the same structure, which is promising for scaling down the chip area and the number of active components in the photonics chip[31]. Better optical arithmetic units that utilize the features of light for scaling and performance optimization should be investigated.

In this paper, we explore possibilities of using novel wavelength-division-multiplexing (WDM) in electronic photonic network design, which exploits the advantages of electronics and photonics. With different input lights, a simple photonics circuit can implement multiple logic functions. In the end, we give an example of applying WDM to the structure of a full adder to extend its functionality.

## 2. WDM-based building blocks

The basic building blocks for optical computing has been concluded in serval works[32,33]. Each building block can generate one or two logic functions according to the number of output ports. In theory, most of the logic functions can be realized with these building blocks under the guidance of advanced logic synthesis algorithms[34]. However, the size of each building block is quite big. For instance, a microdisk modulator is one of the smallest modulators available in current foundries, which is around 5 microns in radius[35]. However, using microdisk modulators to function as EO logic gates is still much less compact than transistor-based logic gates fabricated by the latest 7nm technology. As a consequence, photonics circuits are normally larger than electrical counterparts.

Here we suggest using WDM to increase the throughput/number of logic functions a fundamental building block can generate. To passive components, lights of different wavelengths can propagate the components independently. One can also manipulate the input lights in order to change the logic function of the passive component. For instance, a combiner can implement OR operation if lights of one wavelength will propagate both of the input ports. On the other hand, if lights of another wavelength will only propagate one input port, then the combiner can be treated as a normal waveguide, which has no logical meanings. In this way, lights conveying different logic functions can transmit the same passive waveguide structure independently.

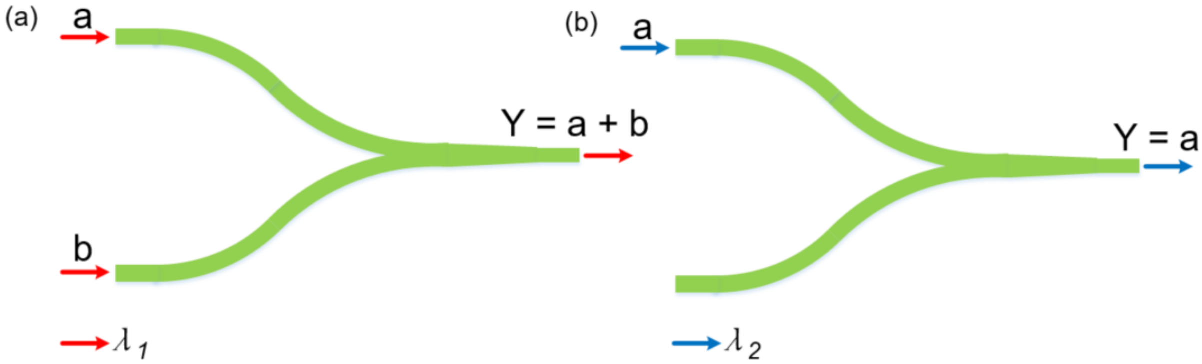


Figure 1. A Y-combiner that can be used for implementing OR function[36], (a) both 2 input ports have incoming lights, the combiner is an OR gate. (b) only one input port has incoming light, the combiner can be treated as a normal waveguide.

To active building blocks, we first broadly classify the current building blocks as broadband and narrowband according to their transmission spectrum. One typical broadband active component is the Mach-Zehnder interferometer (MZI) modulator, which is a 2*2 switch. Shown in Fig. 2 (a), the logic of the output signal depends on the input port where the input light enters the modulator. Using two lights of two wavelengths that enter the MZI modulator at different ports, one can generate two logic signals, which are inverse codes to each other. To narrowband active components such as microresonator modulators, one can set different operating wavelengths in order to implement different logic functions (shown in fig.2 (b),(c)). Recently, a novel active building block called multi-operand logic gate (MOLG) has been presented[37], which is capable of implementing multiple logic functions by manipulating electrical signals as well as selecting operation wavelength. Experiment results show that applying WDM to MOLG can further increase its functionality (shown in fig.3).

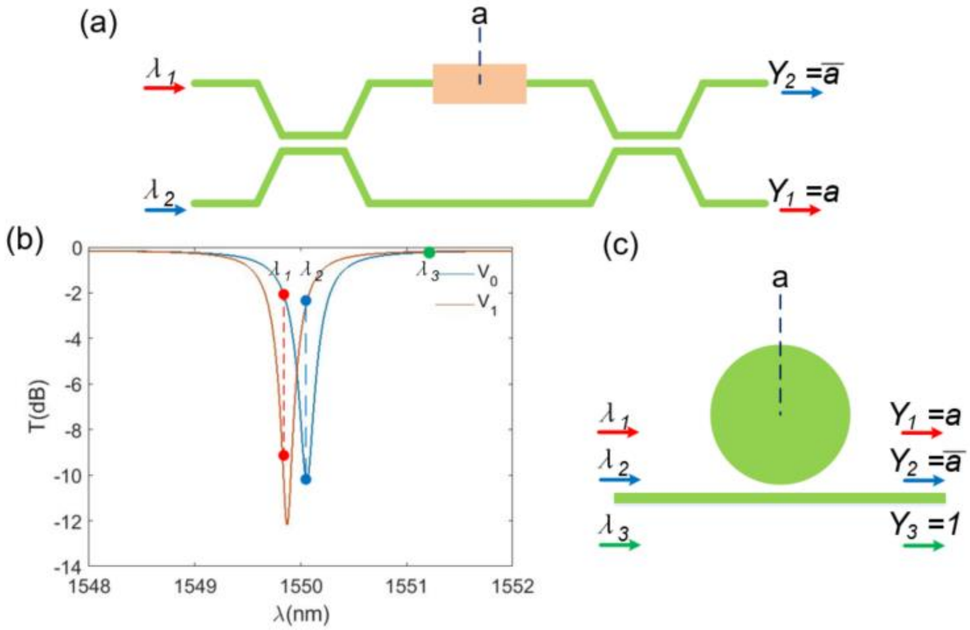
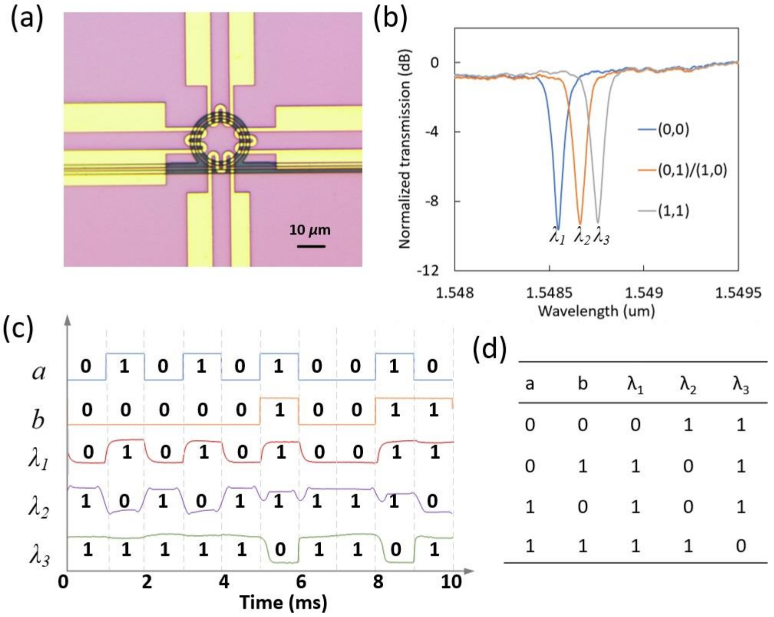


Figure 2. (a) A 2*2 MZI switch, lights coming from different input ports will convey different logic functions (b) The transmission spectrum of a microresonator modulator available in current foundries[19]. The three operating wavelengths are marked in different colors (c) The three different logic functions the microresonator can implement according to the wavelength of the input light.



| a | b | $\lambda_1$ | $\lambda_2$ | $\lambda_3$ |
|---|---|---|---|---|
| 0 | 0 | 0 | 1 | 1 |
| 0 | 1 | 1 | 0 | 1 |
| 1 | 0 | 1 | 0 | 1 |
| 1 | 1 | 1 | 1 | 0 |

Figure **3**. (a)Micrograph of the a MOLG. (b)The spectra of the MOG with different input combination and the operating wavelengths. (c)The testing results at different operating wavelengths. (d)The truth table. These figures shows applying WDM to MOLG will enable MOLG implement multiple logic functions at the same time.[37]

## 3. WDM-based computing architecture

In this section, we propose the idea of using WDM-based building blocks we mentioned above to design an electronics-photonics network to implement multi-functional optical computing. Figure 4 shows a general architecture of the WDM-based electronic-photonic network, which has N input ports and N output ports. We divide the whole optical structure into serval stages, where they are connected to each other with waveguides or other passive components. As we mentioned above, the active and passive optical components that utilize WDM are all available from foundries. The computation is realized when the light propagates these components such as modulators and the directional couplers. After the calculation is done, optical demultiplexers (DMUX) can differentiate lights conveying different logic functions and let them go through different outputs[38]. After propagating the DMUX, lights conveying computation results can go through the next structure or be converted to electrical signals via photodetector arrays for next stage computation. The critical path of this network begins from input port 1 and ends at output port N, where the light will propagate a chain of active or passive components. However, the time delay in the critical path is negligible compared to the switching time of modulators as well as that of transistors since the signal is transmitting at the speed of the light. For example, it only takes around 0.14 ps for the light to go through a 10 um micro-resonator modulator, which can function as an EO logic gate. As a result, our structure makes ultrahigh-speed computing possible.

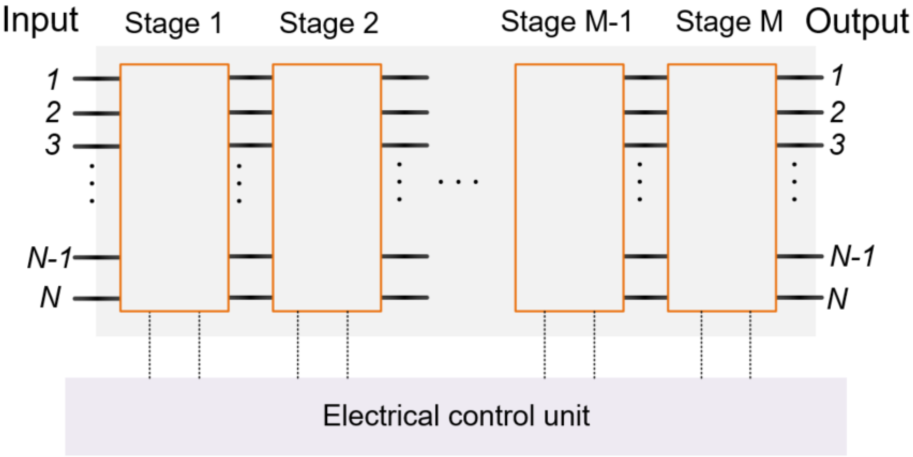


Figure 4. General architecture of a WDM-based electronic photonics network.

In addition to the common merits of optical computing architectures, such as low latency and low power consumption, our proposed WDM-based electronic photonic network is capable of implementing various logic functions by manipulating the input lights. Firstly, to each wavelength, one can decide which ports the input lights will go through. Theoretically, there are $2^N$ combinations to manipulate input lights, leading to $2^N$ different logic functions. To lights of different wavelengths that go through the same input ports, narrowband optical components can further increase the number of logic functions. As a result, multiple logic functions can be realized with our network, and these incoherent lights with different wavelengths that convey the functions can go through the same structure simultaneously and independently. It should be noted that the electrical signals which are operated on the modulators can also be altered by the electrical control unit, which contains multiplexers (MUX), leading to even more logic functions our network can realize.

Although numerous logic functions can be realized in a WDM-based electronics-photonics network, it is not easy to determine which logic function is useful in a specific application. Therefore, designing the appropriate structure, where lights of multiple wavelengths can contribute to the final result we want to obtain, is essential to reveal the power of WDM. So far, some structures that utilize WDM have been found and designed, which will be disclosed in future publications.

## 4. EXAMPLE: OPTICAL FULL ADDER

Here we briefly discuss approaches to enhance the multifunctionality of an optical full adder, which was presented in previous works[39]. Shown in Fig. 5, the light of wavelength $\lambda_1$ implements addition, which has been discussed before. Here we believe the proposed structure can actualize more logic functions. In Fig. 5, the light of wavelength $\lambda_2$ only enters port In 1 and leaves the structure at port out 0. It is not difficult to find that light $\lambda_2$ is conveying the result of a 4-bit AND gate. Besides, there are a number of input ports, such as In 2 and In 3, that have not been used. Theoretically, they can be used as input ports also to realize more logic functions consists of OR gates as well as AND gates instead of addition. Furthermore, we can also detect signals at port Out 1, which also conveys some logic functions. We believe optical full adders, as well as other photonics circuits that used to implement one logic function, have the potential to realize other logic functions that can be used in specific applications.

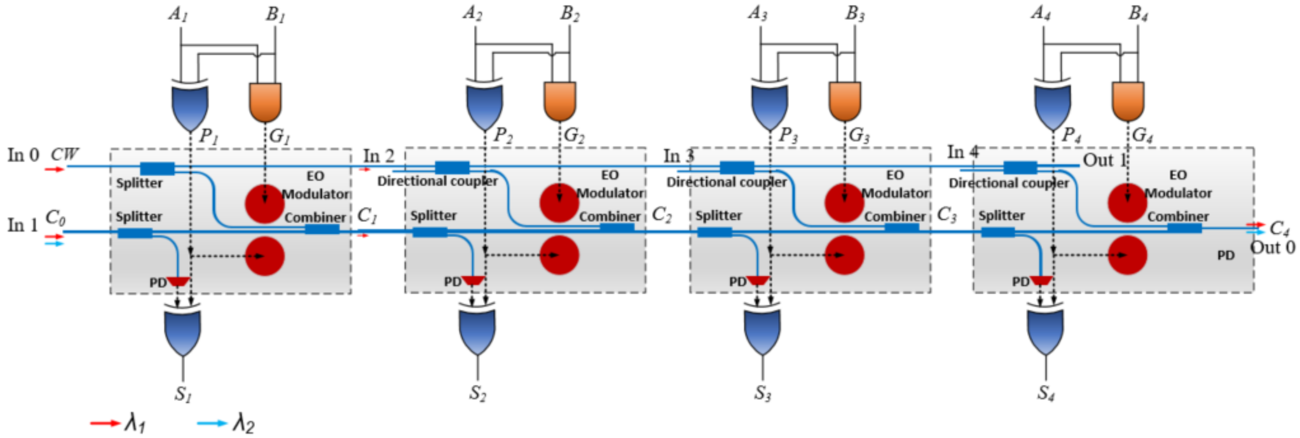


Figure 5. An optical adder proposed in previous works.[39] It has at least 5 inputs and 2 outputs.

## 5. CONCLUSION

In this paper, the WDM-based building blocks for optical computing are introduced. The idea of building a WDM-based optical structure to realize various logic functions is disclosed. We demonstrate that applying WDM to the structure of an optical full adder can increase its functionality. This study paves the way for future high-speed and low-power consumption optical computing.

## 6. ACKNOWLEDGMENT

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